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Why adoption is slow despite promising potential of biogas technology for improving energy security and mitigating climate change in Sri Lanka?

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ABSTRACT

Despite multiple economic, environmental and health benefits of biogas and governmental support to scale up biogas technologies, the rate of biogas adoption has been slow in many developing countries. Although technical barriers in biogas technologies have been mostly addressed, there are persisting gaps in knowledge about the role of administrative (regulatory) and market-based policy instruments in the waste-to-energy value chain for facilitating biogas adoption. Therefore, using the case of Sri Lanka, this study investigates policy instruments along the waste-to-energy value chain that affect biogas technology adoption. Additionally, a consistent analytical framework is developed for simultaneously assessing technical and economic potentials as well as environmental impacts of biogas adoption at large scales. Quantitative assessments are complemented with qualitative assessments including key expert interviews. The findings indicate that biogas energy potential from organic waste recycling is 29–42 PJ which accounts for 16–23% of the household energy demand. Biogas technology adoptions also offset 3.9–4.8 million tons of CO_2 equivalent gases (or 8.6 − 10.8% of nationwide GHG emissions). Despite considerable technical potential and positive environmental externalities, biogas adoptions in Sri Lanka are mainly occurring through administrative enforcement rather than market-based incentives. The ways and impacts of introducing market-based instruments to increase the investment attractiveness of the biogas technology are discussed.

1. Introduction

The demand for alternative renewable energies is rising in order to meet energy needs of growing population and industries [1]. Diminishing reserves of fossil fuels and enormous greenhouse gas (GHG) emissions related with their mining and uses also increase the importance of sustainable alternative energy sources across the world [2,3]. In the developing countries where majority of households rely on firewood, crop residues and dung as their key energy source, indoor air pollution and consequent disease burden are major issues [4]. In addition, poor sanitation and underdevelopment of waste management systems exacerbate the environmental pollution in these countries [5,6]. However, organic waste could be transformed from a burden to a boon, offering multiple-win opportunities, through the adoption of recycling systems [7]. Biogas derived from organic waste can help meet household energy demands and reduce waste disposal requirements, ensuring energy security and environmental sustainability [8,9]. Thus, biogas can be an option contributing to several sustainable development goals (SDGs) related to increasing energy access, improving environmental security and maintaining proper sanitation and healh [10,11].

Despite appearing in various sizes and shapes, biogas plants usually consist of a cylindrical tank for organic matter and a fixed, hemispherical dome for capturing the gas generated through the metabolic processes by anaerobic bacteria or microorganisms [11]. Organic waste including food waste, crop residues, animal dung, fecal and sewage sludge are the main inputs for biogas production. Additional water, chemicals and nitrifiers are important to improve the anaerobic digestion process and efficiency of the biogas generation [12]. The microorganisms break down organic waste and enhance the generation of biogas, which mainly consists of methane (approximately 60%) and carbon dioxide [13]. The produced biogas can be used for cooking

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Abbreviations: CDM, Clean Development Mechanism; GHG, Greenhouse gas; GMP, Global warming mitigation potential; GWP, Global warming potential; LPG, Liquified petroleum gas; WTE, Waste-to-energy

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without additional treatment (e.g., removal of the carbon dioxide) and can substantially reduce demand for firewood and liquified petroleum gas (LPG). Converting biogas into car fuel or electricity is also possible but the removal of non-methane gases is required first to optimize the calorific value of the gas [14].

Transitioning to organic waste derived biogas as an energy source has numerous direct and cascading benefits for society and the environment. First, rural households would be able to reduce LPG expenditures, thus allowing money to be reallocated to other necessities [15]. Second, employment opportunities would increase since biogas construction and maintenance requires labor. Third, the byproduct of biogas production, bioslurry or bio-residues, are rich in plant nutrients and, if properly treated, can be used as a soil amendment to enhance crop yields [16]. Fourth, since women and girls are responsible for collecting firewood in many societies, spending approximately three to four hours each day on this activity, biogas use would ease the burden on female household members, allowing them to reallocate their time. Fifth, biogas can also be used for lighting, extending the number of working hours available to household members. Although this may benefit all members of household, girls in particular may be able to focus on education and complete homework in the evenings. Sixth, since burning firewood in inefficient cookstoves and poorly ventilated rooms concentrates harmful substances in the air (i.e. carbon monoxide, sulfur oxides, nitrogen oxides, formaldehyde and benzopyrene), biogas use instead of firewood and other biomass would decrease smoke exposure during cooking and reduce the incidences of indoor air pollution-related respiratory and cardiovascular diseases [17,18]. Finally, the introduction of biogas also has positive ramifications for the environmental protection due to reduced demand for firewood and consequent lower rates of deforestation [11]. Diverting organic waste away from open dumps also decreases carbon dioxide and methane emissions and prevents the leakage of nutrients into the environment. Thus, increased production of biogas from organic waste can contribute to mitigate climate change as well as reduce water pollution and eutrophication problems.

Given these manifold benefits from biogas, potentials of recovering energy from organic waste though anaerobic digestion have been evaluated for some African [19] and Asian countries such as India [20], Iran [21], Pakistan [22], Bangladesh [23], China [24]. Several studies highlighted environmental improvement effects of biogas technology [25,26]. Some studies focused on technical and socio-economic barriers to biogas implementation [27,28]. However, the role of policy instruments (administrative or market-based) along waste-to-energy value chain on the investment attractiveness of the biogas technologies still lacks sufficient coverage in the literature. Despite growing interest and increasing number of studies on biogas potentials, most previous studies either addressed technical or economic aspects, or focused on environmental impacts, without comprehensively evaluating all technical, economic and environmental aspects of nation-wide biogas technology adoption and providing an integrated analytical framework that transparently describes the steps of the related calculations. This study, therefore, fills the gaps in the literature by investigating the policy instruments along waste-to-energy value chain which determine the success or failure of biogas technology adoptions. Moreover, the study contributes to the development of a transparent analytical framework for an integrated assessment of technical, economic and environmental impacts of adopting biogas technologies at a national scale. Technical calculations are coupled with qualitative methods such as key expert surveys and review of relevant technical reports for assessing the issues and opportunities influencing the biogas technology implementation.

The analysis is conducted using the case of Sri Lanka – a country heavily dependent on fossil fuel energy imports and, therefore, vulnerable to energy price shocks and structural changes in global energy markets [29]. Since more than 80% of the population reside in rural areas [30] and rely on non-commercial energy supplies, primarily firewood, deforestation and subsequent land degradation are among the major threats to environmental security [31]. Additionally, vast amounts of organic waste (e.g., livestock waste, municipal organic waste and sewage sludge) end up in open dumps or waterbodies, exacerbating the environmental pollution in the country. Despite promising potential of biogas in Sri Lanka, related studies on integrating biogas into the national energy-mix are few. One study analyzed technical aspects of biogas generation from kitchen waste and its further uses to heat water in a hotel laundry [32]. Another study addressed quality of the produced biogas and its impact on health and energy value [33]. Technical, institutional and financial challenges to biogas technology adoption were also discussed, identifying lack of financial resources as a key factor contributing to poor performance in the biogas sector [27]. Some studies presented a review of biogas segment development phases [34,35]. Perera et al. [36] provided earlier assessments of the overall potential of energy production from non-plantation biomass including firewood, crop residues and livestock waste. Yet, updates to the technical potential of biogas technology adoption, assessments of its environmental impacts, analysis of policy instruments influencing biogas upscaling could provide useful insights for growing policy debates in Sri Lanka related to renewable energy technology choices.

2. Materials and methods

2.1. Assessment of technical potential of biogas from organic waste

Ways of assessing potential biogas recovery and its economic value are presented in this section in a step-by-step manner. The amount of biogas generated depends upon the available amount of organic waste. Livestock manure (cattle and buffalo dung, swine manure, manure of sheep and goats, poultry litter), fecal sludge, sewage sludge and organic municipal waste serve as feedstock for bio-digesters.

Although dung amount produced per unit of livestock varies depending on the age and livestock species, the average amount of dung per head of livestock species can be considered in assessing overall amount of available dung from the livestock sector. Thus, the total amount of manure produced by l-species of livestock in region-r ($O_{r,l}^{L}$) was calculated considering number of livestock (N_l^L) and average amount of manure generated per head of livestock species (w_l^L):

$$O_{r,l}^{L} = N_{r,l}^{L} w_{r,l}^{L} \tag{1}$$

Human waste (urine and feces) available in rural and peri-urban areas ($O_{r,s}^{DW}$) unconnected to centralized sewerage system was calculated by considering the number of population (P_r^R) and annual generation of urine and feces per capita ($w_{r,s}^{S}$):

$$O_{r,s}^{DW} = P_r^R w_{r,s}^{S} \tag{2}$$

For assessing wastewater generated in municipal areas, either population number or total amount of municipal water consumption can be a basis. In this study the latter approach was used. Thus, wastewater generation in urban areas (O_r^{CW}) connected a sewerage system was assumed to be equal to a fixed portion (σ_r) of total municipal water consumption (Q_r):

$$O_r^{CW} = Q_r \sigma_r \tag{3}$$

Municipal solid waste can be also assessed based on population size and average waste generation. However, since total amount of municipal solid waste is available from national statistical reports, municipal organic waste (O_r^{MW}) was calculated as a fixed proportion (the organic matter content, τ_r) of the total amount of municipal solid waste (S_r^{SW}):

$$O_r^{MW} = S_r^{SW} \tau_r \tag{4}$$

Organic waste available from various activities were further aggregated into four types of organic waste (livestock manure, fecal sludge, sewage sludge and municipal organic waste). Thus, total organic waste from livestock sector ($O_{r,\text{"liv"}}$) was estimated as the sum of manure generated by different types of livestock ($O_{r,l}^{L}$):

$$O_{r,'liv'} = \sum_{l} O_{r,l}^{L} \tag{5}$$

Similarly, the total amount of fecal sludge was estimated as the sum of feces and urine generated in areas not-equipped with a centralized sewerage system:

$$O_{r,'fecs'} = \sum_{s} O_{r,s}^{DW} \tag{6}$$

The amount of sewage sludge (O_r^{CW}) and the total amount of municipal organic waste (O_r^{MW}) was redefined as:

$$O_{r,'sews'} = O_r^{CW} \tag{7}$$

$$O_{r,'muno'} = O_r^{MW} \tag{8}$$

Biogas production levels derived from organic waste ($BG_{r,i,a}$) were calculated by considering total amount of solid waste ($O_{r,i}$), dry matter content (d_i) and biogas yield per amount of dry matter ($y_{i,a}$):

$$BG_{r,i,a} = O_{r,i} d_i y_{i,a} \tag{9}$$

Since biogas yield per waste may vary depending on the quality as well as efficiency of the biogas digester, the maximum and minimum (a) levels of the biogas yield were considered.

The amount of methane gas ($MG_{r,i,a}$) inside biogas was calculated by considering the total amount of biogas from organic waste ($BG_{r,i,a}$) and the methane content of biogas (m_i):

$$MG_{r,i,a} = BG_{r,i,a} m_i \tag{10}$$

Based on this ($MG_{r,i,a}$) and energy worth of a unit of methane gas (e_i), the total energy value of the methane gas was estimated:

$$EO_{r,i,a} = MG_{r,i,a} e_i \tag{11}$$

2.2. Assessment of economic significance

The share of household energy demand substitutable by biogas energy from organic waste was calculated as a ratio of total biogas energy potential ($\sum_r \sum_i EO_{r,i,a}$) to total household energy demand (EDH):

$$PO_a = \frac{\sum_r \sum_i EO_{r,i,a}}{EDH} \bullet 100\% \tag{12}$$

Amounts of LPG and firewood (N_f; f indicates the type of energy source) equivalent to the potentially producible biogas were estimated multiplying to conversion coefficients (c_f) to the potential amount of biogas ($\sum_r \sum_i EO_{r,i,a}$):

$$N_{f,a} = c_f \sum_{r} \sum_{i} BG_{r,i,a} \tag{13}$$

The revenue from organic waste-derived biogas (R_a) was estimated based on the price for one unit of LPG energy (NP_f) and amount of LPG equivalent to potential biogas volume ($\sum_r \sum_i EO_{r,i,a}$):

$$R_a = NP_{'LPG'} N_{'LPG', \ a} \tag{14}$$

Revenues from biogas can be alternatively calculated considering the amount of firewood equivalent to biogas volume and the price of firewood. For investigating the full economic impact of the biogas technology adoptions, lowered costs for collecting and managing organic waste as well as applying chemical fertilizers should be considered in addition to LPG or firewood replacement benefits, and compared to the costs of constructing the biogas digester. Though excluded in financial calculations due to lack of data, health benefits of waste related pollution reduction further improve the economic feasibility of the biogas technology. On the other hand, the current study does include environmental benefits of using biogas for mitigating greenhouse gas emissions.

2.3. Assessment of environmental impacts

Open dumping of waste and discharge of wastewater into environment is one of the key reasons for air, soil and water pollution [5]. This study considered GHG emission impacts related to waste management given the increasing concerns over global warming and climate change. Biogas technology considerably reduces GHG emissions through: 1) reducing the open dumping of organic waste, 2) decreasing the use of firewood and fossil fuels (LPG, kerosene, etc.), and 3) lowering chemical fertilizer applications by using bio-slurry, [25,26]. However, methane gas losses during the operation of the biogas digester contribute to GHG emissions. Therefore, for calculating the net GHG emission reduction impacts of biogas technology adoptions, GHG emissions related to recycled organic waste (to be dumped or composted otherwise; H_g^{STK}), substituted fossil fuel and firewood energy sources ($\sum_f H_{f,g}^{ENQ}$), and substituted chemical fertilizer amounts ($\sum_k H_{k,g}^{FRT}$) were summed up, while excluding the methane gas losses during the operation of the digester (H_g^{LKG}):

$$GHG = \sum_{g} \left[f_g \left(H_g^{STK} + \sum_{f} H_{f,g}^{ENG} + \sum_{k} H_{k,g}^{FRT} - H_g^{LKG} \right) \right] \tag{15}$$

where f_g is global warming potential (GWP) of GHGs (g), index f indicates firewood or LPG choice, and index k stands for type of chemical fertilizer nutrients (N,P,K).

Stocks of organic waste (open dumps, landfills, compost piles, etc.) are one of the major sources of GHG emissions and consequent global warming. In this study, emissions of various GHGs (CO_2, CH_4, N_2O) from organic waste stocks (H_g^{STK}) are calculated considering overall amount of organic waste ($\sum_r \sum_i (O_{r,i}^{CW} d_i)$) and coefficients for GHG emissions per unit of organic waste (q_g^{STK}):

$$H_g^{STK} = \sum_{r} \sum_{i} \left(O_{r,i} d_i q_{g,i}^{STK} \right) \tag{16}$$

GHG emissions related to LPG and firewood uses were calculated based on share of fuel in total energy savings (s_f), total amount of fuel equivalent to potential biogas (N_f), and GHG emission rates per unit of fuel ($q_{f,g}^{ENG}$):

$$H_{f,g}^{ENG} = s_f N_f q_{f,g}^{ENG} \tag{17}$$

The production of the chemical fertilizers also significantly contributes to GHG emissions. For calculating potential GHG emission reductions due to increased uses of bio-slurry, nutrient content of the recyclable organic waste (n_k) and GHG emission rate per unit of soil nutrient ($q_{k,g}^{FRT}$) are considered as:

$$H_{k,g}^{FRT} = \left(\sum_{r} \sum_{i} O_{r,i} d_i \right) n_k q_{k,g}^{FRT} \tag{18}$$

Leakages of biogas may occur during the operation of the digester consequently contributing to GHG emission increases. It is assumed that a fixed share (r) of biogas produced is lost:

$$H_g^{LKG} = r \left(\sum_{r} \sum_{i} BG_{r,i} \right) q_g^{BIO} \tag{19}$$

where q_g^{BIO} is GHG (g) content of the biogas.

2.4. Data

Data from numerous sources were compiled to calculate organic waste volumes, energy use / supply patterns, potential amounts of biogas energy, and environmental effects related to biogas generation. Data on the population and number of livestock for each province in Sri Lanka were retrieved from statistical bulletins [37,38]. State agency reports provided information on energy supply and demand [37,39].

Fig. 1. Location of Sri Lanka. Sources: CartoGIS Services (College of Asia and the Pacific / The Australian National University).

Technical guidelines, research articles and reports were reviewed to calculate the percentage of organic material in municipal solid waste [40], wastewater generation [41], the amount of waste generated by livestock (per head) [42], human waste (per capita) [43,44], and the biogas yield per dry matter content for different types of waste [45]. GHG emission coefficients related to waste stocks, fossil fuel uses, and chemical fertilizer production were compiled from the relevant literature [26,46]. A detailed presentation of the used data and sources was provided in Tables A1-A5 in Appendix. In addition to the quantitative data for the calculations, qualitative data was collected through interviewing experts from biogas plants, technical support services, government environmental authorities, and research institutes, to identify the challenges and threats to biogas adoption. The findings of combined quantitative and qualitative research are presented in the next section.

3. Study area

3.1. Geographic and socio-economic background

Sri Lanka is an island country in the Indian Ocean located off the south of India (Fig. 1). High temperature and air humidity characterize the sub-tropical climate in the country. Annual precipitation varies depending on the agro-ecological zone, with 1100 to 1600 mm in the dry zone and 2500 to 5100 mm in wet zone [47]. Temperatures vary between 24 and 32 °C in the lowlands and 18 and 27 °C in the mountains. Thus, the climatic conditions are favorable for renewable energy technologies such as biogas production given the hot climate and abundant supply of water.

As of 2015, the total population of the country is approximately 21 million people, with the majority living in rural areas [37], and the GDP per capita is USD 4000. Although agriculture contributes only 10% to the Gross Domestic Product (GDP), one-third of the economically active population (7.7 million people) rely on earnings from the agricultural activities. The importance of agriculture for livelihoods assigns a considerable potential of biogas plants to supplement energy demand, improve cooking conditions and manage waste in rural areas.

Management of waste and wastewater in Sri Lanka is a challenging issue, particularly in urban areas [48]. Cities generate large amounts of waste, requiring suitable land for landfills and enormous amount of funds for waste collection and processing. Thus, open dumping is prevalent in low-lying areas, such as abandoned paddy fields and marshes. Industrial and municipal wastewater is often discharged into environment without proper treatment, resulting in environmental pollution and human health risks [41]. The harmful substances and nutrients from waste are leached into the nearby soil and waterways, degrading the ecosystems [49,50]. The sheer amount of waste can also decrease the flood retention area, increasing the flood risk. Additionally, waste can physically block the movement of water in the riparian systems, stagnating the water and creating favorable breeding conditions for mosquitos, flies and insects. These invertebrates are vectors for disease, placing nearby communities at health risk. The scavengers and inhabitants in the areas near open dumping sites are also directly exposed to hazardous materials, such as contaminated needles, fecal matter, toxic wastes, and pathogens [48]. Additionally, open dumping emits carbon dioxides and methane gases, increasing air pollution and contributing to climate change. Overall, open dumping decreases the quality of life for the surrounding communities and damages ecosystems [51]. Organic waste is currently a source of environmental pollution, health problems, and social unrest; however, waste can also be a source of energy when properly recycled, improving energy security in Sri Lanka.

3.2. The role of biogas and biomass energy in the current energy balance of Sri Lanka

3.2.1. Energy demand and sources in Sri Lanka

Growing waste mountains and increasing demand for energy highlight the importance of recovering energy from waste and wastewater. In 2010, energy demand by transport, industry and households was approximately 367.4 Petajoule (PJ); by 2015, total energy demand increased to 416.7 PJ following the rapid economic expansion (Table 1). Petroleum consumption by transport and industry sectors and electricity consumption by households accounted for this increase. Petroleum supplied 125.5 PJ of energy, 80% of which was consumed by the transportation sector in 2010. By 2015, petroleum consumption in the transportation sector increased by 20% and tripled in the industry sector. On the other hand, biomass consumption (primarily firewood) decreased slightly between 2010 and 2015 but remained as a dominant source of energy. If biomass accounted for more than half of total energy consumption (206.5 PJ) in 2010 this share reduced to 48% of the total energy consumption in 2015.

Share of biogas in overall energy consumption is small due to low adoption rate which will be thoroughly discussed in the next section.

Although the consumption of petroleum and coal-based energy has increased, Sri Lanka lacks fossil fuel reserves and imports these commodities. Therefore, increased uses of renewable, local energy sources would improve energy security in the country. Sri Lanka does possess natural resources capable of generating renewable energy, including abundant water availability in several large rivers capable of generating electricity. At present, hydropower production averages 6000–8000 GW h annually, depending on water availability (Fig. 2). Thermal plants fulfill the remaining electricity demand, supplying 3000–6000 GW h year^{-1}. Starting from 2008, the share of solar and wind energy has been increasing. At present, there is no electricity trade with neighboring countries though some preliminary assessments exist to connect the grids between India and Sri Lanka through submarine cables to exchange the extra amount of the electricity generated.

Table 1
Energy consumption (in PJ) in Sri Lanka (in 2010 and 2015). Source: Based on SLSEA [39].

	Households	Transport	Industry	**Total**	**Share (in %)**
2010					
Biomass	143.8		62.7	**206.5**	**56.2**
Petroleum	14.9	100.4	10.2	**125.5**	**34**
Coal			2.5	**2.5**	**0.7**
Electricity	21.8		11.3	**33.1**	**9**
Sub-total	**180.5**	**100.4**	**86.7**	**367.6**	**100**
2015					
Biomass	125.2		75.5	**200.7**	**48.2**
Petroleum	15.8	119.8	35.8	**171.4**	**41.1**
Coal			2.3	**2.3**	**0.6**
Electricity	28.3		14	**42.3**	**10.2**
Sub-total	**169.3**	**119.8**	**127.6**	**416.7**	**100**

Since most of the areas are connected to the electricity grid in Sri Lanka, lighting is mostly based on electricity usage (Fig. 3; [37]). Kerosene is still utilized as a form of lighting, particularly in the northern region where kerosene use reaches 32% of the lighting energy demand. Solar energy is relatively new technology which is gaining in popularity. Sri Lanka has significantly accelerated the deployment of solar energy by implementing progressive electricity tariff systems which is now resulting in significant roof-top solar installations.

Cooking is mostly based on firewood uses which accounts for about 80% of the energy required for cooking nation-wide (Fig. 4; [37]). Dependence on firewood is the highest in less developed regions, such as the North-Central Province. Yet, in urbanized areas, such as the Western province, LPG uses are also common, with firewood uses still accounting for about half of the cooking energy demand. Overall, firewood uses contribute to deforestation, greenhouse gas emissions and high labor requirements for households [52]. Thus, biogas produced from recycled organic waste is a more environmentally friendly and healthy alternative to cooking with firewood in rural areas.

3.2.2. Status of biogas production from organic waste and supporting policies

The adoption of renewable energy technologies, including biogas plants, have been widely supported by the government to improve energy and environmental security in Sri Lanka. Biogas derived from organic waste was introduced in the country to cope with skyrocketing energy prices in the 1970s [29]. Civil unrest, however, limited the adoption of the biogas technology despite the potential to reduce dependence on imports. After the civil war (ended in 2008), the government refocused on economic development and renewable energy and as estimated 7000 biogas plants currently exist nationwide (Mr Tuan Arifeen, Personal communication, 01.09.2017). Despite the governmental promotion of the biogas technology, the rates of biogas technology adoption are quite low compared to the adoption rates in China, India and Nepal. If we assume two out of three bio-digesters are functioning and has an average size of 6 m^3 on average, considering biogas yield and energy content we can estimate total biogas based energy generation in the country is about 0.12 PJ which accounts for less than 1% of current household energy demand.

The most common types of biogas digesters adopted in Sri Lanka are Sirilak Umaga and Chinese Fixed Dome. Since the Chinese biogas units are available at much cheaper price they account for over 80% of all adoption cases [53]. Households primarily use cow dung (in 63% cases) as a feedstock in the bio-digester due to availability and social acceptance. On the other hand, fecal and sewage sludge is rarely used (only 3% of cases) to generate biogas due to concerns with safety and cleanliness [53]. The generated biogas is mostly (in 90% of cases) used for cooking [53]. Although biogas can be converted to electricity, households rarely use biogas to generate electricity due to the low methane content of crude biogas, and high cost and low efficiency of the conversion technology. The installation costs for the biogas unit vary between USD 1100 and 7.900 thousand depending on its size and payback periods for these installations are relatively short (2.5–3 years, Table 2).

While small-scale waste-to-energy (WTE) facilities were mostly adopted by rural households and medium-scale biogas plants were built to manage waste by hotels, catering services, schools, hospitals and livestock farms, large-scale WTE plants have not been used in Sri Lanka. Although large-scale WTE facilities can help reducing waste environmental pollution related to open dumping, low calorific value and high moisture content of organic municipal waste limit the adoption of this practice [40]. The government only recently approved a plan to construct the first large-scale WTE plant at Karadiyana landfill – one of the waste dumping sites in the capital city Colombo. The plant will cost about USD 170 million and will have the capacity to recycle 450–500 t

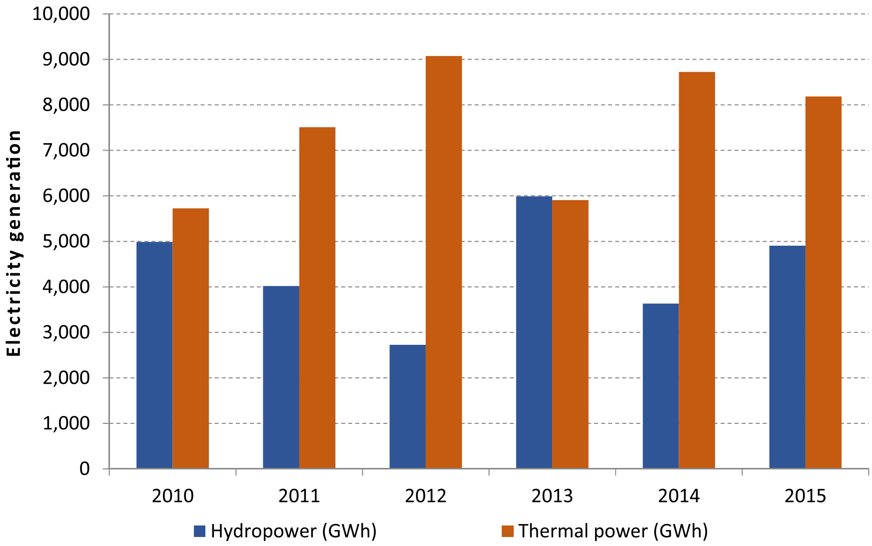

Fig. 2. Dynamics of electricity generation (2010–2015). Source: Based on CBSL [37].

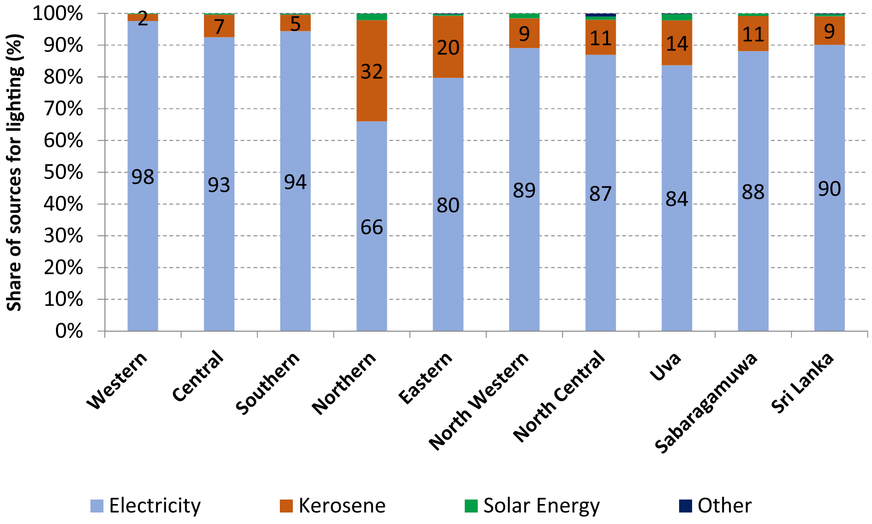

Fig. 3. Energy sources for lighting (2012/2013). Source: Based on CBSL [37].

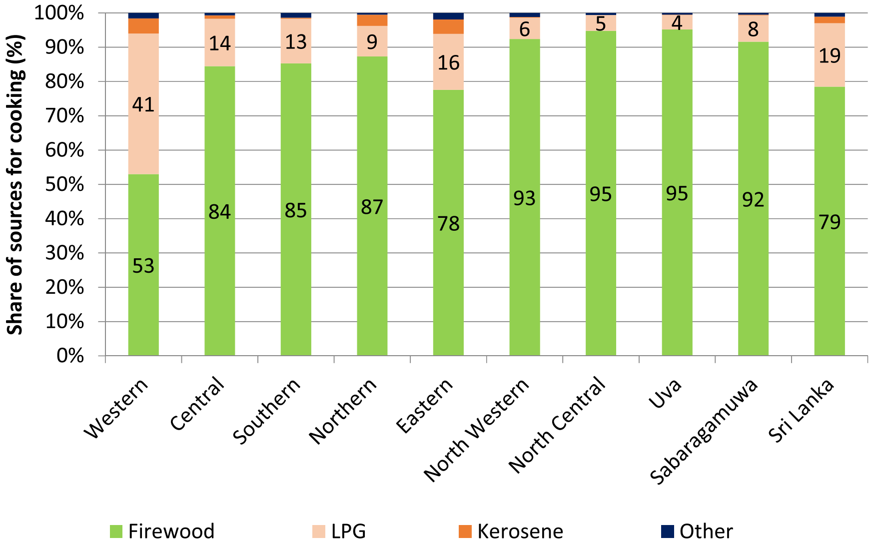

Fig. 4. Energy sources for cooking (2012/2013). Source: Based on CBSL [37].

Table 2
Biogas unit feedstock requirement, biogas yield and construction costs depending on size. Source: Personal communication with Mr Tuan Arifeen (01.09.2017) and considering USD 1 = 145 Sri Lankan Rupees (SLRs).

Biogas unit size (m^3)	Average waste feed (kg day^{-1})	Average biogas production (m^3 day^{-1})	Cost of construction (USD)	Payback period (years)
4	30	1.8	1103	3
6	50	3	1655	3
10	90	5.4	2759	3
15	140	8.4	4000	2.5
20	180	10.8	5241	2.5
30	280	18.8	7931	2.5

of the collected waste per day, consequently diverting 90% of daily waste from the landfill [54]. An important part of this WTE plant is the biogas plant for source-separated organic waste. The remaining calorie-rich inorganic (plastic, paper, etc.) waste are incinerated to generate electricity. The biogas and incineration plant are expected to generate 10 MW energy that can be sufficient to meet the energy demand for 24,000 households in Colombo.

4. Results and discussion

4.1. Potential biogas recovery from organic waste

4.1.1. Availability of organic waste and wastewater

On average, Sri Lanka generates 9000–10,000 t of solid municipal waste each day, 60% of which is organic [40]. Only 30% of the waste is properly collected and landfilled [41]. Considering these, dry matter volume of municipal organic waste is estimated to be 0.49 – 0.51 million tons $year^{-1}$ (Table 3). Since wastewater generation in the country is 250 – 300 million m^3 $year^{-1}$, sewage sludge available was calculated to be at the level of 0.06 – 0.07 million tons $year^{-1}$. Together sewage and fecal sludge amounts to about 0.4 million tons $year^{-1}$. Compared to the total amount of organic waste, human waste is only a small fraction of the total. On the other hand, livestock manure is the main type of organic waste and almost 3.6 million tons of dry cattle dung was available for recycling in 2010. Although the number of cattle and buffalo decreased in 2015, they still generate to 3.2 million tons $year^{-1}$ of dry cattle dung.

Table 4
Energy content of organic waste (million m^3 $year^{-1}$). Source: Own calculations.

Provinces	Biogas from organic waste ($BG_{r,i,a}$)		Methane (CH_4) content of biogas ($MG_{r,i,a}$)	
	Minimal	Maximal	Minimal	Maximal
Western	158.8	228.2	99.9	142.2
Central	84.6	126.2	53.1	78.8
Southern	87.9	128.6	56.0	81.6
North	112.2	174.2	71.9	111.2
Eastern	155.0	235.5	99.7	151.0
North-Western	202.8	308.0	131.0	197.9
North-Central	149.0	224.5	96.3	144.6
Uva	102.9	153.4	66.3	98.6
Sabaragamuwa	43.6	63.3	27.6	39.7
Sri Lanka	**1096.8**	**1641.9**	**701.8**	**1045.7**

4.1.2. Technical and economic potential of producing biogas from organic waste

Biogas production from organic waste is an effective option to reduce the environmental and health burden associated with open dumping [9,29]. The energy available through recycling organic waste can also supplement national energy demand [55]. As calculated, if all organic waste is diverted to biogas plants, Sri Lanka could produce 1.1–1.6 billion m^3 of biogas that can yield 700–1045 million m^3 of methane gas (Table 4). Specifically, the North-Western, Eastern, North-Central and Western provinces could each generate more than 150 million m^3 of biogas due to their large quantities of livestock manure and municipal waste.

As shown in Table 5, most of the biogas energy generated from waste can come from livestock manure, with only 6–13% is from fecal and sewage sludge. Thus, not fecal and sewage sludge but the availability of livestock manure should be prioritized in biogas technology upscaling programs. Overall, the total biogas energy potential from a mix of organic waste is a minimum of 29 PJ and a maximum of 42 PJ. Respectively, this biogas can account for 8–11% of total energy supply (367.8 PJ) and 16–23% of energy demand by Sri Lankan households (143 PJ, as of 2010). Biogas energy may therefore partially replace LPG for cooking, consequently saving between USD 445–628 million in annual expenditures. The value of biogas from organic waste is even higher when accounting for the positive externalities, such as the bio-slurry as byproduct, carbon emission reductions, decreased

Table 3
Organic waste (dry matter, $O_{r,i}d_i$) availability (million tons $year^{-1}$, in 2010 and 2015). Source: Own calculations.

	Cattle dung	Swine manure	Manure of sheeps and goats	Poultry litter	Fecal sludge	Sewage sludge	Municipal organic waste
2010							
Western	0.217	0.010	0.006	0.019	0.087	0.037	0.160
Central	0.226	0.001	0.010	0.008	0.038	0.007	0.072
Southern	0.293	0.001	0.004	0.002	0.037	0.008	0.053
North	0.455	0.000	0.025	0.004	0.016	0.000	0.026
Eastern	0.655	0.000	0.017	0.005	0.023	0.003	0.036
North-Western	0.612	0.011	0.017	0.036	0.036	0.002	0.052
North-Central	0.599	0.003	0.013	0.005	0.018	0.003	0.028
Uva	0.426	0.001	0.005	0.002	0.018	0.002	0.027
Sabaragamuwa	0.104	0.001	0.003	0.004	0.028	0.002	0.038
Sri Lanka	**3.588**	**0.027**	**0.100**	**0.084**	**0.333**	**0.064**	**0.492**
2015							
Western	0.204	0.011	0.006	0.021	0.087	0.038	0.165
Central	0.221	0.001	0.009	0.009	0.038	0.007	0.076
Southern	0.243	0.000	0.003	0.002	0.037	0.008	0.055
North	0.605	0.000	0.022	0.005	0.016	0.000	0.027
Eastern	0.671	0.000	0.015	0.004	0.023	0.003	0.038
North-Western	0.462	0.008	0.014	0.048	0.033	0.002	0.054
North-Central	0.418	0.001	0.007	0.004	0.018	0.003	0.030
Uva	0.297	0.000	0.004	0.003	0.018	0.002	0.028
Sabaragamuwa	0.095	0.000	0.004	0.004	0.028	0.003	0.040
Sri Lanka	**3.217**	**0.023**	**0.083**	**0.101**	**0.333**	**0.067**	**0.513**

Table 5
Potential energy from organic waste ($EO_{r,i,a}$; in PJ). Source: Own calculations.

Provinces	Waste types					Value (in million USD)
	Livestock manure	Fecal sludge	Sewage sludge	Organic waste	Total	
Minimum						
Western	2.3	1.0	0.2	1.0	4.5	67.9
Central	1.4	0.4	0.0	0.4	2.3	35.1
Southern	1.6	0.4	0.1	0.3	2.4	36.3
North	2.6	0.2	0.0	0.2	3.0	44.3
Eastern	3.6	0.3	0.0	0.2	4.1	61.6
North-Western	4.7	0.4	0.0	0.3	5.4	81.1
North-Central	3.5	0.2	0.0	0.2	3.9	59.2
Uva	2.4	0.2	0.0	0.2	2.7	41.1
Sabaragamuwa	0.7	0.3	0.0	0.2	1.2	18.4
Sri Lanka	**22.9**	**3.4**	**0.4**	**3.0**	**29.6**	**445.0**
Maximum						
Western	3.5	1.0	0.2	1.0	5.7	85.5
Central	2.2	0.4	0.0	0.4	3.2	47.3
Southern	2.5	0.4	0.1	0.3	3.3	49.0
North	4.1	0.2	0.0	0.2	4.4	66.8
Eastern	5.5	0.3	0.0	0.2	6.0	90.7
North-Western	7.2	0.4	0.0	0.3	7.9	118.9
North-Central	5.4	0.2	0.0	0.2	5.8	86.9
Uva	3.6	0.2	0.0	0.2	3.9	59.3
Sabaragamuwa	1.0	0.3	0.0	0.2	1.6	23.9
Sri Lanka	**35.1**	**3.4**	**0.4**	**3.0**	**41.8**	**628.4**

environmental pollution and improved health outcomes. Therefore, an in-depth financial analysis should incorporate both the direct and indirect costs and benefits associated with biogas construction and operation.

Previous estimations of biogas potential for Sri Lanka for 1997 showed biogas energy potentials from livestock manure, human waste and municipal organic waste were 5.1, 1.3–1.5, and 2.8–4.8 PJ respectively [36]. Thus, biogas recovery from municipal waste estimated in this updated study is similar to the levels in the earlier assessment. Biogas potential from human waste in the updated assessment is two to three times higher than the earlier research; it can be explained by increased population growth over time and assumption of full collection of the waste in contrast to partial collection of waste in the earlier assessment. Potential biogas recovery from animal manure in the updated estimation is four to five times higher than the levels assessed in the earlier study. Consideration of pig manure which has almost ten times higher biogas yield than other types of manure, increased number of poultry over the years as well as full collection of the animal manure assumed in the updated research can explain the difference. Indeed full collection of waste is hardly achievable and biogas recovery from waste can be restricted due to underdevelopment of waste collection infrastructure as well as limited capacity of anaerobic digestion and poor governance. However, the potential in this study meant the vision or scenario when there is no such infrastructural or institutional constraints except the availability of material supply (e.g. organic waste). Under less optimistic assumptions (e.g., much lower waste collection rates), biogas energy from waste can account for much less share (less than 16–23%) of the overall household demand and therefore biogas should be seen as a supplementary energy option.

4.2. Environmental benefits of biogas production

The environmental effect of the biogas technology accounts for considerable GHG emission reductions due to increased recycling of organic waste to produce biogas in Sri Lanka (Fig. 5). Global Warming Potential (GWP) can be reduced by 3.9–4.8 million tons of CO_2 eq. by adopting biogas technology. When considering that nationwide GHG emissions amounts to 45 million tons of CO_2 eq (as of 2011; www.climatewatchdata.org), biogas from organic waste option alone has a potential of offsetting 8.6–10.8% of these emissions. Decreased uses of firewood greatly reduces the GHG emission and accounts for substantial share of biogas related global warming mitigation potential (GMP). Reductions in fertilizer uses due to increased uses of bioslurry from biogas digesters can also play considerable role to offset GHG emissions. Thus, along with improved efficiency of cookstoves and bioenergy use facilities as well as transitioning to renewable energy uses (solar and wind energy, small hydropower stations), adoption of biogas technology can play crucial role to offset GHG emissions. When considering US$ 10 per ton of reduced CO_2 eq. emissions through Clean Development Mechanism (CDM), total benefits from reduced GHG emissions due to country-wide organic waste recycling to produce biogas can reach USD 39–48 million.

4.3. Technical and social challenges to scale up biogas technology

Despite multiple benefits of biogas, once constructed, challenges arise in the operation of biogas plants. If properly constructed and maintained, biogas plants should function for more than 10 years; however, 35% of the biogas plants became dysfunctional due to technical failures and inadequate care (Table 6). About 4% of biogas plants fail within a year, additional 15% fail within five years. These are consistent with the result that 9% of the biogas digester users were not satisfied with the performance of the digesters and 25% of the users did not recognize significant change following the biogas technology adoption [53].

Poor construction or a lack of technical skills of the masons are usual reasons for fast and frequent failures. Cracks in the plant may appear in a short time after the construction because of using low quality construction materials (Mr Chandana Seneviratne, Personal communication, 28.08.2017). Construction standards for biogas plants and certificates for construction companies need to be introduced to ensure quality control.

A lack of sufficient feedstock for the digester and improper management of organic waste also results in the failure. For instance, smaller households are not able to sustain a biogas plant since they cannot generate enough organic waste required to operate the biogas plant. Moreover, owners lacking the required knowledge often feed the bio-digester inorganic waste, such as plastics, that slows or stops the anaerobic digestion process. Maintaining proper C/N ratio of the bio-digestate is also important for controlling the bacteria population and enhancing the bio-digestion process [12]. Operating a bio-digester is thus knowledge intensive. As observed, 98% of households with functioning biogas units are trained in handling the bio-digester while only 29% of the households with failed biogas plants are trained (Table 6). Biogas owners should therefore receive technical trainings and access to extension services to ensure that biogas facilities operate effectively and efficiently. For fixing operational problems quickly and maintaining the stable operation of the plants, customer support services should be established.

Social acceptance of biogas technologies is another hurdle to the adoption. Stigma surrounding biogas generated from human waste causes households to reject the uses of biogas. (Mr Chandana Seneviratne, Personal communication, 28.08.2017). Although some hotels support biogas technologies to manage waste and benefit from their “green” status, this biogas is primarily used to heat laundry water or cook for the workers (Mr Gerard Sunil Samarakoon, Personal communication, 07.09.2017). In reality, biogas is less different than natural gas, a common energy source for cooking around the world. Education campaigns therefore should aim convincing the rural households about the safety of biogas uses for cooking.

Social stigma attached to sludge also influences the use of by-products of bio-digestion such as bio-slurry. Although bio-slurry can be used as bio-fertilizer to enhance crop yields, many households were not aware of the benefits of the bio-slurry by-product or prefer not to use it to grow crops (Mr. Tuan Arifeen, Personal communication,

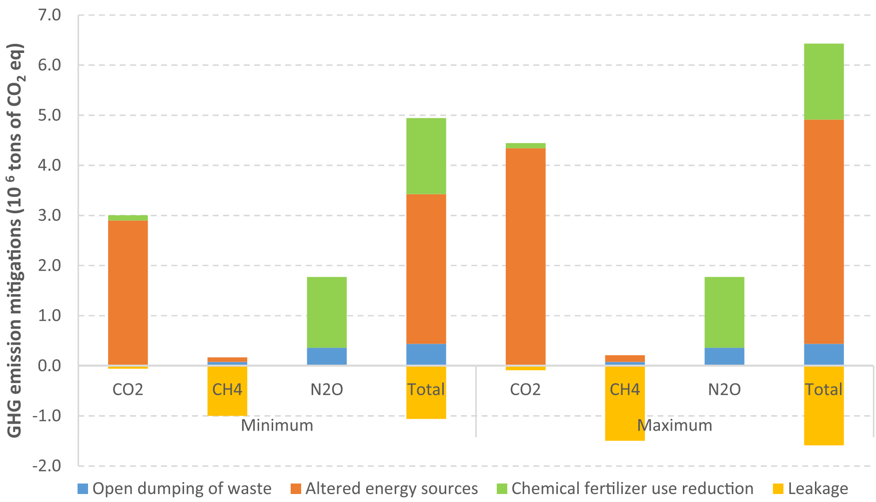

Fig. 5. Potential GHG emission mitigations related with biogas adoptions in Sri Lanka.

Table 6
Characteristics of biogas adoption across Sri Lanka (according to the survey of 138 households using biogas technology).
Source: Based on Rajapaksha [53]

Indicator	Category	Share of owners (%)
Functionality		
Working condition	Operational	65%
	Non-operational	35%
Failure time of the non-operation biogas plants	Less than 5 years	15%
	5 to 10 years	23%
	More than 10 years	56%
Being trained on biogas construction and maintenance	Operational	98%
	Non-operational	29%
Perception		
Satisfaction of biogas plant use	Satisfied	66%
	Unsatisfied	9%
	Neutral	25%
Finance		
Financing sources to construct biogas plant	Own	4%
	Full government subsidies	8%
	Full NGO support	42%
	Partial government subsidies	31%
	Partial NGO support	15%
Incentives for constructing biogas plant	Government or NGO support	52%
	Economic benefits	14%
	Recommendation by other biogas plant owners	12%
	Bio-fertilizer availability	7%
	Health benefits	5%
	Environmental benefits	1%

01.09.2017). Only 5% of households used the bio-slurry in their gardens as a soil amendment [53]. Studies on bio-slurry application effects on soil health and crop growth are also rare. Investigating the opportunities to increase the safe applications of bio-slurry and the potential to enrich biochar using bio-slurry can highlight additional benefits of biogas technology.

4.4. Financial incentives and policy instruments along the waste-to-energy value chain

In addition to technical and social challenges, financial constraints remain as a key barrier to the biogas technology adoption [53]. The high initial investment costs exceed average household income, making the technology affordable for only a few households (less than 5%) without external support. Although richer households can afford to construct biogas units without external aid, it may not be a priority for them. Energy or gas consumption may only be a small fraction of their overall budget, and thus the small savings generated by transitioning to biogas is an insufficient incentive. For a majority of households which adopted the biogas technology in Sri Lanka, financial support or government subsidies have been a key incentive: 50% of the adopters received full support and the remaining 46% received partial support from the government or non-governmental organizations (NGOs) [53]. This leads to a conclusion that households willing to adopt biogas technology in the future could be able to do so only with financial support (subsidies). In this case, since overall amount of government subsidies are quite limited, the government cannot subsidize each household which is willing to adopt the biogas technology. To address this gap, microcredit or leasing programs carefully designed to prevent any credit frauds need to be developed to support the implementation of biogas plants [56].

At present, enterprises such as hotels and catering services as well as new house owners adopted the biogas technology since they are obliged to manage their own waste according to regulations. New houses and buildings are beginning to integrate biogas plans in the planning phase due to new government regulations. In order to begin construction, the government must issue an Environmental Protection License (EPL). This license will be issued only if the construction blueprints contain a waste management plan, thus increasing the attractiveness of biogas facilities. While constructing the biogas digester as a waste management facility is mandated by strict government regulations, there seems less interest in using the produced biogas and maintaining the bio-digester properly to increase its duration.

Under administrative governance, low demand for biogas, lack of economic incentives, and improper policies and regulations in the sectors related to biogas segment reduce the attractiveness of the biogas technology. In addition to underdeveloped markets for biogas, subsidized prices for electricity and LPG reduce the competitiveness of the renewable biogas energy. Inadequate control of forest logging also makes firewood uses more attractive than biogas technology that requires considerable investments that can be recovered over time.

Likewise, lack of mechanisms to control the disposal of waste into open dumps or inadequate fines for such behavior cannot provide incentives for increasing waste collection and recycling. Reduced fees for dumping the waste into landfill sites also reduce the attractiveness of the waste recycling activities. At farm level, biogas technology competes with composting since livestock dung is a main source for both activities.

An alternative approach that stimulates biogas technology adoptions can be employment of market-based instruments to influence commodity flows and technologies along waste-to-energy chain rather than reliance on administrative regulations that oblige the enterprises and households to the adoption. So far, market-based instruments to influence biogas adoptions and increasse the investment attractiveness of the technology did not gain adequate attention in Sri Lanka. Increased fines to open dumping of waste, higher fees for landfilling and subsidized cattle rearing can improve supply of organic waste into waste recycling facilities. For example, in Germany, closing landfilling sites for organic waste and higher subsidies to the production of renewable energy sources significantly raised biogas technology adoption rates [28].

Tightening the punishments and fines to illegal logging can help maintain forest sustainability and reduce firewood uses concurrently boosting demand for non-firewood energy sources. Moreover, since many households use cook-stoves fitted for firewood burning, a wider availability of cook-stoves for biogas use will improve the attractiveness of the biogas technology. Eliminating subsidies to electricity and LPG given their high GHG emission impacts further improves the investment attractiveness of the waste-derived biogas options.

4.5. Future perspectives

As shown in the previous sections, from a technical perspective, inadequate supply of feedstock (organic waste), feeding the bio-digester with mixed waste, improper skills to handle the biogas digester, and the use of low quality construction materials accelerates the failure of biogas digesters. Certifying the biogas construction companies, ensuring post-construction customer service and training bio-digester users on proper handling of the waste and operating the plant are therefore important for improved and sustained performance of biogas units. Since currently a majority of people and government officials in Sri Lanka do not recognize environmental safety as important as economic prosperity, educational campaigns and programs should focus on raising environmental awareness and promoting resources recovery options for sustainable development.

From institutional and financial perspectives, proper institutions and financial arrangements are important to support upscaling biogas technology. The government plays an essential role in creating an enabling environment for wider implementation of the biogas technology and maintaining environmental protection. Current administrative approach in governance does not create sufficient economic incentives for users in adopting the biogas technology resulting in frequent failures and dysfunction of the installed bio-digesters. Administrative (regulatory) mechanisms should be largely replaced with market-based policy instruments that greatly influence the commodity flows and technology changes along the waste-to-energy value chain. Adequate fines to illegal waste dumping and logging, leasing and microcredits to adopt biogas technology, and elimination of subsidies to electricity, LPG, and chemical fertilizers, for instance, are options to increase the viability of biogas products. Easing land use permits for waste recycling facilities, improving transparency and controlling corruption also create a favorable investment climate for upscaling biogas technologies. Given the considerable potential of biogas option to mitigate GHG emissions, acquiring financial compensations for these reduced amounts of emissions through the CDM also improve financial feasibility of the biogas innovations.

Mostly small or medium scale biogas plants have been constructed across Sri Lanka but the cases of operating, large-scale biogas plants are rare. Larger facilities of biogas production are more feasible especially in municipal areas where enormous amount of organic waste is collected. The produced biogas in large volumes can be cleaned from non-methane gases and go through compression process. Though the cleaning and compression aprocesses are costly, scale effects may considerably reduce the costs for large plants. The compressed gas could be supplied to households to replace LPG for cooking or sold in gas stations to fuel vehicles. The compressed gas can be also used for electricity generation. Further investigation is required to determine the feasibility of biogas compression in the case of Sri Lanka, particularly given the high cost of the imported fossil fuel. Localizing the production of the gas compression technologies and training local specialists to operate large-scale biogas plants may improve the feasibility of the large-scale technologies.

5. Conclusions

Biogas produced from organic waste can be an effective option in Sri Lanka to supplement energy availability, improve waste management, reduce GHG emission and decrease import expenditures for fossil fuels and chemical fertilizers. Vast amounts of organic waste which are currently not recycled but openly dumped allow for generating considerable amount of energy. Tropical climate is also ideal for generating waste-derived biogas. If small- and medium- scale biogas plants enable households manage their waste and improve energy security, large-scale biogas plants to recycle organic municipal waste facilitate reducing environmental pollution problems in urban areas and produce additional heating or electric energy.

Our estimates show that 29 – 42 PJ energy is recoverable from organic waste in Sri Lanka. Livestock manure serve as main sources for this potential biogas energy. Energy available from sewage and fecal sludge is limited compared to energy potential of other types of organic waste. However, since potential energy from biogas equals to 16–23% of the energy currently consumed by Sri Lankan households, organic waste-derived biogas can only supplement household energy demand. Nevertheless, increased biogas uses could considerably decrease demand and expenditures to firewood and LPG. Potential cost saving from biogas uses is approximately USD 445 − 628 million which otherwise should be spent on LPG purchases from abroad. This redirection of funds from imports to domestic production will boost economic activity in the country. Biogas technology adoptions could also greatly contribute to mitigate global warming due to lower GHG emissions following the reduced firewood and LPG uses. According to our assessments, biogas technology can offset 8.6–10.8% of the nationwide GHG emissions in Sri Lanka.

However, policy efforts are essential to remove the barriers for wider adoption of biogas technologies. Low financial capability of many households is a key barrier that is slowing down the installation of biogas units. Hence, policies facilitating microfinance and leasing schemes can improve investment availability for biogas implementation. Market-based policy instruments along the waste-to-energy value chain also play crucial role for improving marketability of biogas option. For instance, enforcing fines to illegal waste dumping and logging, increasing landfilling fees, and reducing subsidies to electricity, fossil fuels, and chemical fertilizers improve the viability of biogas adoption. These measures are also useful for removing the barriers to biogas technology adoption in other developing countries with similar socio-institutional backgrounds.

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Declarations of interest

None.

Appendix

See Tables A1–A5

Table A1
Number of livestock across the provinces (2010). Source: [37].

Provinces	Types of livestock Cattle	Buffalo	Swine	Sheep and goats	Chicken	Ducks
Western	62,100	37,730	31,555	24,025	3150,740	16,660
Central	78,180	20,470	3375	36,550	1309,030	1660
Southern	72,280	67,520	1915	13,995	395,690	1185
Northern	180,390	7900	230	93,780	706,520	2215
Eastern	211,090	80,450	585	64,840	764,000	1470
North Western	209,700	57,840	33,020	65,135	6061,440	1625
North Central	186,710	83,020	8725	50,,300	783,910	1110
Uva	140,180	48,400	2485	20,175	262,740	420
Sabaragamuwa	29,090	19,230	1895	12,575	584,250	310
Total	1169,720	422,560	83,785	381,375	14,018,320	26,655

Table A2
Manure produced per head of livestock (tons year^{-1}). Source: [42].

Type of animal	Manure per head of livestock (ton year^{-1})
Cattle	15.3
Buffalo	10.7
Swine	1.9
Goats and sheep	0.75
Chicken	0.024
Ducks	0.05

Table A3
Population across the provinces and human waste per capita (ton year^{-1}). Sources: [a] [37]; [b] [43]; [c] [44].

Provinces	Total population (P_r^R, million)[a]	Urine per capita per annum ($w^S_{r,"urin"}$; ton)[b]	Excreta per capita per annum ($w^S_{r,"feces"}$; ton)[c]
Western	5.802	0.5	0.074
Central	2.532	0.5	0.074
Southern	2.444	0.5	0.074
Northern	1.052	0.5	0.074
Eastern	1.531	0.5	0.074
North Western	2.353	0.5	0.074
North Central	1.246	0.5	0.074
Uva	1.245	0.5	0.074
Sabaragamuwa	1.902	0.5	0.074
Total	20.107		

Table A4
Energy content of organic waste. Source: Based on Bond and Templeton [55].

	Cattle dung	Swine manure	Manure of sheep and goats	Poultry litter	Fecal sludge	Municipal organic waste	Sewage sludge
Minimal biogas yield ($y_{i,"min"}$; m^3 per kg of dry matter)	0.2	3.6	0.35	0.35	0.35	0.2	0.2
Maximal biogas yield ($y_{i,"max"}$; m^3 per kg of dry matter)	0.3	4.8	0.8	0.8	0.4	0.3	0.3
Methane content of biogas (m_i, %)	65	68	60	60	70	50	55
Methane gas energy (e_i, MJ per m^3)	40	40	40	40	40	40	40

Table A5
GHG emission coefficients.

	CO_2	CH_4	N_2O	Source
Open dumping of waste				
GHG emissions from organic waste stored (dumped, composted) (g kg-1)	0.165	0.013		[46]
Altered energy sources				
LPG (kg kg-1)	1.9			[45]
Firewood (kg kg-1)	1.83	3.9		[26]
Chemical fertilizer use reduction				
N (kg kg-1)	1.3		0.07	[26]
P (kg kg-1)	0.2			[26]
K (kg kg-1)	0.2			[26]
Leakage (%)	10	10		[26]
GWP factor	1	21	310	[26]

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