The potential for financing small-scale wastewater treatment through resource recovery: experience from Bocas del Toro, Panama

Sebastien Tilmans, Ana Diaz-Hernandez, Eric Nyman and Jennifer Davis

ABSTRACT

The excreta of more than half of the world's population is discharged into the environment without treatment of any kind. Particularly in low- and middle-income countries with limited public finance for treatment infrastructure, resource recovery from wastewater has the potential to finance part of the costs of sanitation systems. Most assessments of resource-recovering treatment systems in low-income settings have focused on their technical performance. In this study, using data collected from 14 upward-flow anaerobic sludge blanket septic tanks in rural Panama, we estimate the proportion of waste treatment system costs that could be offset by biogas sales. We find that biogas revenues would cover between 26% and 49% of system operation and maintenance expenses, and would improve the net present value of the wastewater system investment by 8% to 15%. Aggregate stated demand for in-home biogas delivery among sample households is more than twice the volume of gas that could be generated by a system treating waste from the entire community. In Panama and other countries where public resources are devoted to subsidizing liquid propane gas, investment in wastewater treatment systems with biogas recovery could reduce the cost of energy provision to households while improving public and environmental health.

Key words | anaerobic treatment, biogas, Panama, resource recovery, sanitation, wastewater treatment

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INTRODUCTION

The Millennium Development Goal process has helped focus global attention on the considerable gap in access to sanitation services among low- and middle-income countries. As of 2010, 2.5 billion people – more than a third of the world's population – either use sanitation facilities that are not considered to meet basic hygienic standards (21%), or have no sanitation facility at all (15%) (Joint Monitoring Program 2012). Several decades of applied research suggests that many households in developing countries exhibit low effective demand for sanitation improvements relative to other economic and livelihood priorities (Whittington *et al.* 1993, 2000; Altaf & Hughes 1994).

Less widely discussed, but arguably equally important from a public health perspective, is the fact that excreta produced by approximately 58% of the world's households (4.1 billion people) is discharged into the environment without any form of treatment (Baum *et al.* 2013). Household demand for wastewater treatment has been shown to be even lower than that for sanitation services (Choe *et al.* 1996; Whittington *et al.* 2000; Jenkins & Sugden 2006). Whereas improved sanitation facilities have the potential to provide some private benefits to households, such as privacy, dignity, and status, the benefits of wastewater treatment services typically accrue to the community or environment at large. Moreover, individuals or groups of households cannot easily be excluded from the public-health and environmental benefits of wastewater treatment services once they are provided.

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High-income countries have addressed these public-good characteristics of wastewater treatment by relying on tax revenues, rather than user fees, to finance infrastructure. In the United States, for example, more than US$85 billion in federal funding has been provided since passage of the 1972 Water Pollution Control Act to support treatment plant construction and upgrades (Copeland 2012). For many low- and middle-income countries, however, it has proven difficult to mobilize the public resources necessary for such large-scale investment in wastewater treatment. As a result, whereas the proportion of the global population using toilets connected to sewers has increased from 26% to 36% between 1990 and 2010, the share of sewage that undergoes treatment before discharge has decreased from 59% to 36% over the same period (Baum *et al.* 2013).

One strategy for increasing the return on investment from sanitation and treatment facilities is to incorporate resource recovery into system design. Such an idea is not new; so-called 'sewage farming' was pursued as early as 300 BC in Greece and during the first part of the 20th century in the United States, while small-scale agricultural re-use of excreta has been practiced in parts of Asia for centuries (Tarr 1996). Resource recovery from excreta has the potential to address some of the public-goods characteristics of wastewater treatment, insofar as the nutrients captured and energy generated represent valuable (and marketable) economic goods (Murray & Ray 2010). Shifting sanitation infrastructure planning practice in order to facilitate resource recovery could thus enhance demand for wastewater treatment.

Such a shift has emerged in some high-income countries, where replacement of aerobic with anaerobic wastewater treatment technologies, paired with the recovery of biogas, has reduced the net cost of wastewater treatment (Zeeman *et al.* 2008; McCarty *et al.* 2011; Hering *et al.* 2013). Anaerobic systems have lower energy demands per unit volume of waste treated; they also produce biogas that can be used to generate energy. In low- and middle-income countries in the tropics, upward-flow anaerobic sludge blanket (UASB) septic tanks have been promoted as an effective low-cost sewage treatment option for small-scale systems (Bogte *et al.* 1993; Coelho *et al.* 2003; Elmitwalli *et al.* 2006). When combined with an appropriate post-treatment system such as wetlands or leach fields, UASB systems have been shown to provide effective sewage treatment while also producing valuable biogas (Cavalcanti 2003; de Sousa *et al.* 2003; Almeida *et al.* 2009; Vieira & Sperling 2012).

A wide range of biogas production rates from anaerobic systems treating domestic wastewater has been reported in the literature. Kujawa-Roeleveld *et al.* (2003) measured biogas production of 26.5 liters per capita per day (LPCD) from experimental batch systems in Holland. Chaggu *et al.* (2007) estimated a production of 19 LPCD from a field batch accumulation system in Dar-es-Salaam, Tanzania. Mang & Li (2010) describe digesters in Nepal producing 27 LPCD of biogas with a methane (CH_4) content of 57–78%. Calculations based on empirical results in Verbyla *et al.* (2013) and Muga *et al.* (2009) imply a biogas yield of 16–18 LPCD from a municipal UASB treating sewage in Bolivia. Lettinga *et al.* (1993) measured biogas production rates of 12–15 LPCD from UASB septic tanks in Bandung, Indonesia. The authors found CH_4 content of 65% and 80% for tanks receiving blackwater (feces, urine, and kitchen waste) *versus* blackwater and greywater (bathing and cleaning water), respectively.

Most assessments of UASBs in low-income settings have focused on their technical performance, with little attention given to the incremental costs and benefits of biogas recovery from wastewater treatment. Murray *et al.* (2011) estimated that biogas captured from household-scale fecal sludge treatment systems would have an annual market value in the order of US$50/capita/year, but assumes the addition of manure from livestock. Similarly, UASB systems in Piraí do Sul, Brazil treating sewage from 6,000 people delivered biogas to 286 households for cooking, but relied on the feeding of additional organic substrates to the digesters (Gomes & Aisse 1985). The gas was distributed for free, and its value is not reported. Several studies report on the volumes of biogas and/or energy equivalents produced by systems under study (e.g., Starkl *et al.* 2013; Verbyla *et al.* 2013); however, none was found that monetizes the value of the biogas and compares it to the system's capital and operating costs.

This study provides such a comparison, using data from 14 anaerobic wastewater treatment systems constructed in a small rural town in Panama. Our objectives in this work were to quantify the volume of biogas that could be harvested from domestic sewage at the study site; to assess residents' willingness to pay for in-home connections to a biogas supply for home cooking; and to estimate the proportion of wastewater treatment system capital and operating costs that could be offset by the reuse of biogas. We also discuss the conditions under which biogas systems appear most likely to improve the financial viability of rural wastewater treatment systems, and possible ramifications of biogas recovery in the context of energy subsidies and carbon financing.

MATERIALS AND METHODS

Field site

Bastimentos Town ('Old Bank') is a community of approximately 190 households (740 people) and several tourism-related businesses on Bastimentos Island in Panama's Bocas del Toro Province (INEC 2012). The community is predominantly of Afro-Antillean descent, with the majority of residents speaking both English Patois and Spanish. Old Bank has a primary and secondary school, a police outpost, and a health clinic, as well as electricity supplied from a power plant on Colón Island. The primary fuel used by households for cooking is liquid propane gas (LPG), sold in refillable 25 lb (11.4 kg) tanks at local grocery stores.

A gravity-fed aqueduct delivers untreated water to the community from several springs and one creek reservoir. Census data indicate that most households (83%) have individual water connections (INEC 2012), receiving between 4 to 24 hours of service per day. Because there are no meters or pumps on the system, no estimate of daily water use in the community was found. The system is administered by the Junta Administradora de Acueducto Rural (JAAR), an elected body of volunteer community residents that establishes and collects water service fees. Most households pay a flat monthly fee of $2.50 (those with retired heads are charged $1.75).

Census data indicate that most households (84%) have water-sealed toilets (INEC 2012). Prior to the construction of the wastewater treatment systems through this study, most households discharged untreated waste into the sea. Other residents had concrete-walled cesspits which, when full, discharged into nearby streams or the sea.

System construction

During the period April–July 2008, household-scale wastewater treatment systems were installed at four homes whose toilets previously discharged into a nearby creek. The two-stage gravity-fed systems consisted of a UASB septic tank followed by a trickling filter. Between January and September 2009, ten multi-household systems were installed, each consisting of a UASB septic tank coupled with a sub-surface flow wetland. The multi-household systems served a total of 61 households, 5 hotels, and 4 restaurants at the time the study was carried out. Installation sites were purposively chosen based on technical feasibility, land availability, interest of the home and businesses owners, and visibility for demonstration effects within the community.

Biogas production projections

Projected biogas yields were calculated using data obtained from published literature. Reference values were obtained for blackwater, including feces, urine, and kitchen wastewater, as well as for total wastewater (blackwater plus bathing and cleaning effluent) separately. Significant variation in these values exists, particularly across geographic regions. For this study, wastewater data from Brazil were used as the closest proxy available to Panama (see Supplemental Information, Tables S1–S5 for additional information http://www.iwaponline.com/washdev/004/138.pdf).

Because treatment potential varies with hydraulic and solids retention times, it was assumed that 70% biochemical oxygen demand (BOD) removal could be achieved when treating domestic wastewater, and 80% removal would be possible when treating blackwater (Vieira *et al.* 1994). The methane content of the biogas was assumed to be 60%. The values in Table 1 thus reflect the daily per-capita organic load, and the calculated theoretical biogas yield, for each waste stream.

Data collection

Biogas production was measured from one single-household system (hereafter System A) and three multi-household systems (Table 2). For System A, a resident of Old Bank was trained to take daily readings for 12 days in August 2010, using a Schlumberger wet test gas meter (Paris, France). This same meter was subsequently installed for 6 weeks on

Table 1 | Organic strength of wastes and theoretical biogas production

	Total wastewater		**Blackwater**	
	High	**Low**	**High**	**Low**
BOD production (g/*cap*/d)	68[a]	40[b]	55[c]	30[c]
Biogas production (LPCD)	26	16	24	14

[a] Tchobanoglous *et al.* (2003).

[b] Mara (2004).

[c] Henze & Ledin (2001).

one of the multi-household systems (hereafter System B). For two other multi-household systems (Systems C and D), two wet-tip gas meters (wettipgasmeter.com, Nashville, TN, USA) were installed along with digital data loggers to monitor gas production. Each meter was calibrated to measure 100 mL per tip at atmospheric pressure. Data were downloaded weekly from the data loggers to obtain continuous profiles of gas flow during measurement periods. Except during biogas production monitoring periods and biogas-related experiments, the biogas diverted from the three-phase separator in each UASB tank was piped into the constructed wetland in order to eliminate fire or explosion hazard.

Two household surveys were carried out during the course of the study, in which every household in the community was asked to participate. Three attempts were made to identify and consent an eligible respondent. The first survey, conducted in August 2010, collected information from 80 heads of household regarding residents' current sanitation practices. A second survey was carried out in March 2011 with 65 residents, and obtained information on residents' attitudes toward the use of biogas (instead of LPG) for cooking, as well as their willingness and ability to pay for a connection to a biogas supply line.

Specifically, each respondent was asked about his/her household's willingness to pay US$175 for a connection to a biogas supply system, and a volumetric fee thereafter for biogas supply. Respondents were asked to assume that this biogas supply would fully supplant their LPG use for cooking. The connection fee was set to reflect a realistic estimate of the current cost of a household biogas connection and storage tank in this community, including materials and labor. The volumetric fee was set to be comparable (on a per-unit-volume basis) with the $6.47 mean price per 25 lb (11.4 kg) LPG tank that households currently pay. The limited sample size precluded use of a split-sample experiment to evaluate demand over multiple prices.

Respondents who said they were interested in connecting to a biogas line for $175 were asked whether they would prefer paying the connection fee up-front or of financing this fee at a 15% interest rate, paying $6 per month over a 36-month period. Respondents who said their household was unwilling or unable to pay $175 were asked whether they would connect if the installation fee were $90 (or $3.10/month for 36 months).

All surveys were conducted by an anthropology student from Stanford University, USA, who is a native Spanish and English speaker. Most surveys were conducted in Spanish, although 20% of respondents preferred to speak in English. Data from the household surveys were collected on personal

Table 2 | Biogas system characteristics and performance, Old Bank

	System A	**System B**	**System C**	**System D**
Connected households	1	11	5	4 blackwater; 3 greywater[a]
Connected businesses	None	1 restaurant; 1 hotel[b]	1 hotel	1 office; 1 clinic
People served	6	37	23	16
Reactor volume (L)	390	6,100	5,400	6,100
Mean biogas production (LPCD)	23.3 ± 3.0	7.1 ± 0.8	4.7 ± 1.4	3.6 ± 2.5
Max. production (LPCD)	29.0	15.9	39.9	14.5
Min. production (LPCD)	12.4	2.5	0.2	0
Number of days' readings	10	43	86	78

[a] Three homes had their own UASB septic tanks, whose effluent was discharged into the sewer to System D.

[b] The hotel's occupancy was not monitored during the measurement period. It has two permanent residents and can house up to eight guests.

digital assistants (PDAs), and all statistical analyses were carried out using SPSS (IBM, Chicago, IL) and Excel (Microsoft, Redmond, WA).

Financial analysis

A comparative net present value (NPV) analysis of an investment in wastewater treatment only, *versus* wastewater treatment with biogas production, was carried out using data collected through the activities described above. Initial capital costs for the wastewater collection and treatment system were estimated at US$165 per capita, which are somewhat higher than those reported in the literature for other (non-island) communities (e.g., Mara 1996; Nelson & Murray 2008). We assumed that capital costs for the biogas system installation were financed through the connection fees paid by residents. Annual revenues of US$4,560 were assumed based on projections of the JAAR, who planned to charge households and businesses US$2 and US$7 per month, respectively, for wastewater treatment services. It was also assumed that the JAAR would derive no profit or loss from financing biogas connections, such that the capital costs of biogas connections to the JAAR would be zero.

A 20-year lifespan was assumed for major assets, and a discount rate of 8% was used for all analyses (Indexmundi 2012). It was assumed that recurrent costs would increase by 3% each year (IMF DataMapper 2012), but the JAAR would increase service rates once every five years by an amount that reflected an annually compounded 3%. A parallel increase in LPG prices is also assumed, since biogas prices must match LPG prices in order to remain attractive to residents. Because the government of Panama has subsidized the price of LPG for residential consumers since 1992 (Dirección de Crédito Público 1992; Ministerio de la Presidencia 2011), and the outcomes of ongoing subsidy reform efforts are unknown (Solis 2012), we also examined the impact of stagnant fuel prices on the system's NPV.

Ethics

All protocols involving human subjects in this study were approved by the Institutional Review Boards of Stanford University (California, USA) and the Smithsonian Tropical Research Institute (Panama City, Panama; Washington DC, USA). Additionally, permissions for system construction were obtained at the community (Representante, Corregidor), District (Mayor), and Province (Governor) level. Authorization for primary data collection specifically was obtained from the Representante and the Corregidor of Old Bank. Complete informed consent and privacy protection procedures were employed with all study participants.

RESULTS

Household characteristics and system performance

Of the 65 respondents interviewed in the second survey, 23 (35%) respondents were male and 32 (65%) were female. The majority lived in houses occupied by a single family (95%) and owned their home (88%). The mean household size was 4.8 people. Nineteen respondent households (29%) were connected to the recently constructed wastewater treatment systems, 45 (69%) were not, and 1 respondent (1.5%) did not know his connection status.

Observed biogas production rates, along with 95% confidence intervals, are presented in Table 2. Whereas the 23.3 LPCD average production of System A is comparable to the median of the literature-based theoretical yields (20 LPCD), the multi-household systems produced a weighted mean of only 4.8 LPCD.

Given the variation in biogas production rates between the single- and multi-household systems, we extrapolated production for the entire community under three alternative scenarios. First, we assume that the yields at the community scale would be comparable to the mean yield of the multi-household systems (4.8 LPCD). Second, we assume that yields would be equivalent to the mean observed production of the single-household system (23.4 LPCD). Finally, we assume that production would be equal to the median value of literature-based estimates, or 20 LPCD. In all cases, annual production estimates assume constant production rates year round and a population of 740.

Household LPG use and demand for biogas

Mean annual LPG use among the 64 households interviewed was 36 ± 5 kg *per capita*, with an annual expenditure of $84 ± 8 per household. (One respondent who reported usage of 1,122 kg per year – suggesting commercial uses – was excluded from the analysis.) Assuming similar LPG usage throughout Old Bank, households in this community spend $15,335 ± $2,285 on 26,848 ± 3,784 kg of LPG annually.

Sixty-three respondents were asked about their households' willingness and ability to pay $175 for a connection to the biogas system. Thirty (48%) said they would connect at this price, of which 9 (30%) reported that they would pay the full cost up front and 21 (70%) said they would use the installment payment option. Among the 33 households who were unwilling to pay $175 for a biogas connection, 17 respondents (52%) said they would connect if the fee were $90. Thus, a total of 47 out of 63 respondents (75%) expressed a willingness to pay at least $90 for a biogas system connection. An additional six respondents (10%) said they would be willing to pay a volumetric rate for biogas equivalent to their current LPG expenditures, but were unwilling and/or unable to pay the connection fee. The most common reasons cited for wanting a connection were the modernity and convenience of in-home gas delivery, as well as the perception that using locally produced biogas would promote community development. Among the ten (16%) respondents who expressed no willingness to pay for biogas at all, three cited concerns about safety and explosions, two disliked the fecal origin of biogas, and one expressed doubts about the capacity of community institutions to operate the system.

The stated demand for biogas in Old Bank far exceeds the biogas that could be produced from the community's domestic wastewater. Assuming that 1,000 L of biogas is equal to 0.43 kg of LPG (Mang & Li 2010), typical demand is projected to be 216 ± 31 LPCD with a seasonal peak (in December) of 249 ± 35 LPCD. Extrapolating to the entire community, aggregate annual demand is estimated as 45,584 ± 6,345 m^3 of biogas. Even in the most optimistic biogas Scenario 2, the biogas production capacity of 6,320 m^3/year from domestic sewage is only 14% of the extrapolated willingness to pay for biogas in Old Bank. We thus conclude that household demand is not a limiting factor for the feasibility of biogas use in this community.

Financial analysis

We assume that the $175 connection fee fully covers the capital costs of the biogas connections, because 30 respondents expressed willingness to pay this amount yet at most 17 households could be served by the system under Scenario 2. As shown in Table 3, the financial viability of a stand-alone biogas service financed and operated independently of the wastewater treatment system varies considerably based on projected biogas production rates. Assuming a system treats all wastewater generated in Old Bank and sells all produced biogas, the minimum biogas production necessary to achieve a non-negative NPV is 10 LPCD.

The NPV of the wastewater treatment system alone is $-97,651 (see Supplemental Information, Tables S6 and S7 for additional information http://www.iwaponline.com/washdev/004/138.pdf). In Scenario 3, the biogas system improves the overall NPV of the wastewater treatment system by between 8% and 15%, depending on assumptions made about operation and maintenance costs. For example, we assume conservatively that the biogas and wastewater treatment systems are operated separately, with no labor synergies achieved. If we instead assume that the labor for biogas system maintenance can be incorporated into the wastewater treatment system maintenance schedule with negligible incremental staff cost, the NPV almost doubles to $14,498.

Table 3 | NPV of stand-alone biogas service in Old Bank, Panama

Scenario	Assumed biogas yields comparable to …	Biogas yield (LPCD)	Initial biogas revenue (US$)	System NPV
1	Mean of multi-household systems	4.8	$315	$–4,254
2	Mean of single-home system	23.4	$1,545	$10,397
3	Mid-range estimate from literature-based yields	20	$1,321	$7,724

Note: Analysis assumes that biogas is produced from the waste of 190 households and is supplied to 17 households.

A sensitivity analysis identified daily per-capita gas production and fuel prices as the factors with the greatest influence over the biogas system's NPV (Figure 1). A 20% reduction in either of these parameters reduces the NPV by 41%. Large reductions in LPG prices seem unlikely given the considerable subsidies in place for this fuel. At the same time, our analysis assumes biogas (and LPG) price increases equivalent to 3% per year. If LPG subsidies are maintained such that biogas price increases cannot be implemented, the NPV of the stand-alone biogas service in our analysis would drop 36% to $4,969.

DISCUSSION AND CONCLUSIONS

When Old Bank's wastewater treatment systems were commissioned, the established user fees for households and businesses with sewer connections were sufficient to cover the recurrent costs of operating and maintaining the new infrastructure. Whether the JAAR will have the ability to continue collecting these fees over time is critical to the long-term sustainability of the community's system. Political pressures often depress user fees to a point that they cannot sustain water and sanitation infrastructure (Davis 2005). It is also common for collection of user fees to becomes less regular over time for community-managed systems in resource-constrained settings. Observations from our follow-up visits to Old Bank suggest that the JAAR is already struggling with these challenges. Thus, whereas the initial situation for wastewater financing in Old Bank appeared solid, a large literature and early warning signs in the community suggest grounds for concern going forward.

The revenues generated by recovering biogas from sewage could provide a buffer against declining prices and/or collection efficiencies. Our results suggest that, in Old Bank, biogas could finance between 26% and 49% of recurring costs for wastewater treatment, depending on the particular scenario under consideration. Alternatively, these funds could be used to extend subsidies to disadvantaged groups, or to create a 'rainy day' fund for repairs and upgrades in the future.

These results depend critically on there being a reliable supply of biogas in the community. The single-family system in Old Bank achieved a mean production rate of 23 LPCD while treating both bathroom and kitchen effluent, which is comparable to yields observed in similar settings. The multi-family systems, however, had biogas yields that were well below expectations, indicating design flaws and/or operational failure. For example, households may have disposed of chemicals in their wastewater that upset the balance of the systems' microbial communities. Sporadic changes in the concentration of influent, along with unusually heavy hydraulic loads, could also affect biogas yields. As noted in the sensitivity analysis, such reduced performance can quickly eliminate the financial benefits of a biogas system.

In some settings, the nutrient-rich slurry from biogas systems is used to irrigate agricultural lands (Laramee & Davis 2013; Verbyla *et al.* 2013). The additional values associated with averted expenditure on synthetic fertilizer, increased yields, and improved household nutrition could further enhance the economic benefits of a UASB system. At the same time, important public health considerations exist both for farmers applying effluent to fields and for

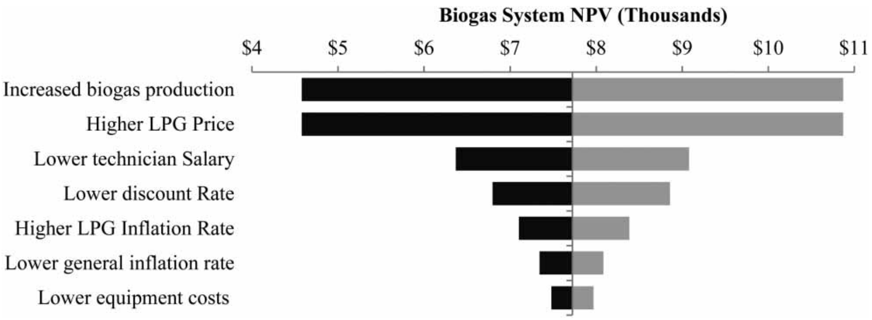

Figure 1 | Effect of 20% variation in parameter values on biogas system NPV.
Notes: NPV with baseline values of all parameters is US$7,724. Category descriptions are phrased in terms of an increase in system NPV.

consumers of wastewater-irrigated produce (Amoah *et al.* 2007; Seidu *et al.* 2008; Verbyla *et al.* 2013). Such issues were excluded from consideration in our analysis of Old Bank, where wastewater irrigation is not practiced.

Financing of wastewater treatment through biogas sales is also contingent upon sufficient demand for the gas. In Old Bank, a substantial proportion of households reported being willing to pay the full cost of a biogas connection, primarily because of its perceived convenience and modernity. These findings should be interpreted cautiously given the scope for social desirability bias associated with stated preference methodologies (Arnold & Feldman 1981). However, given that demand for biogas connections exceeded the maximum available supply by several fold, our findings are robust to a fair amount of over-optimism.

Demand for biogas can also be shaped by socioeconomic and cultural context. In Old Bank, a few survey respondents expressed reservations about the safety of biogas use, while others expressed doubt regarding the community's capacity to administer the system. A few individuals expressed disgust at the fecal origin of biogas. Such concerns have been documented to varying degrees in different locations; assessing and managing them is key to implementing a wastewater-to-biogas project successfully (Lohri *et al.* 2010; Jewitt 2011).

Biogas recovery also introduces new considerations into wastewater system design. A system optimized for biogas recovery would locate treatment systems near biogas consumers and size them according to biogas demand. By contrast, wastewater systems are typically designed to minimize capital costs while maximizing the share of sewage collected, subject to the requirement that all sewage flows by gravity. In Old Bank, the decentralized wastewater system design enabled gravity flow of sewage, but dispersed the biogas production locations. Such dispersion can create inventory management problems if local biogas production is not sufficient to meet nearby demand. Designing a system that optimizes both wastewater collection and biogas recovery thus requires spatial data on estimated effluent volumes and user demand for biogas.

Other important inventory management considerations were excluded from this analysis. The key value proposition of a biogas connection in Old Bank is that the biogas is always available. Moreover, continuous biogas availability is desirable so that residents are not required to supplement biogas with LPG. Stoves for each of these fuels are different (Sasse *et al.* 1991), and a dual-fuel system would increase complexity, cost, and vulnerability. As production will not always match instantaneous or seasonal fluctuations in demand, excess biogas storage may be necessary. Unlike other utility providers, a biogas operator has no way to modulate production to meet varying demand. Instead, installing storage capacity would help to satisfy periodic peaks in demand, while excess inventory could be burned when storage capacity was met. The costs of such gas storage and flaring were not considered in our analysis. Distributing biogas in containers as opposed to via a pipeline could mitigate these inventory problems, although this approach would present no clear advantages over existing LPG canister use to residents of communities like Old Bank.

Integrated waste management has the potential to boost production in biogas systems, but introduces other technical and operational hurdles. Adding food scraps and kitchen wastes to an anaerobic sewage treatment system has been shown to double biogas yield (Kujawa-Roeleveld *et al.* 2005). An experienced system operator could thus feed different types of waste into the digesters as needed to match biogas production with demand, as was done in Piraí do Sul, Brazil (Gomes & Aisse 1985). This approach requires knowledge of feedstock degradation kinetics and interactions, however, as well as a system for collecting and storing organic wastes. It also increases the risk of provoking process instabilities in the treatment systems (Gomes & Aisse 1985).

It is also worth noting that the benefits of systems to recover biogas from sewage are shaped by domestic energy policy. In Panama, the government subsidizes LPG such that the price paid by consumers for a 25 lb canister (US $6.46) is only 37% of the full market price (US$17.24) (Solis 2012). The parity price of a 25 lb tank of LPG increased at a compounded annual rate of 7% from 1992 to 2011 (Secretaria Nacional de Energía 2012); in 2012, the government of Panama spent $90 million to finance the LPG subsidy (Solis 2012). Our analysis assumes that biogas prices in Old Bank must be competitive with LPG. If the price of biogas could be increased, the net benefits of incorporating resource recovery into wastewater treatment would increase concomitantly. More generally, the government of Panama might consider investment in wastewater treatment and biogas recovery systems as a means of reducing the cost of energy provision to its citizens while also improving public and environmental health.

The potential also exists for wastewater/biogas systems to access carbon emissions reduction financing through the Clean Development Mechanism, although the magnitude of such benefits is unclear (Laramee & Davis 2013). The avoided emissions associated with LPG combustion could be largely offset by biogas leakage to the environment, as methane is a more potent greenhouse gas than CO_2. Some methane also remains dissolved in the effluent of sewage treatment systems (Gomes & Aisse 1985; Lettinga *et al.* 1993). If the strength of the wastewater is weak (<700 mg/L chemical oxygen demand (COD)), as is often the case with domestic wastewater, methane dissolved in the effluent can pose a substantial greenhouse gas risk (Matsuura *et al.* 2010). Other research, however, suggests that UASB wastewater treatment emissions are lower than those from direct discharge of wastewater to the environment (Miller-Robbie *et al.* 2013). Future work that characterizes the magnitude of emissions reductions that could be expected from rural anaerobic wastewater treatment systems would be useful for sector policy.

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