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Transforming Waste Management Operations to Green Energy Initiatives: Opportunities and Challenges

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ABSTRACT

Emerging challenges for the landfill enterprise include the increasing difficulty in siting and permitting landfills, rising energy costs, and impending reduction in greenhouse gas (GHG) emissions. A roadmap is presented to overcome these challenges as well as transform landfill operations to green energy initiatives. A feasibility study including financial analysis was performed for electric energy production from the captured landfill gas, solar-electric energy from closed landfill cells, and bioenergy from buffer and idle lands bordering the landfilling areas. While the landfill- and solar-electric energy options are economically viable, the bioenergy option requires due consideration of production capacity and tax credit and incentives. Returns on investment can provide sustainable solid-waste tipping fees, offset funding required for post-closure expenses, and reduce GHG emissions without direct land-use change. Energy policies for carbon credits and tax incentives are critical elements to sustain the financing of green energy projects for the waste management industry.

Keywords: Landfill Operation, Renewable Energy, Greenhouse Gas, Environmental Economics
JEL Classifications: P18, Q53, Q59

1. INTRODUCTION

Global generation of municipal solid wastes (MSW) is expected to reach 2.2 billion tonnes year^{-1} or 1.42 kg capita^{-1} day^{-1} by 2025, as compared to 1.3 billion tonnes in 2010 (Hoornweg and Bhada-Tata, 2012). MSW generation rates can vary considerably by region, country, city or even within cities. However, land disposal of MSW and its residuals remains a viable practice for both developed and under developing countries. Landfilling operation represents one of the largest anthropogenic sources of methane, which accounts for about 12% of global methane emissions (US Environmental Protection Agency [USEPA], 2012). In the United States, landfills are the third-largest human-related source of methane, amounting to 148 million metric tons CO_2e in 2014 or about 20% of the US greenhouse gas (GHG) emissions (USEPA, 2016a; The White House, 2014). With the ever-increasing energy costs, coupled with the reduction requirement of GHG emissions, the landfill enterprise is prompted to seek economically viable solutions for on-site mitigation of GHG emissions. Modern waste management facilities can no longer function solely as single-purpose containment for waste disposal; they must transition into an eco-friendly complex that also maximizes resource recovery and energy independence. Landfill sites offer tremendous land-based opportunities to explore green energy initiatives that contribute to social and economic development, with simultaneous reduction of the negative impacts on environmental and human health. Landfill gas (LFG) is a reliable fuel source for electric and renewable energy production (Ahmed et al., 2014).

Past practices have been to flare this potential source of energy or apply microbial mitigation in cover soils to reduce methane emission (Chiemchaisri et al., 2012). The US Landfill Methane Outreach Program (LMOP) has successfully encouraged the capturing and beneficial use of LFG, and numerous landfills in the US are now implementing cost-effective measures to turn methane into an energy resource. Another land-based opportunity is to install solar-electric generating devices on closed landfill locations rather than to convert these sites to golf courses, e.g., the installation of solar photovoltaic (PV) systems without cap penetrations to protect cover soils (Salasovich and Mosey, 2011). An opportune time thus exists for municipalities to develop solar-electric systems on closed landfill sites (Massachusetts Department of Energy Resources, undated). Moreover, idle and buffer lands surrounding active landfill cells can be used to grow bioenergy crops before these lands are prepared for soil removal or, ultimately, become new landfill cells. As the trend continues to show an increase in the average landfill sizes (USEPA, 2016a; USEPA, 2014), larger facilities are more financially capable of investing green energy projects. Revenues generated from these projects can help offset landfilling costs and ease the financial burden when the facility enters the lengthy process of post-closure care. At the county or municipal level, waste management professionals are seeking implementation guidance to overcome investment challenges for these sustainable technologies.

In recent literature, an assessment of mixed energy production scenarios for waste management facilities has not been duly reported; therefore, this paper provides a review of the essential technical and financial aspects of those sustainable technologies and presents a roadmap to guide modern waste management facilities in developing on-site green energy projects. The intent is to assess the financial returns and environmental benefits resulting from the implementation of LFG-to-energy, solar-to-energy, and bioenergy programs throughout the lifecycle of an operating landfill facility. Key environmental benefits are quantified with respect to the reduction in GHG emissions. These landfill-based energy projects require no direct land-use change to avoid environmental impact, and render business opportunities of carbon trading and low-carbon intensity goals. An investment strategy is presented to justify that green energy projects are promising financing instruments for landfilling operations as well as post-closure care. Net present value (NPV) analysis is conducted to determine payback periods, internal rates of return (IRR), and benefit-to-cost (B/C) ratios, with and without due considerations of carbon credits and/or tax incentives. Specifically, this paper will address the following questions:

1. What are the likely economic returns and environmental impacts among the studied green energy initiatives?
2. How could a waste management facility optimally implement these mixed green energy projects throughout the lifecycle of landfilling and post-closure operations?
3. To what extent can an energy policy provide incentives for waste management facilities to develop green energy projects?

2. BACKGROUND INFORMATION

This section reviews the current literature relevant to financial implications and environmental benefits associated with the implementation of green energy projects at landfill facilities. Information resources are commonly available from governmental agencies, research institutes, and industrial sources. Justifications for developing these green energy options for waste management facilities are described in light of experiences gained from field investigations and case studies.

2.1. LFG to Energy

Methane is a major component of emitted LFG. It contributes a global warming potential more than 21 times greater CO_2. The economy of energy recovery from LFG has been shown to be significantly better in terms of CO_2 reduction than other alternative forms (Gardner et al., 1993). LFG-to-energy projects enable communities and landfill facilities to turn a liability into an asset for the energy market (Amini and Reinhart, 2011; Wustenhagen and Bilharz, 2006). In particular, the collection and conversion of LFG to electric energy could render the benefits of energy saving, capital recovery, and protection of the environment by reducing GHG emissions.

Extensive literature is available pertaining to the economic, technical, environmental, and social benefits of LFG utilization for electric energy production (de Abreu et al., 2011; Tsave and Karapidakis, 2008; Bove and Lunghi, 2006; Jaramillo and Matthews, 2005). LFG-to-energy projects have been shown to be both economically and socially viable, resulting in <4.0 cents kWh^{-1} of breakeven price and a social subsidy that can be significantly lower than the federal tax break of 1.5 cents kWh^{-1} (Jaramillo and Matthews, 2005). This earlier study was based on assumptions of a capital cost of \$1,000 kW^{-1}, zero energy tax credit, and a 12% discount rate. Its validity for today's economy needs to be revisited.

As of March 2016, the USEPA has reported 823 active LFG energy projects in the LMOP database, of which 83% are LFG-electric projects with an average capacity of 3 MW per project (USEPA, 2016b). Utilization of LFG for electric power generation can qualify to earn carbon credits, provided that the facility is not under the New Source Performance Standards or other regulatory requirements for gas collection and destruction. Eligible landfill-to-energy credits must satisfy the requirement of "additionality" that extends beyond the business-as-usual practice (Sherlock, 2014). Producers of electricity from LFG may take advantage of the Business Energy Investment Tax Credits (ITC) or the Renewable Electricity Production Tax Credit (REPTC) that allows a 1.1-cent credit kWh^{-1} for up to 30% of the project cost. Thus, using LFG to generate electricity can turn a potential liability into a benefit.

At the close of a landfill, continued monitoring and maintenance are generally required for a 30-year post-closure attention, which could incur an annual cost of approximately \$100,000. A performance-based strategy for post-closure care was proposed to attain increased environmental benefits at a compatible cost (Morris and Barlaz, 2011). The required funding may come from a landfill tax or an aftercare rebate to finance accelerated landfill care (Beaven et al., 2014). Green energy projects examined in our paper can certainly be an alternate option to ease the financial burden on closure expenses for the waste management industry.

2.2. Solar to Energy

The solar market has evolved and expanded rapidly in various parts of the world. According to the latest statistics from the Solar Energy Industries Association (2016), the total installed capacity in US has reached 31.6 gigawatts (GW), enough to power

6.2 million American homes. The cost of electric generation from solar energy can be ranged from of 8.7 to 40.00 cents kWh^{-1}, which is generally higher than the 4.9 cents kWh^{-1} for pulverized coal (Sim, 2004). For this reason, the ITC plays an important role in public policy for the solar industry. Environmentally, the solar PV system emits zero carbon kWh^{-1}, which equates to emission savings of 229 g of carbon kWh^{-1} or \$175-\$1,400 ton^{-1} of carbon avoided (Sim, 2004).

The solar industry can transform closed landfill cells into ideal sites for electric energy production. These cells currently have limited redevelopment potential due to the differential soil settlement over time and regulatory concerns regarding soil erosion and disruption of the cover cap, which precludes the possibility of growing bioenergy crops. As of April 2016, the US Re-powering Initiatives have identified 179 renewable energy installations on 171 contaminated, mine, and landfill sites, including some 102 solar and wind energy projects on landfills and landfill buffer lands (USEPA, 2016c). The 10-MW system on a 47-acre (19-Ha) site at Freshkills in Staten Island, New York, is a good example of solar-to-energy projects on landfills (Kroh, 2013).The trading of Solar Renewable Energy Certificates (SRECs) is available through open exchange markets in several eastern states and one SREC is equivalent to 1 MWh of solar electricity. The June 2016 SREC settlement price from the FLETT Exchange has reached \$270 $SREC^{-1}$, up from around \$230 $SREC^{-1}$ at the end of 2015 (The Flett Exchange, 2016).

2.3. Bioenergy Production

Those idle and buffer lands at a landfill facility offer another unique land-based opportunity to grow bioenergy crops. As explained earlier, these lands will remain un-utilized until they eventually become new landfill cells or are commissioned for soil removal. The utilization of idle and buffer lands at a landfill facility to grow bioenergy crops is similar, in principle, to produce biofuels on marginal lands (Milbrabdt et al., 2014; Bansal et al., 2013; Cai et al., 2011; Rowe et al., 2009; Zhou and Thomson, 2009). This non-traditional type of agronomic land does not compete with food production and already incurs a management cost. Because of the time constraints and the scale of economy for longer-term projects, growing bioenergy crops on these once-available lands will help create a self-sufficient biofuel supply for the utility while reducing its impact on the local environment and, collectively, increasing energy independence for the nation. A utility-based biodiesel production model allows waste management facilities to incorporate the produced biofuel into their daily fuel consumption while reducing fuel costs for MSW collection and transportation needs.

The financial perspectives for biodiesel can vary from \$2.80 $gallon^{-1}$ (\$0.74 L^{-1}) of production cost for a B100 plant with an annual capacity of 50 million gallons (189 million L) to over \$4.00 $gallon^{-1}$ (\$1.06 L^{-1}) for small scale productions. The feedstock cost of commodity oil is currently around \$2.40 $gallon^{-1}$ (\$0.63 L^{-1}) (Pienaar and Brent, 2012). US producers of biodiesel and renewable diesel that meet the ASTM specifications are eligible for the Renewable Identification Number (RIN) certificate, with a current value of \$0.60 RIN^{-1}, or for the fuel tax incentive at \$1.00 $gallon^{-1}$ (\$0.26 L^{-1}) (US Department of Energy, 2016).The latter has lapsed and has been reinstated several times over the past 4 years, which is creating an uncertain climate for industry investment (Progressive Fuels Limited Markets Daily, 2016).

3. METHODOLOGY

A hypothetical site is used to demonstrate the conceptual development and implementation strategy of green energy projects on typical landfill facilities. These projects include currently acceptable technological options: LFG-electric, solar-to-electric, and bioenergy productions. Although previous research has addressed individual project option, integrating these project types for waste management facilities has not been examined in the recent literature.

This hypothetical site includes a landfill cell with a 20-year operating period, followed by a 30-year post-closure maintenance. The LFG-to-energy project starts approximately 3-5 years after the first filling of the landfill cell, and the bioenergy-biodiesel plant begins its biofuel production during the same time frame. The installation of solar-PV systems begins shortly after the landfill cell is closed and considered appropriate. The logical sequence of project implementation is shown in Figure 1.

In addition, the spatial layout for project locations is demonstrated using a site diagram taken from a municipal facility located in Catawba County, North Carolina (Figure 2). This Catawba EcoComplex occupies 805 acres (326 ha) of county-owned land and includes a 100-ac (40 ha) landfilling area, namely the Blackburn landfill with a nearby 3-MW electric generator. The open circle in Figure 2 represents the next landfill cell upon the closing of the Blackburn landfill. Various oilseed crops for biodiesel feedstock are planted on buffer lands of 150 acres (60 ha) distributed throughout the complex. The harvested crops are processed by an integrated oilseed crusher, and a biodiesel facility with a 130,000 gallons $year^{-1}$ (492,050 L $year^{-1}$) capacity is located on-site to produce biofuel and seed meals. The Catawba complex has demonstrated its success in implementing the LFG-to-energy project in conjunction with its landfilling operations. Table 1 summarizes the key features of this hypothetical facility. Additional assumptions are:

a. The landfill cell occupies 100 acres (40 ha) with an ultimate designed capacity of 11 million tons of MSW. This was

Figure 1: A planning horizon for green energy project implementation

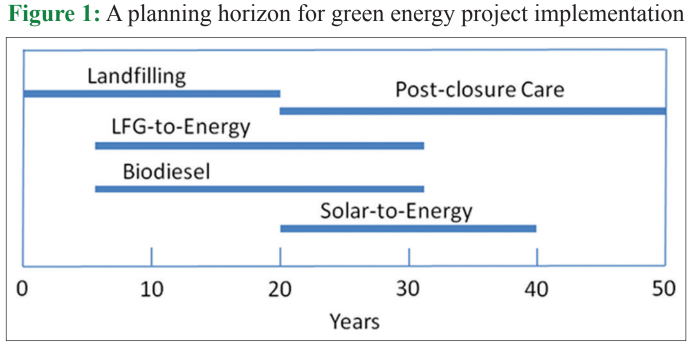
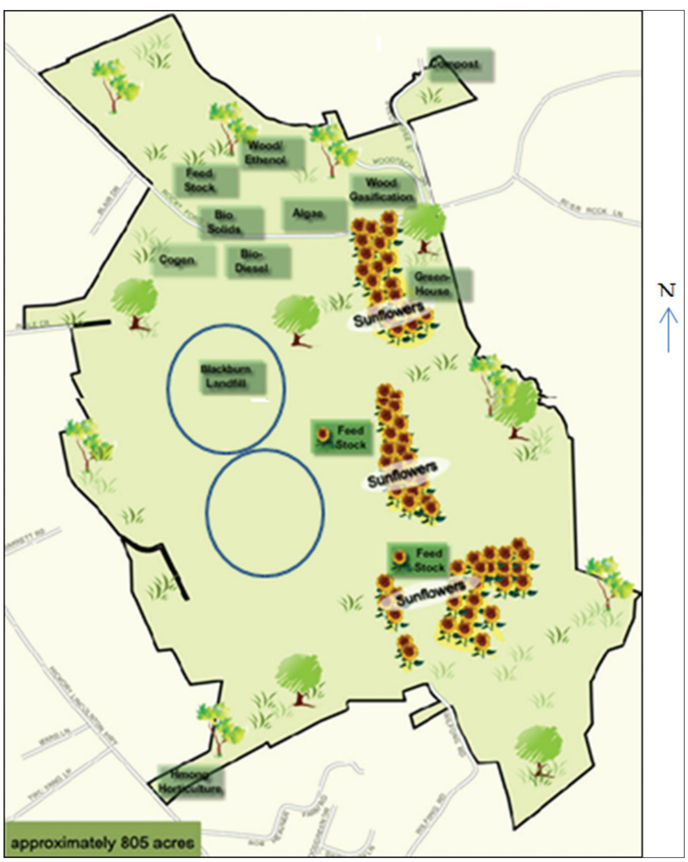


Table 1: Key features of the hypothetical MSW facility

Parameters	LFG energy (A)	LFG energy (B)	LFG energy (C)	Solar energy (A)	Solar energy (B)	Bioenergy
Basic						
Land, ha	40	40	40	20	40	60
MSW, million tons	3.6	2.9	1.8	-	-	-
Generator capacity, MW	3.0	3.0	3.0	-	-	-
Generator downtime, %	25	25	25	-	-	-
Vegetable oil, L ha^{-1} $year^{-1}$	-	-	-	-	-	608
Project duration, years	25	25	25	30	30	25
Technical						
LFG, m^3d^{-1}million-ton^{-1} MSW	12,230	12,230	12,230	-	-	-
Methane in LFG, %	50	50	50	-	-	-
Methane heating value, MJ m^{-3}	34	34	34	-	-	-
Thermal-electric conversion, %	35	35	35	-	-	-
Land required, ha GWh^{-1} $year^{-1}$	-	-	-	1.13	1.13	-
Available solar radiation, hours $year^{-1}$	-	-	-	1,530	1,530	-
Vegetable to biodiesel, %	-	-	-	-	-	90
Household energy usage, MWh $year^{-1}$	11	11	11	11	11	-
EV charged*, km kWh^{-1}	-	-	-	7.85	7.85	-
Utility truck, km L^{-1}	-	-	-	-	-	10
Vehicle usage, km $year^{-1}$	19,310	19,310	19,310	19,310	19,310	19,310
Economic						
Down payment of investment, %	100	100	100	100	100	100
Savage value, $	0	0	0	0	0	0
Inflation rate, %	1.0	1.0	1.0	1.0	1.0	1.0
Marginal rate of return, %	3.5	3.5	3.5	3.5	3.5	3.5

*Tseng et al. 2013. LFG (A)=Average LFG generating scenario, LFG (B)=20% MSW reduction, LFG (C)=50% MSW reduction, Solar (A)=50% use of closed cell area, Solar (B)=100% use of closed cell area. MSW: Municipal solid wastes, LFG: Landfill gas

Figure 2: Spatial orientation of green energy projects on landfill sites (Courtesy of Catawba County, NC)



derived from analyzing the capacity data from 52 landfill sites in the LMOP dataset. We assume the long-term average waste-in-place to be one-third of the ultimate capacity, or 3.6 million tons, which is designated as the average plant. Additional reductions of the annual average by 50% and 80% are included for worst-case scenarios.

b. The annual average of methane emission is estimated using the waste-in-place method (Morgan and Yang, 2011) [35], although other approaches are available to account for annual variations of gas production, e.g. USEPA LandGEM model (USEPA, 2005).
c. Based on estimates from the Environmental and Engineering Study Institute (2013), the LFG supply is averaged at 432,000 cu. ft day^{-1} million-ton^{-1} (12,233 cu. m day^{-1} million-ton^{-1}) of MSW and the conversion of methane energy to electricity is at 35% efficiency, or 0.65 MW million-ton^{-1} MSW. The latter figure is slightly lower than the 0.78 MW number suggested by USEPA (2005)[1].
d. The solar PV system is installed on the 50-ac (40-ha) landfill cell upon closing at the end of the operating lifetime. Each GWh $year^{-1}$ of solar-electric output requires 2.8 acres (1.1 ha) of land area (Ong et al., 2013). The unit cost for the solar system is \$1.00 W^{-1} with an understanding that this cost may vary from 60 cents to \$3.00 W^{-1}. An alternate decision is to turn entire closed landfill area of 100 acres (40 ha) into solar-electric energy production.
e. Buffer lands of 150 acres (60 ha) are used to grow bioenergy crops, and the conversion of vegetable oil to biodiesel is at 90% efficiency. Yield data collected from a 3-year rotational planting of soybean; winter cover crops of rye and vetch; sunflower; winter wheat; corn; and canola at

1 Other options of LFG utilizations, such as compressed and liquefied natural gas, as well as cogeneration were not included in our analysis.

the Catawba complex suggest an annual average yield of 65 gallons acre^{-1} (608 L ha^{-1}) of biodiesel[2].

f. Each ton of methane combusted avoids 17.25 tons of CO_2, and each MWh of solar electric output eliminates 0.69 tons of CO_2 (SMA, 2016).
g. The NPV analysis is based on a 1% inflation rate, 3.5% marginal rate of return, 100% down payment, and zero salvage value.[3]
h. Environmental and social benefits for these green energy projects are enumerated by the number of electric vehicles (EVs) charged, the number of homes powered, the number of trucks fueled, and the avoidance of CO_2 emissions.[4]

4. RESULTS AND DISCUSSIONS

LFG-to-energy generates a total of 19,896 MWh year^{-1} for the 3.6-million-ton scenario. This is equivalent to a 2.33 MW generation capacity with 25% downtime. Results for all three case scenarios are included in Table 2. The capital cost of 6 million dollars, shown in Table 3, is based on a unit cost of \$2,000 kW^{-1} (Environmental and Engineering Study Institute, 2013) applied to the 3-MW generator capacity. The resulting annual operating costs are shown in Table 3. The sale of electricity at 6 cents kWh^{-1} would generate 1.19 million dollars of annual revenue for the average LFG plant. However, network connection and maintenance fees were not accounted for in this preliminary economic evaluation.

The installation of the PV solar system atop the 50-ac (20-ha) landfill cover is estimated to cost 2.04 million dollars for a 2.04-MW PV system (Table 3). The annual operating cost is based on \$11.4 MWh^{-1} (USEPA, 2014), and the electricity generation is calculated from the generation capacity and the available solar hours of 4.2 h day^{-1} for 365 days year^{-1}. The 2.04-MW and 4.08-MW solar systems produce significantly fewer MWh than the average LFG plant because of the lower annual solar hours; i.e., 17.5% solar insolation versus 75% generator uptime.

Biodiesel production is estimated at an annual yield of 8,775 gallons (33,220 L) of biodiesel (Table 2), based on the yield data of 608 L ha^{-1} year^{-1} obtained from the Catawba complex. The capital cost is estimated at \$250,000 for the oil-seed crush and biodiesel facility; the operating cost is based on \$3.00 gallon^{-1} (\$0.79 L^{-1}), which includes on-site harvest of feedstock, chemicals, processing, and maintenance.

4.1. Economic Analysis without Energy Credits

Results of economic analysis are summarized in Table 3. Under the scenario of no applicable energy credits, the average LFG-to-energy project is shown to be financially viable with a B/C ratio of 1.47, NPV payback of 10 years, and an IRR equal to 10.85%. This is not surprising because the beneficial use of LFG for electric power generation is well recognized for its economic value. A return of 10.85% compares well to the typical yields between 8% and 11% reported by the Standard and Poor 500. The LFG projects are still considered viable for the worst-case scenarios of 20% and 50% reductions in MSW because their B/C ratios equal to 1.33 and 1.05, respectively.

The solar-to-energy option has B/C ratios of 1.41-1.46, which are close to that of the average LFG project. Their payback periods are in the order of 16-17 years and IRRs of 5.5-6.5% as compared to 10.85% of the average LFG project. The B/C ratio for biodiesel production is below 1.0, implying that it is not an economically attractive investment; furthermore, the payback period is greater than its project duration (Table 3). Production of biodiesel without tax credits is not practically viable due to the economic scale of production and the under-utilization of the processing facility's capacity. However, the biodiesel project can provide an internal source of liquid fuel for the waste management facility.

Environmentally, the average LFG project will avoid 91,500 tons of equivalent CO_2 emissions or 39,270 tons MW^{-1} output. The solar project provides a feasible option for implementation on landfill cap areas, which allows an avoidance of 1057 tons CO_2 emissions MW^{-1}. Together, both projects can power 2000-2400 homes or charge 9,350-10,620 EVs operating at 12,000 miles (19,310 km) year^{-1}. The biodiesel option helps reduce 78 tons of annual CO_2 emissions and provides enough fuel to run 18 trucks annually.

4.2. Economic Benefits with Energy Credits

The economic perspective for all energy projects becomes more promising when appropriate energy credits are considered (Table 3). For instance, in applying the REPTC credit of 1.1 cents per kWh for the average LFG-energy project, the NPV payback period is shortened by 2 years and the IRR increases by 29%. For the solar-energy project, a SREC value of 4 cents per kWh helps shorten the payback period by 4-5 years with an increment of 38% for IRR. Although SREC prices may fluctuate with uncertainty, the solar-energy project is an attractive and viable investment even in the absence of financial subsidies. The most encouraging economic improvement is observed for the biodiesel fuel production. By including the \$1.00 gallon^{-1} (\$0.26 L^{-1}) tax credit, the biodiesel production becomes economically viable with a NPV payback of 16 years and a B/C ratio of >1.0.

4.3. Economics for Landfill Closure Care

In a typical landfill facility, landfilling operation starts at one cell and progresses gradually to the next cell until the entire site is fully utilized. Accordingly, the time sequence of developing energy projects should be aligned with the staging operation of landfilling. It includes (a) landfilling on the landfill cell from 1 to year 20, (b) post-closure care from 21 to year 50 at a cost of \$100,000 year^{-1}, (c) LFG and biodiesel projects from 5 to year 30, and (d) solar-to-energy project from 21 to year 50 (Figure 1).

The NPV benefit for a project can be calculated as the difference between the real values of benefit and cost adjusted to year

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2 Cultivation of higher yields and more density feedstocks such as the second generation cellulosic crops, which requiring a large scale operation, is not considered in our research.

3 Economic analysis is based on currently acceptable technological practices and for comparative purposes, such economic factors as discounting and interest rates are not subject to uncertainty analysis. Detailed financial analysis will be needed for individual project investments.

4 Issues relevant to environmental sustainability, including physical and chemical changes of the landscape and water quality concerns, are not part of this study.

Table 2: Economic and production data for the hypothetical MSW facility

Parameters	LFG energy (A)	LFG energy (B)	LFG energy (C)	Solar energy (A)	Solar energy (B)	Bioenergy
Economic						
Capital, $ kW^{-1}	2,000	2,000	2,000	1,000	1,000	-
Annual O&M, $ kW^{-1}	210	210	210	-	-	-
Annual O&M, $ MWh^{-1}	-	-	-	11.4	11.4	-
Production including O&M, $ L^{-1}	-	-	-	-	-	0.79
Sale of electricity, $ kWh^{-1}	0.06	0.06	0.06	0.06	0.06	-
Avoidance cost, $ L^{-1} diesel	-	-	-	-		0.98
Production						
LFG, m^3 min^{-1}	31	25	16	-	-	-
Methane, m^3 min^{-1}	16	13	8	-	-	-
Methane energy, MJ min^{-1}	519	519	519	-	-	-
Electricity production, GJ $year^{-1}$	71,620	57,300	35,810	-	-	-
Electricity production, MWh $year^{-1}$	19,890	15,920	9,950	3,125	6,250	-
Electricity production, MW	2.33	1.86	1.16	2.04	4.08	-
Biodiesel production, L $year^{-1}$	-	-	-	-	-	33,220

MSW: Municipal solid wastes, LFG: Landfill gas

Table 3: Results of environmental and economic assessments

Parameters	LFG energy (A)	LFG energy (B)	LFG energy (C)	Solar energy (A)	Solar energy (B)	Bioenergy
Investment costs						
Initial investment, $	600,000	600,000	600,000	2,038,490	4,076,970	250,000
Annual operating cost, $	489,000	391,210	244,500	35,630	71,250	21,940
Gross annual savings*, $	1,193,740	954,990	596,870	187,500	375,000	32,550
Environmental benefits						
Home powered by green energy, # $year^{-1}$	1,810	1,450	900	350	568	-
EV charged, # $year^{-1}$	8080	6,470	4,040	1,270	2,539	-
Utility truck fueled, # $year^{-1}$	-	-	-	-	-	18
Avoidance of CO_2 emission, tons $year^{-1}$	91,500	73,200	45,750	2150	4310	78
Economic benefits (without energy credits)						
IRR, %	10.85	8.01	3.23	5.49	6.50	-
NPV payback, years	10	13	23	17	16	-
Benefit-cost ratio	1.47	1.33	1.05	1.41	1.46	0.92
Economic benefits (with energy credits)						
IRR, %	13.96	10.73	5.70	9.01	8.99	5.90
NPV payback, years	8	10	16	12	12	16
Benefit-cost ratio	1.74	1.58	1.24	1.62	1.62	1.17

*Based on overall energy produced. NPV: Net present value, IRR: Internal rates of return, LFG: Landfill gas

zero. These NPV benefits are at least more than $7.0 million for LFG-to-energy, -$2.1 million for post-closure care, more than $1.0 million for solar-to-energy, and $0.01 million for biodiesel production. The net total of these NPV benefits would be more than $8.0 million, which is sufficient to cover the closure-care costs. The LFG-to-energy alone is shown to provide sufficient return for offsetting the post-closure expenses. It also helps to comply with regulatory requirements for gas collection and utilization, resulting in a significant reduction of GHG. The solar project is less profitable than the LFG project. However, solar radiation is an unlimited energy source that will produce solar-electric energy on the closed landfill site for as long as the site has no other use. The project can provide both a continuous electricity supply to the local community and a reduction in GHG. The biodiesel project is the least profitable, but it essentially provides the required transportation liquid fuels for the municipality and helps reduce their dependence on foreign imported oil. The sequential implementation of these green energy projects has demonstrated the feasible and maximum utilization of the lan opportunities and energy resources in conjunction with landfilling operations.

5. CONCLUSIONS

This paper has presented opportunities and challenges to integrate green energy production into the lifecycle management of landfill operations. The research provides a roadmap to guide the implementation of green energy production, including LFG, solar energy, and bioenergy. A financial analysis and environmental assessment were performed to evaluate the integration of green energy projects for MSW management facilities. It is found that a typical 3-MW LFG-to-energy project using LFG as fuel source is sufficient to power 1809 homes and avoids 39,270 tons of CO_2 emission MW^{-1} output. The NPV payback is 10 years or less with an acceptable IRR, and the economy of solar-electricity yields a positive return with a NPV payback within the project duration. These two energy projects have the potential to keep solid waste tipping fees stable and to galvanize interest and support for other renewable energy and resource projects.

The viability of biodiesel production within the landfill facility is relatively uncertain. It requires due consideration of proper sizing of the in-house processing facility, the economic scale of production and available tax credits. Biodiesel production at the facility scale is not favorable based on economic analysis; nonetheless, with the aid of $1.00 tax credit gallon^{-1} ($0.26 L^{-1}), the production can result in a NPV payback of 16 years and a B/C ratio of 1.17. A regional facility that aggregates feedstock materials from neighboring municipalities represents a more promising model for biodiesel production.

As the concept and function of landfill facilities evolve to resource recovery and renewable energy production, there is a business case for these sites to transition into eco-friendly complexes with the implementation of sustainable technologies. A systematic planning and integration of green energy projects will maximize the use of unutilized lands and free energy sources and will provide the required funding for post-closure expenses. Landfill sites also have excellent existing infrastructure in terms of road and utility access that can facilitate the transport of materials to a regional biomass processing plant or grid interconnection for electricity generation. Energy policies pertaining to carbon credits or tax incentives are crucial to sustained growth of green energy production from waste management facilities.

6. ACKNOWLEDGMENT

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