GREENHOUSE EFFECT REDUCTION BY RECOVERING ENERGY FROM WASTE LANDFILLS IN PAKISTAN

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ABSTRACT:

Landfills all around the world are one of the major sources that contribute towards global warming and climate change. Although landfilling should be prioritized last in the waste management hierarchy due to highest greenhouse gas emissions as compared to other waste management systems but is still very common around the world. In this study, methane emissions are estimated by applying First Order Decay model to landfills in Pakistan over the latest data available by Pakistan Environmental Protection Agency. Results demonstrate that nearly 14.18 Gg of methane are emitted from the landfills in Pakistan each year. By combusting this methane in the form of biogas collected from the landfills as a waste management scheme can reduce greenhouse effect up to ~88%. Same percentage is observed when we apply the similar analysis over the potentially improved practice. Also, Pakistan is facing severe economic crises due to continuous increasing gap between energy demand and supply. Demand is increasing exponentially while supply is observed to remain constant over the last few years due to frozen capacity in spite of having significant renewable/alternate energy resources. Current electricity shortfall has reached up to 6000 MW. Present operational landfills in Pakistan can only contribute up to ~0.1% to cater the total deficit which does not make any significant difference but if 75% of the total waste generated today is collected and 50% of it landfilled then Pakistan has the potential to produce ~83.17 MW of power that can contribute up to 1.4% to overcome the current power shortage. The outcomes of this paper may also be applicable to other developing countries having similar resources.

Keywords: Landfills, Renewable Energy, Biogas, Greenhouse Effect, Pakistan

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NOMENCLATURE:

CDA	Capital Development Authority
CDM	Clean Development Mechanism
CHP	Combined Heat and Power
$DDOC_m$	Mass of decomposable DOC, Gg
$DDOC_{mo}$	DDOC in the disposal site at time 0, Gg
DOC	Fraction of degradable organic carbon
DOC_f	Fraction of DOC that can decompose
EfW	Energy from Waste
EPA	Environmental Protection Agency
EU	European Union
F	Fraction of CH_4 in landfill gas
FOD	First-order decay
GHG	Greenhouse gas
GMI	Global Methane Initiative
GWP	Global Warming Potential
HPWS	High Pressure Water Scrubbing
IPCC	Intergovernmental Panel on Climate Change
JI	Joint Implementation defined in Article 6 of the Kyoto Protocol
k	Reaction constant, 1/year
L_0	CH_4 generation potential, Gg CH_4
LFG	Landfill gas
LHV	Lower Heating Value
LULUCF	Land use-land use change-forestry
MOCC	Ministry of Climate Change
MSW	Municipal solid waste
NGO	Non-government Organization
NTDC	National Transmission and Dispatch Company
P_e	Electrical power, MW
P_t	Thermal power, MW
Pak-EPA	Pakistan Environmental Protection Agency
PSA	Pressure Swing Adsorption
r	Methane collection/recovery rate, %

$t_{1/2}$	Half-life time, year
UNFCC	United Nations Framework Convention on Climate Change
W	Mass of waste deposited, Gg
η_e	Electrical efficiency, %

1. INTRODUCTION

Global warming is one of the most important issues of our time; it refers to rise in global surface temperature due to climate change induced by the ongoing human activities. These activities have led to the enormous greenhouse gases (GHG) emissions (CO_2 – 76.7%, CH_4 – 14.37%, N_2O – 7.9%, other high global warming potential (GWP) gases - 1.1%) causing severe environmental degradation [1]. Almost all the countries worldwide are making immense efforts to reduce these GHG emissions in accordance to United Nations Framework Convention on Climate Change (UNFCCC). According to the Intergovernmental Panel on Climate Change (IPCC), from 1970-2004 the emissions of the GHGs increased from 28.7 to 49.0 $GtCO_2$-eq (by 70%). The largest contributor to this increase, almost 80% came from carbon dioxide (CO_2) emissions followed by methane (CH_4) emissions that rose by 40% from its initial value [1]. Both these major contributors to greenhouse effect comes from various sectors but majorly from energy, transportation, industry, agriculture, livestock, forestry, waste generation etc., refer to Figure 1. While the major CO_2 comes from power generation, transportation and industrial processes, key sources of CH_4 are agriculture, fossil fuel (retrieval, processing and distribution) and waste (disposal and treatment) sector.

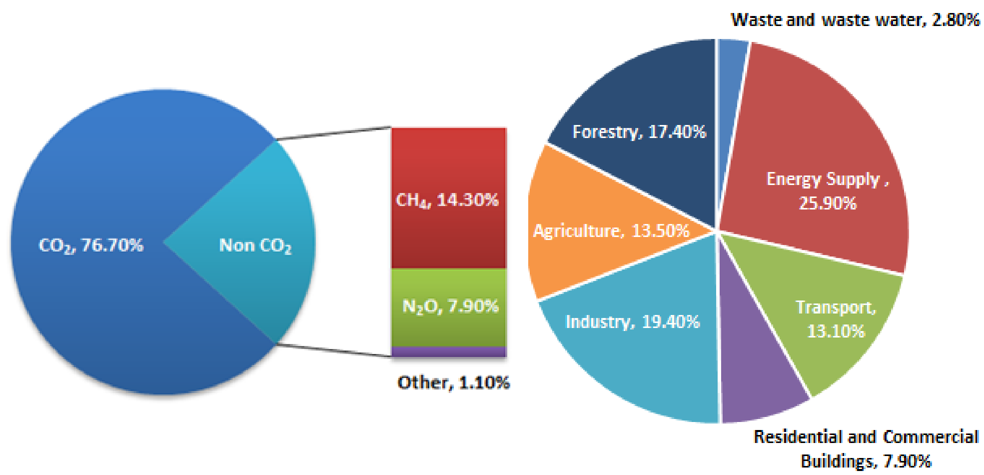

Figure 1 Worldwide GHG status and contribution (Source: IPCC, 2006)

Countries endorsing the Kyoto Protocol are required to submit their GHG inventory annually to UNFCC. The submitted inventories are later disseminated through reports and online website. Countries are classified into Industrialized parties (Annex-I) submitting annually inventory report and Developing parties (Non-Annex I) presenting their GHG emissions as part of their national communications [2]. According to UNFCC top 30 countries emitting most GHGs from 1990 to 2008, China is topping the list with 7500 $MtCO_2$-eq while U.S. is second with around 7000 $MtCO_2$-eq followed by Russia being third with around 3300 $MtCO_2$-eq [3]. Although all the GHG emissions should be monitored and their emissions reduction is essential, this paper primarily focuses on methane emissions, specifically from waste due to the fact that it can serve as an alternative energy source.

According to the Global Methane Initiative (GMI) [4], in 2010 the global anthropogenic CH_4 emissions were estimated to be 6.875 $GtCO_2$-eq and it is expected to increase by approximately 20% to 8.586 $GtCO_2$-eq by 2020, if no or little efforts are done. Efforts are being made worldwide to reduce anthropogenic CH_4 emissions through advancement of the technologies. Methane is the second most powerful among GHGs (i.e. more effective in trapping heat than CO_2), having 21-23 times higher global warming potential than CO_2 [5]. This GHG is either naturally emitted by termites, coal beds, grasslands, lakes, wildfires, livestock and wetlands, and/or by the anthropogenic activities like agriculture, burning of fossil fuels, coal mining, oil and gas operations, rice production and solid waste disposal (landfilling) and wastewater. Methane is combustible and a valuable clean energy source, hence if captured, can be utilized as green fuel in process industries, generating electricity or use in the production of methanol and fertilizers [6].

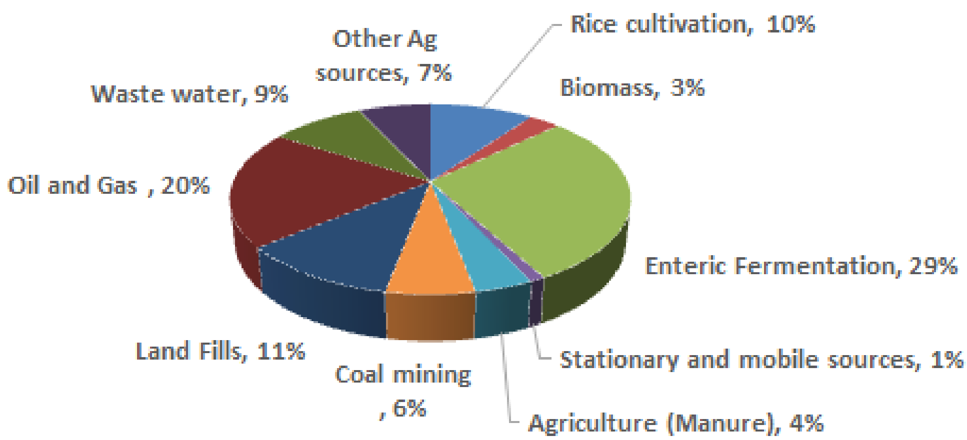

Figure 2 Estimated global anthropogenic methane emissions by source, 2010 (Source: GMI, 2013)

Municipal solid waste (MSW) sector is the fourth largest contributor to global emissions of non-CO_2 GHGs that contribute towards global warming and climate change due to their emissions and approximately contribute 5.5-6.4% towards global methane (550 Tg) emissions annually [1,7,8]. Methane is produced by decomposition of organic matter either in handling and treatment of municipal wastewater or when municipal solid is deposited in landfills [9]. Figure 2 shows the estimated anthropogenic methane emissions by source, 2010 globally. The MSW landfills are the 3rd largest anthropogenic source of methane, followed by agricultural and enteric fermentation [10], accounting for 11% of the global methane emissions as biogas consisting of methane in 50-55% by volume. These emissions from landfills are expected to grow up to 816 $MtCO_2$-eq by 2020 [11]. Biogas from landfills is commonly referred to as Landfill Gas (LFG) since it defines its origin but for the sake of consistency throughout the paper, term ‘biogas’ is used from now onwards.

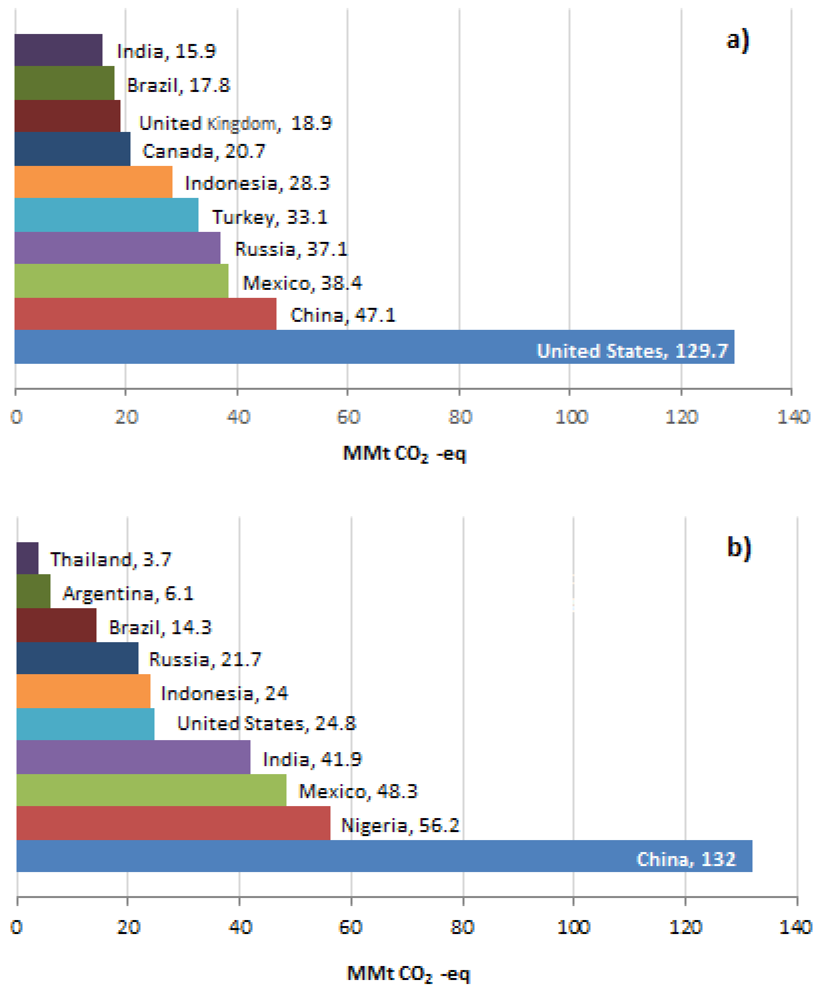

Figure 3 Global methane emission estimates in top ten GMI countries a) from landfills, b) municipal wastewater (Source: GMI, 2013)

In 2010, approximately 779 MtCO$_2$-eq of landfill methane emissions were recorded of which more than half (50%) comes from just 10 countries as shown in Figure 3a [4]. The figure shows that U.S. tops the methane emissions chart with 129 MtCO$_2$-eq, China being second 47.1 MtCO$_2$-eq, Mexico (38.4 MtCO$_2$-eq), Russia (37.1 MtCO$_2$-eq) and Turkey (33.1 MtCO$_2$-eq) being 3rd, 4th and 5th respectively while India stood at 10th position with 15.9 MtCO$_2$-eq. Figure 3b shows worldwide municipal wastewater statistics. China, Nigeria and Mexico stand on 1st, 2nd and 3rd places with 132, 56.2 and 48.3 MtCO$_2$-eq respectively. In 2012, municipal wastewater methane emissions accounted for more than 629 MtCO$_2$-eq making it the fifth largest source of anthropogenic methane emissions source i.e. approximately 9% of the total global methane emissions. These global emissions are likely to grow up to 665 $MtCO_2$-eq by 2020 [4]. According to the forecast done by UNFCC, the landfill & municipal wastewater methane contributions are likely to increase by 13% and 19% respectively by 2030 making their contribution 20% of the total global methane emissions from all sources [12]. It is therefore universally acknowledged that a significant opportunity lies in the waste sector to reduce GHG emissions.

Waste management is not only an important step towards sustainability but it is also an effective solution against reducing negative environmental impacts. Due to rapid urbanization world has seen a tremendous increase in all sorts of wastes including municipal solid waste, industrial, medical, mining hazardous, agricultural, construction and demolition waste, packaging waste, wastes from electrical and electronic equipment and end-of-life vehicles etc. Municipal Solid Waste (MSW) is referred to waste generated in households, markets, streets, commercial areas, industries (non-hazardous) etc. According to [8], in 2007 the global MSW generation was 1200 Tg/yr of which some 70% was landfilled while rest was recycled and/or used in energy-from-waste facilities. Although MSW landfilling is prioritized last in the waste management hierarchy [13] it is still the most widely used option around the world especially in developing countries as effective infrastructure is required to divert the waste for reuse and recycle from landfilling that only exist in developed countries. According to IEA projected estimates of methane emissions from MSW, methane emission from developed/industrialized countries are likely to decrease as a consequence of stringent regulatory laws, advancement of energy-from-waste (EfW) technologies and their adoption, reuse, recycle and composting while methane emissions are likely to increase in developing countries due to rapid urbanization, inconsistent MSW collection, treatment, handling and disposal [14].

According to [8], waste generation is expected to be doubled by 2030 signifying that methane emissions from waste will rise considerably in future. Therefore, for developing countries like Pakistan, these studies are essential to be done for the sake of environmental protection and sustainable development. This paper presents preliminary the estimates of methane gas emissions from MSW in Pakistan with the help of First Order Decay model developed by IPCC and then discusses the potential of greenhouse effect reduction by recovering energy-from-waste i.e. utilization of methane gas in the form of biogas emitted by landfills for power generation. It also estimates the current amount of waste generated in the country and its projected growth up to 2050. Structure/organization of the paper is presented in Table 1.

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Table 2 Pakistan's GHG inventory results for the year 2008

	Thousand tonnes (CO_2-eq)				
Sector	CO_2	CH_4	N_2O	CO	NMVOC
Energy related	140,160	11,838	2,440	1,706	675
Fuel Combustion	140,160	7,128	2,440	1,704	623
Power sector	44,310	30	63	21	16
Manufacturing	42,408	69	120	93	46
Transport	30,693	243	496	1,533	508
Other sectors	22,750	6,786	1,761	57	53
Fugitive Emissions	-	4,710	-	2	52
Non-Energy related	26,471	99,369	26,098	322	315
Industrial Process	17,551	-	-	-	315
Agriculture	-	94,636	25,326	322	-
Forestry	8,920	-	-	-	-
Waste	-	4,733	722	-	-
Total	166,631	111,207	28,538	2,028	990

Source: National Economic and Environmental Development Study: Case of Pakistan 2011.

2. NATIONAL GREENHOUSE GAS INVENTORY OF PAKISTAN

Pakistan signed the United Nations Framework Convention on Climate Change (UNFCC) as a Non Annex-I Party in June 1994, adopted the Kyoto Protocol in 1997 and acceded to it in January 2005 [12]. In Pakistan, Ministry of Climate Change (MOCC) is responsible for drafting legal framework and policies dealing with environmental protection e.g. Pakistan Environmental Protection Act-1997. The implementation of this act is provided by its department called Pakistan Environmental Protection Agency (Pak-EPA or PEPA) and provincial EPA's. Presently, Pakistan stands on 135th rank globally on per-capita basis and contributes about 0.8% of the total global GHG budget [15]. Compared to major GHG contributing countries, Pakistan's contribution is minimal, however keeping in mind, the growing population rate, rapid urbanization, increasing transport, energy and waste sector, rise in above global standing is expected by 2030.

Table 3 Projected sector-wise GHG emissions 2011-2050

Total GHG emissions ($Mt\ CO_2$ eq.)	2011	2020	2030	2040	2050
	347	577	1,046	2,156	4,621
Energy	176	295	560	1,250	2,730
%share	50.6	52.9	53.5	58	59.1
Agriculture	134	210	408	812	1,765
%share	38.7	37.7	39	37.7	38.2
Industry	20	30	52	61	75
%share	5.8	5.4	5	2.8	1.6
LULUCF	10	13	15	20	35
%share	2.9	2.3	1.4	0.9	0.8
Waste	7	9	11	13	16
%share	1.9	1.6	1.1	0.6	0.3

Source: National Economic & Environmental Development Study. Ministry of Environment of Pakistan; 2011

From 2008 inventory of GHG emissions, 4.733 $MtCO_2$-eq of methane was contributed by waste management facilities in Pakistan, with 2832 tonnes from solid wastes and the rest from waste water. In addition to that, 772 thousand tonnes CO_2-eq of N_2O is also discharged from these sources [11]. The projected GHG emissions from 2011 to 2050 under business-as-usual scenario are given in Table 3. The Government of Pakistan has made plans to enforce mitigation efforts to reduce GHG emissions due to its strong projected growth and energy use through coal in future. In this scenario, the efforts are not limited to the major contributing sectors but also be used to curtail emissions from every possible sector.

3. MUNICIPAL SOLID WASTE MANAGEMENT IN PAKISTAN

3.1. Demographics of Pakistan

Pakistan is situated in one of the most geographically important location of the world i.e. South Asia between the latitudes of 24° and 37° north and longitudes of 61° to 75° east. It borders with India in east, Afghanistan and Iran in west, China in north and Arabian Sea and Gulf of Oman in south. Pakistan is not only the 36th largest country with a covering area of 796,095 sq. km; it is also the 6th most populated country in the world [16]. The population of Pakistan is approximately 188.02 million recorded in 2014, which is an increase of about 2% from the last year`s population estimate (184.35 million) [17]. About 36% of its current population lives in urban areas, the remaining 64% in rural settings. Furthermore out of this 36%, more than 54% lives in ten major cities of Pakistan [18]. Economists predict that if this growth rate continues, Pakistan's population is expected to be more than 230 million in 2030 and over 300 million by 2050, promoting it to the fifth most populated country with almost 60% living in urban areas [19].

3.2. Waste Generation in Pakistan

Pakistan like most of the developing countries is not only faced by the fast growing rate of its population but also an increase in its MSW generation. Due to the increased urbanization, city municipal corporations are unable to cope up with the significant boost resulting in inadequate utility services. In monsoon seasons, the waste management issue aggravates to an extent that the major cities come to standstill due to blocked drains, clogged sewers and stagnant effluent ponds. Even though Pakistan is among the most populated countries of the world, still no proper/systematic solid waste management system exists in any of its major cities. The major MSW disposal process in Pakistan has been open dumping and landfilling for many decades, however after acceding Kyoto Protocol in 2005, Pakistan has proposed many projects through Clean Development Mechanism (CDM) to reduce its reliance on landfilling, but still these initiatives have been lagging behind than those of its neighboring countries due to lack of interests by provincial governments, funds and expertise.

According to an estimate, 67,500 tonnes of solid waste is generated per day in Pakistan, of which only 50-69% is picked up and sent to open dumps and landfill areas outside of cities. Rest is left as piles of garbage at roadsides, in storm drains, open sewers and in vacant plots [7,20–22] posing serious health risks to public. Note that there exists a large difference between the quantities of MSW generated, collected and received at disposal sites. This is due to the fact that generation rates are increasing in major cities due to rapid urbanization, over burdening the existing infrastructure and thus collection from cities is not done on regular basis. In frequent cases even the waste collected does not reach the disposal sites and may be dumped at illegal points within or outskirt of cities.

Table 4 Estimates of solid waste generation in Pakistan on the basis of population of 2004

City	Population (million) 1998 Census	Population (million) 2004	Solid Waste Generation Rate (kg/c/day)	Waste generated (Tonnes/day)	Tonnes/year
Urban Areas					
Karachi	9.269	10.818	0.613	6,632	2,420,680
Faisalabad	1.977	2.307	0.391	902	329,230
Hyderabad	1.151	1.343	0.563	756	275,940
Gujranwala	1.124	1.312	0.469	615	224,475
Peshawar	0.988	1.153	0.489	564	205,860
Quetta	0.56	0.654	0.378	247	90,155
Bannu	0.046	0.054	0.439	24	8,760
Sibi	0.082	0.095	0.283	27	9,855
Remaining Urban Areas	27.261	31.818	0.453	14,414	5,261,110
Rural Areas	88.121	102.853	0.283	29,108	10,624,420
Sub-total	130.579	152.409		53,289	19,450,485
Add 3% of hazardous waste				1,599	583,635
Grand Total				54,888	20,034,120

Source: Pak-EPA. Guideline for Solid Waste Management. 2005.

The population growth rate is directly linked with solid waste generation. According to a comprehensive study done by Pak-EPA in 2005 on solid waste management in eight cities of Pakistan, it was estimated that the population of the selected 8 cities was likely to double in a decade resulting into higher amounts of waste generation [7]. From the same report, the solid waste generation rate in these 8 major cities from 1994-2004 was estimated to be 54,888 tonnes per day in Pakistan, see Table 4 [7,21]. It can be seen from the table that on average, all type of waste varies from 0.283 kg/capita/day (or 1.896 kg/house/day) to 0.613 kg/capita/day (or 4.29 kg/house/day) determined on the basis of location and socio-economic background. Generally this trend of waste generation represents low middle income countries whereupon the lower value represents smaller city and maximum indicate larger city. In comparison to above, World Bank report in 2012 [23] on solid waste management reports average waste generation rate in urban areas to be 0.84 kg/capita/day with an expected increase up to 1.05 kg/capita/day by 2025. Nevertheless due to poor infrastructure of collection, handling and treatment, presently only 50-60% of generated waste is collected while around 40-50% of the generated waste remains in streets or collection points [18].

This work done here draws a great deal upon the previous works. It is to be noted that estimates presented here are conservative due to lack of past yearly data on waste generation along with inconsistency between existing data sources and locations. As recent waste generation data is not available, hence calculations has been done with the current population estimate of 188.02 million with urban to rural ratio of 36:64 and solid waste generation rate of 0.453 kg/capita/ day (urban) and 0.283 kg/capita/ day (rural), see Table 5. Nevertheless it is acknowledged here that these figures are on conservative offside and hence are estimates only. Table 5 also shows the estimates based on the generation rates given by World Bank 2012 report.

Table 5 Estimated solid waste generation in Pakistan on the basis of population of 2014 (Present work)

		Pak-EPA, 2005 (World Bank, 2012)		
	Population (million) 2014	Solid Waste Generation Rate (kg/c/day)	Waste generated (tonnes/day)	Tonnes/year
Urban Areas	72.50	0.453 (0.84)	32,842.50 (60,900.00)	11,987,512.50 (22,228,500.00)
Rural Areas	115.52	0.283 (0.30)	32,692.16 (34,656.00)	11,932,638.40 (12,649,440.00)
Sub-total	188.02		65,534.66 (95,556.00)	23,920,150.9 (34,877,940.00)
Add 3% of hazardous waste			1,966.0398 (2,866.68)	717,604.53 (1,046,338.20)
Grand total			67,500.70 (9,8422.68)	24,637,755.43 (35,924,278.20)

3.3. Municipal Solid Waste Composition in Pakistan

The MSW composition varies with geographical location, life style, standard of living, scale of city etc., for example in urban areas, paper and cardboard forms the major portion while in rural household biodegradable waste i.e. food and green waste is found to be more in MSW. The presence of higher organic/biodegradable items (food and green wastes) represent lower and lower middle income countries where upon this waste find its use for gasification, composting and landfilling and thus has recyclable value as well. The physical composition of the waste like size, density and moisture is crucial; smaller size organic waste decompose at a faster rate and vice versa. The high density signify biodegradable waste and will undergo quicker decomposition compared to less density waste that represents more combustible material (paper, cardboard, plastics). The high moisture content makes the waste not suitable for thermal energy conversion process as additional energy may be required to lessen the moisture and more suitable for anaerobic digestion, landfill gas and bio-digester gas.

Table 6 Physical composition of MSW (%) in major cities Pakistan

Cities	Karachi	Hyderabad	Faisalabad	Peshawar	Quetta	Average
Plastic and rubber	6.4	3.6	4.8	3.7	8.2	5.34
Metals	0.75	0.75	0.2	0.3	0.2	0.44
Paper	4.1	2.4	2.1	2.1	2.2	2.58
Cardboard	2.4	1.5	1.6	1.9	1.3	1.74
Textile/ Rags	8.4	4.7	5.2	4.3	5.1	5.54
Glass	1.5	1.6	1.3	1.3	1.5	1.44
Bones	3	2	2.9	1.7	2	2.32
Food	21	20	17.2	13.8	14.3	17.26
Animal	3	5.8	0.8	7.5	1.7	3.76
Green (Leaves, grass etc)	14	13.5	15.6	13.6	10.2	13.38
Wood	2.25	2.25	0.7	0.6	1.5	1.46
Fines	29.7	37.9	43	42	44	39.32
Stones	3.5	3	4.6	7.3	7.8	5.24

Source: Pak-EPA. Guideline for Solid Waste Management. 2005.

It is important to consider the waste composition while evaluating a biogas recovery project, in particular the organic content, level of moisture, and degradability of the several waste fractions. For example, landfills with a higher percentage of food wastes, which are highly degradable, will tend to produce biogas sooner but over a shorter length of time. Generally in Pakistan, MSW comprises of paper, plastic, metal, rubber, glass, textile items, cardboard, food waste (including bones etc.), animal waste, green waste (leaves, grass, straws, wood, fodder) and inerts (including stones, fines) [7]. It is essential to have percentage composition of MSW of the whole country to estimate potential for methane generation for end use. Table 6 shows physical composition of MSW in some of the major cities of Pakistan. The cities shown in the table lie in different provinces covering all over Pakistan, therefore average values of their waste composition can be considered a reasonable estimate for the composition of the whole country. Average percentage of each component of MSW is also listed in Table 6.

Table 7 shows the MSW composition in 1996 whereupon organic waste forms the major fraction of MSW in Pakistan. Recently World bank reported organic content to be 67% and inorganic to be 26% and 7% others in MSW [23] as demonstrated in Figure 4. As obvious, organic forms the major fraction along with recyclables accompanied with large amount of fines (dust etc.). According to Pak-EPA in Pakistani MSW, recyclable plastics` contribution is high [24]. Plastics are the great menace as far as environment is concerned, their presence in unwanted places like roadsides, drains and storm sewers causes blockages and health issues to human. If these are not recycled before composting, will remain for decades due to non-biodegradability (developing counties like Pakistan do not use biodegradable plastic!) and if not removed before any energy-from-waste process, can cause toxic emissions e.g. airborne particulate emissions, volatile organic compounds, particulate bound heavy metals etc. Such toxins remain in air and when settles down can enter food chain and thus can be harmful for humans.

Table 7 Typical composition of MSW (%)

MSW Content	%
Food	8.4 – 21%
Green (Leaves, grass etc.)	10.2 – 15.6%
Fines (Other)	29.7 – 47.5%
Recyclable	13.6 – 23.5%

Source: Pak-EPA. Guideline for Solid Waste Management. 2005.

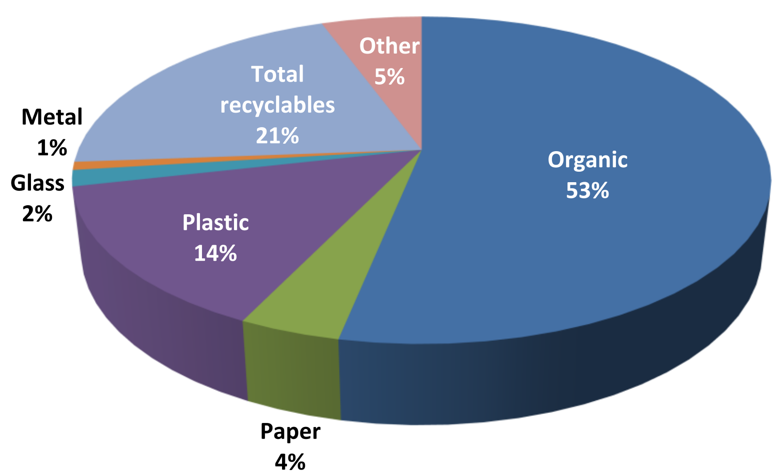

Figure 4 Typical composition of MSW (%) given by World Bank in 2012

3.4. Prevailing Solid Waste Disposal Management in Pakistan

Currently, Pakistan does not have any international standard landfills; open dumping and open burning are the common methods of waste disposal causing severe environmental degradation and great risks to public despite the fact that burning of waste is illegal [22]. In major cities of Pakistan untreated municipal waste is either landfilled or dumped in area designated as landfill. In some cities even industrial waste and hospital wastes are not treated and directly sent to landfill sites posing further menace. Currently, the municipal waste (excluding industrial and hospital wastes) that is sent to landfills does not undergo any comprehensive recycling. However, due to keen interests of some non-government organizations (NGOs) and few private sector environment awareness campaigns, recent decade has seen a general trend towards keeping the city clean and recycle movement in some of the major cities of Pakistan e.g. Karachi, Lahore and Islamabad. Nevertheless, these initiatives are still limited in size and location. Some of these organizations buy and collect waste (green waste, paper, plastics) and reprocess it to produce fertilizer, plastic bottles, refuse-derived fuel (RDF) etc. Usually the only recycling done; is at the point of source mainly domestic, commercial, and offices, where the waste especially metal scraps and paper is separated.

According to [20] some 9% is recycled at the source and sold to local street vendors called *'kabaris'* by household person/maids or industrial/office's lower staff while rest of the waste is directed to the empty plots known as *'kachra kundis'* in the area. It is estimated that some 50-60% of the waste is picked up by local municipal council from these places and transported to the closest landfill. However, the collection from *'kachra kundis'* is not a regular show due to financial constraints, unavailability of suitable infrastructure (inadequate collection and transportation system) and ghost employees issue in many cities. These *'katchra kundis'* and open dumps are regularly raided by scavengers or street waste pickers who collect any leftover recyclable waste and sell it in local *'kabari'* (waste) market. According to some sources, estimated 20% of the waste is picked up by these street waste pickers and sold to recycling industry [7]. The waste send to dispose, often ends in improper and unscientifically managed landfills or in open dumps and unplanned illegal locations in and around the city. In some cases these wastes are burnt despite the fact that it is illegal [22]. The perception is 'out of sight, out of mind' as this is relatively inexpensive and easier waste disposal route. These sites later become breeding ground for flies, mosquitoes and birds which subsequently transmits diseases to animals and humans. However, this is not the end of the story because heaps of trash and their decomposition results in liquid effluents, bad odors and die-back of vegetation in that area, further disturb the eco-system resulting into local issues along with the GHG emissions from these sites as global issue. All the major cities are in extreme and urgent need of proper waste management and disposal activity to reduce its dependence on open dumps, landfilling and burning of waste requiring considerable focused solution.

Although burning waste or incineration is a less efficient technique for energy harvesting, still if burning is done in a controlled environment contrary to what is done in case of burning at illegal locations will have benefits but still less than engineered landfilling. In major cities of Pakistan untreated MSW is either landfilled or dumped in area designated as landfill, however if this waste is properly landfilled and biogas formed by it, is captured and used then there is great potential for not only reducing GHG emissions but also getting an alternative source of energy, better air quality, improved sanitary conditions at disposal sites, low risk of leachate affecting groundwater and soil in the vicinity. If landfills with sufficient quantities of biogas generation and suitable composition can be identified especially near the major cities, they could be used to meet local energy demands. However to implement all this, dedication is required with a considerable action in the form of national policy for waste management, integrated action plan along with the financial support from Government of Pakistan.

4. GREENHOUSE GAS EMISSION MANAGEMENT STRATEGIES

There is a general consensus across the globe that the highest climatic benefit is achieved through improvement of materials management leading to waste prevention, and in this regard, reuse and recycling is considered the best option. Even the improvement in GHG reductions from municipal waste must be directed in context of integrated solid waste management. In many parts of the world e.g. in Europe recycling is made mandatory, resulting in almost recycling of 41% of its municipal waste [25]. Other major recycling countries are United Sates recycling almost 32% of its municipal waste; China is recycling 35%, Germany 48%, Belgium and Sweden 35%, Netherlands and Ireland 32%, Austria 29% and UK 23% [25]. Nevertheless, these options are not always possible and there always exist non-recyclable fractions that are landfilled. However, in such cases rather than landfilling the waste, greenhouse savings can be achieved by energy recovery using energy-from-waste (EfW) processes as this will reduce the use of fossil fuel and reduction in GHGs. EfW is a global practice and takes form of incineration, pyrolysis/gasification, landfill gas/biogas and anaerobic digester biogas from waste with efficient energy recovery. The European union is targeting on producing 25% of their energy demand by renewables by 2020 and in this regard EfW projects; incineration, gasification, and biogas production are priority options [25].

Table 8 shows a comprehensive review of both pros and cons of several waste management strategies most commonly practiced around the globe to tackle GHG emissions. Description of all the methods discussed in the table can be found in the following references [26–32]. Although landfilling is the least favored option in waste management practice, it's the ultimate or the end of waste management route (as there will always be some waste left even after reuse and recycle), and thus making the GHG emissions from existing and old landfills a challenging task. Despite the fact that landfills are not aesthetically pleasing; there are several benefits to landfills as one of them is biogas recovery which can be utilized for multiple purposes further explained in sub-section 5.5. The technology is matured enough to be implemented for energy retrieval and therefore present study is focused on determining energy recovery potential in Pakistani scenario.

Table 8 Pros and cons of most common waste management strategies practiced around the globe

Pros	Cons
Reuse	
Preserves original item	Requires decontamination first to make sure safe reuse
Saves resources	Requires sampling to certify item is clean
Saves space in landfills	May increase risk to public
Recycle	
Generates income by selling the material	Requires pre-treatment to make sure safe usage
Produces usable product	Requires sampling before recycle
Saves resources, energy and space in landfills	Public perception regarding usability of product
Composting	
Cost effectiveness	Requires dedicated space for a period of time
Reduces spread of pathogens	Requires maintenance/monitoring
Produces a potentially usable product	Requires control of pests and other courses
Growing acceptance by states and industry	Possible runoff/odors
Saves landfills' space	Public perception regarding usability of product
	Limited capability if the ambient temperatures are very low
Open Burning	
Potential option in remote areas or cold climates	Restrictions on waste streams and approved sites
Eliminates on-road transportation	Requires air monitoring
	Requires special permission
	Weather can severely limit effectiveness/use
	Possibility of spreading contamination
	Public acceptance

Incineration	
Reduces waste volume needs to be disposed	Residues still require proper testing and disposal
Can reduce waste toxicity	Produces undesirable by-products
Can inactivate disease agents	Facility indemnification
Can produce energy	Capacity limitations
	Transportation concerns/costs
	Reluctance of some owners/residents/operators
Digestion/Gasification	
Suitable for bacteria and viruses except prions	Transportation costs/concerns
Can produce energy	Limited availability
	Limited capacity
	Residues need proper management and handling
Landfilling	
Proper characterization of waste	Transportation costs/concerns
Facilities are sited properly with necessary controls	Potential spread of pathogens from biological incidents
Suitable for various waste streams	Limited capacity in each landfill
Can produce energy	Facility indemnification
	Reluctance of some owners/residents/operators

Source: US EPA. Waste Management Options

5. WASTE DISPOSAL IN LANDFILLS

5.1. Waste Collection – General Considerations

Landfilling involves structures designed cautiously built into or on top of the ground in which waste is kept isolated from the surrounding environment. There are different types of landfills designed especially to handle particular waste streams. Generally each landfill is given a license for a particular kind of waste and the landfill cannot accept a waste stream which lies outside the scope of its permit [32]. Also, there is general agreement that reuse and recycling lessen pollution, saves energy and cut down finances along with reduction in GHG emissions. The reduction in GHGs is achieved by keeping the recycling material out of landfill and/or reducing the need to mine, refine and use virgin material e.g. use of plastic bottles to form other products will result in reduction in energy needed to produce it from virgin product, use of aluminum beverage cans for remaking it will result in lowering of mining and refining of virgin aluminum. Unfortunately in Pakistan, waste segregation is improperly done. Pakistan needs to focus strongly on developing a methodology for the management of general waste storage and collection. The developers should take start by initiating public awareness campaigns or other methods to provide information about how residents must prepare solid waste and recyclables for collection [32,33].

In residential areas where the waste is prepared manually, either plastic bags or standard sized containers are required for storage. Local municipalities can limit the volume, weight and the number of containers to be collected under usual service. Also, developing a collection system for a community needs to specify how often the waste will be collected. Recyclables can be collected on a different schedule from the regular garbage [33]. In urban areas, the most usual configuration of the pick-up points for collection might be the curbside or the alley service. This strategy is considered more economical but requires greater participation of the residents. Due to low density and limited budget in rural areas, a suitable alternative is to place the waste near routes along major roads or a drop-off arrangement which can serve as a small transfer station. Once the solid waste is collected by the local government, it needs to be stored at a transfer station prior to recycling or final disposal. Determining the system funding structure is another critical issue and it varies from one country to another due to the several reasons including variation in the magnitude of waste collected per collection point, type of vehicles used and the labor costs. Size of crew is also crucial when collection costs are evaluated and it affects the overall economic efficiency of the project [33].

5.2. Environmental Concerns of Landfills

The major concerns related to landfilling includes leaking/migration of biogas and liquid effluents (leachate) in environment as well in ground that further causes groundwater pollution, surface water pollution along with bad odors and vegetation damage [34]. While later issues are local in nature the former is global and needs considerable measures for its reduction. Landfill waste streams (solid & leachate) have inconsistent composition due to which solid as well as generated leachates and associated groundwater show presence of variable organic contaminants [35]. No two different landfills can be same in terms of leachate quality [36]. However, mostly both the waste streams contains biodegradable waste apart from most common organic contaminants such as pesticides, chlorinated aliphatic hydrocarbons, BTEX (Benzene, Toluene, Ethyl-benzenes and Xylenes) and chlorinated benzene compounds [37]. Substantial level of concentrations of some emerging compounds including nanomaterials, perfluronated compounds, flame retardants and pharmaceuticals have also been reported in leachates and underlying groundwater. Since landfilling causes serious threats to the environment in context of soil, water and air pollution, therefore waste-to-energy approach will play a vital role in municipal solid waste (MSW) management since it can reduce the waste by 90% and 70% in volume and weight respectively [35].

5.3. Landfill Operation and Biogas Control

Landfill operations consist of managing work face, waste compaction, daily cover, vector, litter, odor, stormwater and sediment control and road access. Working face is the most acute part of any landfill operation as it is the area where the fresh waste is dumped or exposed and it is the center of equipment and personnel activity. Hence the overall performance of the landfill is affected by the standard of working face operation. The first layer of waste sited in a cell is always crucial as it should be loose enough in order to avoid damage to the liner and the leachate collection system. Base liner system can easily be damaged if the initial cell filling is not managed carefully. The damage will negate even a good design and construction and compromise the landfill's containment performance. Also, it is essential to keep truck and equipment movement orderly and working face as small as practicable [38]. Waste compaction is another important component and a good landfill site always has an efficient and practical method to achieve high degree of waste compaction routinely. Compaction methods create pathways for the flow of biogas and leachate and therefore should be directed inwards towards pathways especially designed for drainage within the waste mass to encourage their flow and minimize the risk of leachate breakout [38].

Vectors include birds, insects, rodents and other animals. They can carry disease agents and be a threat to the public health and the community. The most important measure for vector control is the application of daily cover. Daily cover can be soil or any other alternative such as tarpaulins or an artificial material. Sites with poor daily cover practices often lead towards vermin, litter and surface water quality problems. Therefore, it is critical to cover waste completely and ensure it remains covered in all parts other than the active face which should be kept as small as practicable. Design of a stormwater drainage system at the landfill site is another key to optimize operations, manage risks of flood damage and avoid adverse offsite due to leachate, sediment and waste contamination in site runoff [38].

Term 'biogas control' encompasses all methods for controlling movement of biogas which includes minimizing sub-surface migration, emissions and nuisance odors, protecting groundwater, reducing fire risk in the landfill waste mass, collection for its energy benefit and protecting structures. Control requirements are strictly site specific and for smaller sites, biogas control can be achieved by passive venting. These systems do not involve any active mechanical means. The pressure gradient created by the gas generated within the landfill directs the gas towards a well which then intercepts the gas and conducts it to the surface. However active control systems use blowers within the landfill to create vacuum and withdraw biogas via network of wells and pipelines. In order to ensure that the excessive biogas migration and/or emissions are not occurring, monitoring is done using detectors, probes and similar devices [38].

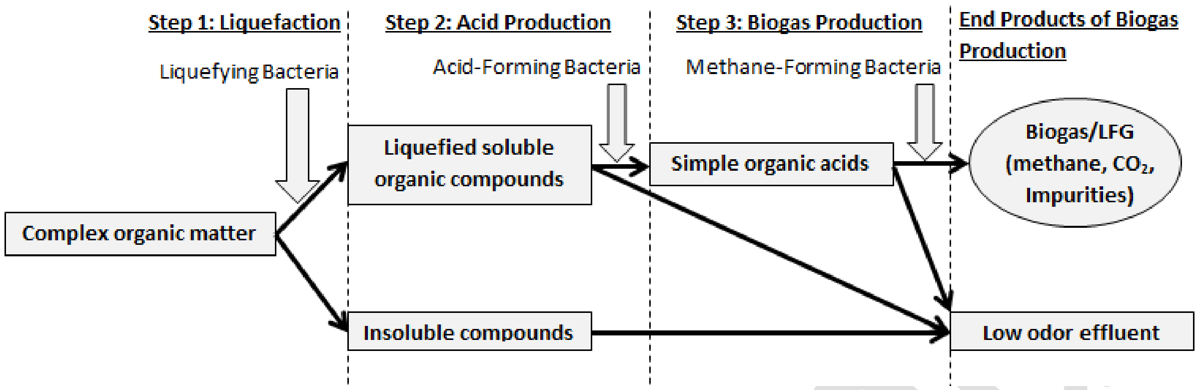

Figure 5 Three steps of conversion from complex organic matter to biogas in anaerobic digestion

5.4. Biogas Generation in Landfills

A landfill has two life stages (i) operating stage where MSW is being dumped and biogas production starts and other (ii) is closed stage; when the storage capacity passed its maximum biogas production. Methane emissions are more from landfills that are operational as compared to the closed landfills. It is due to the fact that majority of the waste degradation occurs in the first few years and emission rates decreases with time after closure [39]. As soon as MSW is landfilled, the organic content undergoes biochemical degradation, which is actually anaerobic digestion that occurs in three (3) stages resulting into methane generation in the form of biogas [40] as shown in Figure 5. In the first stage i.e. liquefaction, bacteria convert carbohydrates, fats, proteins and other insoluble, fibrous materials into soluble substances. The liquefied and soluble substances are further converted into biogas by the acid and methane forming bacteria in the further steps. Acid forming bacteria convert soluble organic matter into volatile acids in the second step while in step three methane forming bacteria convert these volatile acids into biogas. Note that this phase of biochemical degradation lasts for weeks or months however not all volatile acids and soluble organic substances are converted to biogas as some remain as effluent. The biogas formed typically consists of Methane 50-75%, Carbon dioxide 25-50%, Non-methane volatile organic compounds 0.01-0.60%, Water vapor 6-6.5%, Nitrogen 3.9-4.1%, Oxygen 0.9-1.1% and Ammonia <0.1-1% [40,41].

Generally, only CH_4 is accounted in the approximation of GHG emissions from these landfills [42]. Although CO_2 is also produced in the process that also has large global warming potential (GWP) but considering the fact that waste responsible for the emissions is of biogenic origin, hence, the overall net effect of CO_2 becomes neutral [42] and therefore not included in emissions while nitrogen oxides, carbon monoxide and ammonia can indirectly cause carbon dioxide and nitrogen dioxide thus should be estimated if data is available. Under optimum conditions, methane production begins within 2 years of MSW dump with building up to maximum within first 5-6 years, thereafter declining slowly. However, the gas production does not stop and is still measurable for decades later but usable amount is produced for about 10-15 years only [43]. Lou and Nair plotted the general trend of CH_4 emissions from landfills from operational to post-closure years using IPCC First Order Decay (FOD) model, see Figure 6. The figure clearly unveils that CH_4 generation in current landfills will remain for several years even if these landfills are to be aloof right now [42].

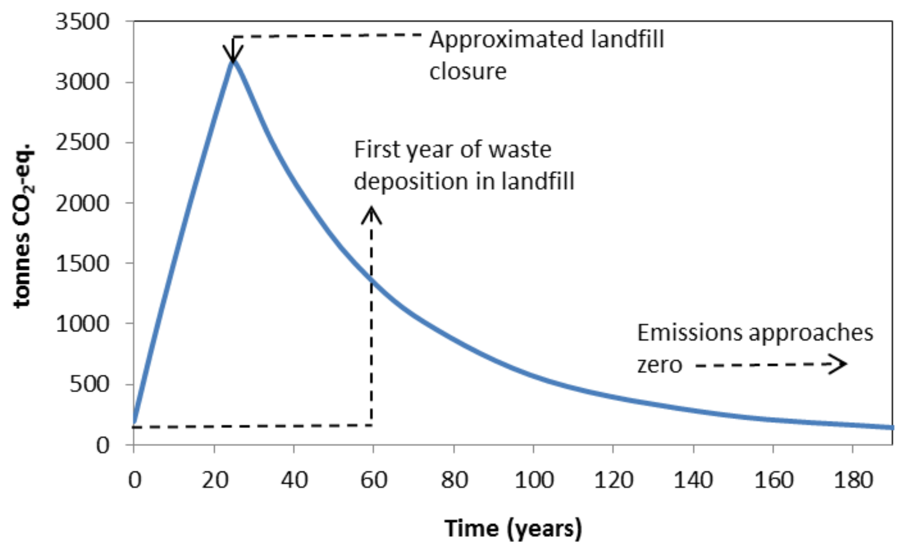

Figure 6 General trend of CH_4 emission from landfills in their operating post closure years

5.5. Biogas Utilization

Biogas formed can be collected and flared if not suitable composition is achieved for further use. Using produced biogas directly as a fuel with little gas pre-treatment (condensate removal and filtration) is often the most simplest and cost effective application making it an attractive option for industrial boilers, furnaces, burners, dryers and kilns. Alternatively, biogas could also be used for electricity generation but this may require more extensive gas cleaning up to remove corrosive trace constituents and may depend upon the balance of additional capital cost for power generation prime movers e.g. spark ignition engines, dual fuel engines, gas turbines or a micro turbine and steam turbine. It is to be noted that in later option the landfill site will use some of the generated electricity to operate its own systems and will sell the rest [38]. Present study is focused on utilizing biogas for power generation since Pakistan is facing severe power deficit due to lack of resources.

5.6. Global Scenario of Biogas Utilization for Power Generation

According to GMI as of October 2011, installed generating capacity from biogas plants worldwide is 3228 MW_e with the following distribution: US 1730, UK 1012, Australia 164, Canada 67 and developing/transitional countries (CDM and JI) as 242 and 13 respectively [4]. In USA, there are almost 3518 municipal solid waste landfill sites which are capable of producing 4314 GWh of electricity per year [35]. A survey in 2010 indicated a decline in landfilling from 8000 landfill sites in 1988 to 1908 sites in 2010. In 2009, there are over more than 425 operational biogas projects in the US which created 1180 MW_e of electricity and produce 6.65 million m^3 per day of renewable fuel [25]. However according to EPA as of 2011, approximately 560 biogas energy projects were operational generating 1730 MW_e per year and producing 8.78 million m^3 per day of biogas to direct-use applications. They further estimated that an additional 570 landfill projects present attractive opportunity and if operational would likely to generate additional 1370 MW_e per year or 19.68 million m^3 per day of biogas [44].

In the year 2012 UK produced 32 Mt of MSW, around 40.3% of this MSW was landfilled in 725 active landfills that produced 4979 GWh of electricity while some 16.1% of MSW was processed in energy-from-waste plants for electricity generation. Overall UK MSW generation has decreased 11% from 2007 and 13% decrease from 2002 figures, during this about 1700 landfill sites have stopped operation in 2001 showing decrease in landfill option and more towards recycle. A further decrease to 29.5 Mt of MSW is forecasted by 2030 [30]. China in spite of disposing 43% of its total waste into landfills has the potential to generate 18,801 GWh of power per year [35]. In comparison to above developed countries, some of the other countries like Turkey, Mexico, Greece and New Zealand dispose 98%, 96%, 91% and 84% of their waste into landfills respectively [45].

5.7. Factors Affecting Landfills Development in Pakistan and Possible Solutions

We all are well aware of the acronym NIMBY – Not in My Backyard. No one wants a landfill to be established in the vicinity of their house. If landfills are not managed properly, it may result into ground water contamination and air pollution in the area. The existing landfill sites in Pakistan are poor in design, no proper monitoring is done and are generally not manned by skilled personnel. It is due to this fact that usually the residents use all means to stop its development. The other major hurdle in the establishment of landfills in Pakistan is the land mafia. The sites previously selected for landfills are currently occupied by housing schemes. The land mafia provokes the local population against the landfill with reasons such as water and air contamination, drop in property value and increase in the traffic of waste carrying trucks. The apathy of the municipalities and local governments is another reason for not establishing the designed landfills. They rather prefer to sell the waste to a vendor for money instead of depositing it in a landfill. In addition, they can also raise funds by establishing a housing scheme which they would not be able to do with a landfill. Also, better equipment and facilities are needed for developing new landfill sites which are currently unavailable due to several reasons

The Kuri landfill site in the capital city Islamabad selected by the Ministry of Planning and Development, Pakistan is a good example for understanding the aforementioned issues. The landfill was designed according to the standards of US EPA and finalized after conducting detailed scientific research considering all the technical, social and environmental aspects of the project. But a writ petition was filed against the project by the residents and environmental activists in the court of law in 2006, hanging the fate of the project. Several meetings were held in this regard between the consultants, Capital Development Authority (CDA) and Pak-EPA. Presentation on the said project was also given to the minister of Ministry of Environment in June 2008 attended by all committee members to solve the issue but all in vein and the conflict still exists [46].

Developing a landfill is not a rocket science but still cities in Pakistan do not have proper landfill sites available. In general, the sole reason is lack of awareness and negligence. While policies exist, level of implementation is poor due to ill-equipped government institutions. Despite of having expertise in this area, governmental environmental institutions are generally directed by either public sector workers or politicians who do not have sufficient knowledge on waste management and strategies. Also for implementing these policies, a sound source of funding is required to the environmental institutions which is not present at the moment [47]. Therefore, better policies and regulations need to be made and enforced, scientific research needs to be undertaken in order to improve the technical and economic aspects of landfilling operation and financial constraints should be removed by taking several initiatives by the government. Public awareness of waste segregation is also required which will help institutions to come up with appropriate designs of landfills.

Since the health issues are escalating regularly all over the country, Ministry of Environment in collaboration with environmental protection agencies of all the four provinces and local governments has now started to take keen interest in developing waste management strategies and studies regarding many of the landfill sites throughout the country are under consideration. Development of these landfills will be carried out with the help of local experts and contractors while land, operating costs and machinery will be provided by the respective local governments. Health concerns are not the only driving force but Pakistan is also keen on promoting clean energy and sustainable development in the light of Kyoto Protocol and hence so far attracted several landfill projects that are at different stages of development [47].

Out of many ongoing projects, one good case example is of Peshawar which is among the fastest growing cities in Pakistan. Due to the ongoing conflict in the areas neighboring Afghanistan, massive influx of refugees in the area has increased the volume of municipal waste which is beyond the existing capacity of the landfills and posed dangerous hygienic conditions in the city. Recently, the municipality of Peshawar and the Asian Development Bank has initiated a project to develop a sanitary landfill site for the city. The project will involve waste sorting, compost generation from organic substances, removal of residues from the compost, landfilling of residues in sanitary conditions, direct landfilling of MSW in case of sorting plant malfunctioning, power outage or insufficient capacity and power generation from biogas. The plant is expected to treat 1000 tonnes of MSW per day with the option for future expansion in case of continuous population growth and economic activities [47]. These kinds of projects should be initiated throughout the country for which the present study aims to deliver motivation for the government think tank by providing attractive numbers for the whole country.

6. POTENTIAL YIELD OF BIOGAS FROM LANDFILLS IN PAKISTAN

6.1. Methodology: First Order Decay (FOD) Model

First order decay (FOD) model proposed by IPCC estimates the flow rates of biogas (majorly CH_4 and CO_2) by a landfill for MSWs by conducting a mass balance that requires biodegradable organic carbon *‘DOC’* fraction in the wastes. Just a segment of the total mass present in landfill wastes is decomposable into biogas ‘$DDOC_m$’ which can be determined by the following equation:

$$DDOC_m = DOC \times DOC_f \times W \quad (1)$$

where ‘DOC_f’ is the fraction of *‘DOC’* that is decomposable and it is recommended to determine via theoretical model that varies only with the temperature *‘T’* in the anaerobic zone of a landfill and is given by Equation (2). As per guidelines of IPCC, the temperature in anaerobic zone can be assumed to be remains constant at about 35ºC [48]. The value of temperature in anaerobic zone also seems justified as the normal temperatures in Pakistan are high enough due to its climatic conditions and geographical location. Default and range values of *‘DOC’* content in wet waste are given in Table 9. *‘W’* is the mass of waste deposited.

$$DOC_f = (0.014 \times T) + 0.28 \quad (2)$$

Table 9 Default and range values of DOC content in wet waste

Types of waste	DOC Content in Wet Waste (%)	
	Default	Range
Food Waste	15	08-20
Paper and cardboard	40	36-45
Plastic	-	-
Metals	-	-
Glass	-	-
Wood	43	39-46
Textiles	24	20-40
Yard waste	20	18-22
Bulk waste	18	12-28

Source: IPCC Guidelines on National Greenhouse Gas Inventories. 2006.

The methane generation potential 'L_o' can be calculated by Equation (3):

$$L_o = DDOC_m \times F \times (16/12) \quad (3)$$

where, 'F' is the fraction of CH_4 in biogas and its suggested value by IPCC Guidelines is given as 0.5. 16 and 12 are the CH_4 molecular mass and the carbon atomic mass respectively [49]. FOD model can be used to describe the production process of biogas according to which the rate of generation declines exponentially with time [49,50]. Mathematically, it can be expressed after simplification as Equation (4):

$$DDOC_m = (DDOC_{mo}) \times exp\ (-kt) \quad (4)$$

where, 'k' is the reaction rate constant depending upon the temperature, nature of waste, moisture and can be expressed in terms of half-life '$t_{1/2}$' by Equation (5). Half-life is the time required for the '$DDOC_m$' in waste to deteriorate to half of its initial mass and is affected by climate of landfill site, composition of waste, landfill site characteristics and management. Short half-life corresponds to slow degradation of the waste and vice versa.

$$k = (ln\ 2) / t_{1/2} \quad (5)$$

Depending upon the waste composition and climate of the landfill site, waste does not start decomposing straightaway after disposal but a delay exists. Biogas production from the MSWs is assumed to pledge after one year of disposal and FOD model takes into account the same assumption for its calculations [49]. This means that the model should be applied to all yearly landfilled quantities and the net biogas yield can be determined by adding the resulting biogas sizes produced from waste landfills in different years.

Due to the strong dependence of the model on the waste characteristics, it is important to use the appropriate approach for the calculations. As enough and up-to-date data for MSWs compositions and generation in Pakistan is not available, therefore average values of the waste composition of its major cities spatially located in Pakistan (see Table 6) are considered a reasonable estimate for the composition of the whole country. A *'DOC'* value of 9% is calculated for the MSW generated in Pakistan based on the *'DOC'* values of each component given in Table 9 using Equation (6) which is formulated in accordance with the approach given by IPCC:

$$\% DOC = 0.15 (A) + 0.4 (B) + 0.43 (C) + 0.24 (D) + 0.2 (E) \qquad (6)$$

where *'A'*, *'B'*, *'C'*, *'D'* and *'E'* are percent MSW that is food waste, paper and cardboard, wood, textiles and yard waste respectively. Results of DOC values are shown in Table 10.

Table 10 DOC calculations for MSW generated in Pakistan (Present work)

Waste Stream /MSW Component	Default DOC Values (frac)	MSW Composition (%)	DOC (%)
Food Waste *(A)*	0.15	17.26	2.59
Paper and Cardboard *(B)*	0.4	4.32	1.73
Wood *(C)*	0.43	1.46	0.63
Textiles *(D)*	0.24	5.54	1.33
Yard Waste *(E)*	0.2	13.38	2.68
Overall			9.0

6.2. Model Application and Results

Figure 7 shows the estimated methane inventory of MSW in Pakistan from 2010 to 2050 based on the generations rates extracted from the only study done by Pak-EPA in 2005 for the solid waste generation in Pakistan [24]. Solid waste collection system owned by the government and other operating services in Pakistan's cities presently averages only 50% of the total waste generated. Although 75% of the waste quantities generated should be collected to ensure cities to be relatively clean [7]. Also, approximately 5% of the total waste generated goes into the landfills in Pakistan [45,51]. In countries like Pakistan where no organized waste collection systems exist in rural areas, the population considered should include only the urban population. Therefore, by applying IPCC FOD model over the latest data available and current urban population, results demonstrate that nearly 14.18 Gg of methane are emitted from the landfills in Pakistan each year. FOD model calculations are shown in Table 11.

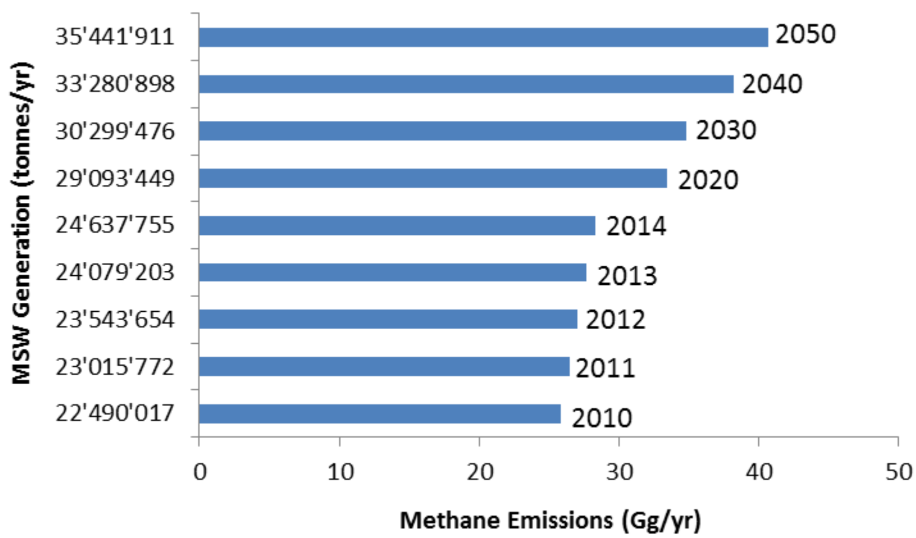

Figure 7 Methane inventory of MSW in Pakistan from year 2010 to 2050

Table 11 FOD model calculations for the current scenario (case of using internal combustion engines)

Data	
Urban Population	72500000.00
Solid waste generation rate (kg/day/capita)	0.45
Fraction landfilled	0.05
Landfill temperature (T)	35.00
Fraction of methane in landfill gas	0.50

Lower heating value of methane (kJ/m^3)	33905.67
Density of methane (kg/m^3)	0.66
Waste collection (frac)	0.50
Power deficit (MW)	6000.00
Methane global warming potential	23.00
Waste Generation	
Waste generated (kg/day)	32842500.00
Waste generated (tons/day)	32842.50
Waste generated (tons/year)	11987512.50
Waste with 3% hazardous waste (tons/year)	12347137.88
Waste collected (tons/year)	6173568.94
Waste landfilled (W) (tons/year)	308678.45
Methane Generation	
Fraction of DOC decomposable (DOC_f)	0.77
Biodegradable organic carbon (DOC)	0.09
Total mass decomposable in biogas (tons/year)	21273.53
Methane generation potential (tons/year)	14182.35
Methane generation potential (kg/year)	14182350.60
Methane generation potential (Gg/year)	14.18
Power Generation Potential	
Methane recovery rate (frac)	0.75
Electrical efficiency (frac)	0.30
Energy potential (MJ)	728578994.88
Energy potential (kWh)	202383054.13
Power generation potential (MW)	5.20
Power substitution (%)	0.09
Greenhouse Effect Reduction	
Greenhouse effect equivalent of CO_2 for methane (Gg)	326.19
CO_2 emitted if combusted (Gg)	39.00
Greenhouse effect reduction (%)	88.04

7. BIOGAS CAPTURE AS AN ENERGY SOURCE FOR PAKISTAN

7.1. Pakistan's Energy Profile

Pakistan is an energy deficient country facing severe energy crises over the last few years. Due to the rapid progression in population and economy, an enormous pressure has been put on the government to invest in the energy sector of Pakistan for sustainable development and economic growth. Electricity demand escalates every year which results into an amplified difference between supply and demand. According to National Transmission and Dispatch Company (NTDC) Limited, electricity demand during July-March 2011-2012 was 18,860 MW while the energy supplied was 12,755 MW. The deficit of almost 6000 MW resulted into extreme power crises and load-shedding [52,53]. Increasing trend of demand is exponential while supply remains stagnant due to no new major power plant installation for the last few years. According to a latest study, the exponential growth in the electricity demand for next 18 years will heighten up to 66,000 MW approximately [53]. Share of renewable energy technologies excluding hydro power is negligible in the current energy portfolio of the country [54]. It is obvious that if Pakistan has to deal with its energy catastrophes, the country must explore its renewable energy resources. Biogas capture as an energy source from waste disposal sites in Pakistan for power generation is a productive option that can contribute significantly towards demand management and environment conservation.

7.2. Recovering Energy from Waste Landfills

According to the waste generation estimate determined and FOD model discussed in sub-section 3.2 and 6.1 respectively, waste landfills in Pakistan are capable of emitting 14.18 Gg of methane in the form of biogas as shown in Table 11. A considerable amount of energy can be generated by arresting this biogas and either guiding it towards combustion engines for power generation or utilizing it for the heating purposes. Biogas is often upgraded to bio-methane with an equivalent calorific value of natural gas to either use it as a separate product or use as a blend at various proportions with natural gas. From the economic point view, best revenues can be attained by selling bio-methane as a fuel rather than using biogas in combined heat and power (CHP) systems where around 50% of the energy is produced in the form of heat. Therefore, where there is no substantial heat demand, biogas must be upgraded to bio-methane and sold as a fuel [55].

Other than methane and carbon dioxide, biogas also has trace amounts of water vapor, hydrogen sulfide, oxygen, nitrogen, siloxanes, ammonia and particles. It is necessary to remove contaminants and energy gases from the biogas for better and efficient operation, prevention of the mechanical equipment from corrosion and maximization of volumetric energy density [56]. Hydrogen sulfide is usually removed by the addition of iron hydroxide to the anaerobic digester but if the amount exceeds more than 2000 ppmV, bio-scrubbers must be used for scrubbing hydrogen sulfide before carbon dioxide removal. For carbon dioxide exclusion, various techniques including cooling, compression, precipitation, adsorption or absorption are involved. But depending on the upgrading technology, the three most commercially available techniques are Pressure Swing Adsorption (PSA), High Pressure Water Scrubbing (HPWS) and amine scrubbing. A number of European countries including Sweden, Germany and Switzerland have set standards to avoid the contamination of the end product. PSA and HPWS are currently dominating the biogas upgrading industry. HPWS systems are considered as less complex and economical in operation and are the most employed systems in Europe. Also the reported methane losses from the system are approximately 1.5% [56].

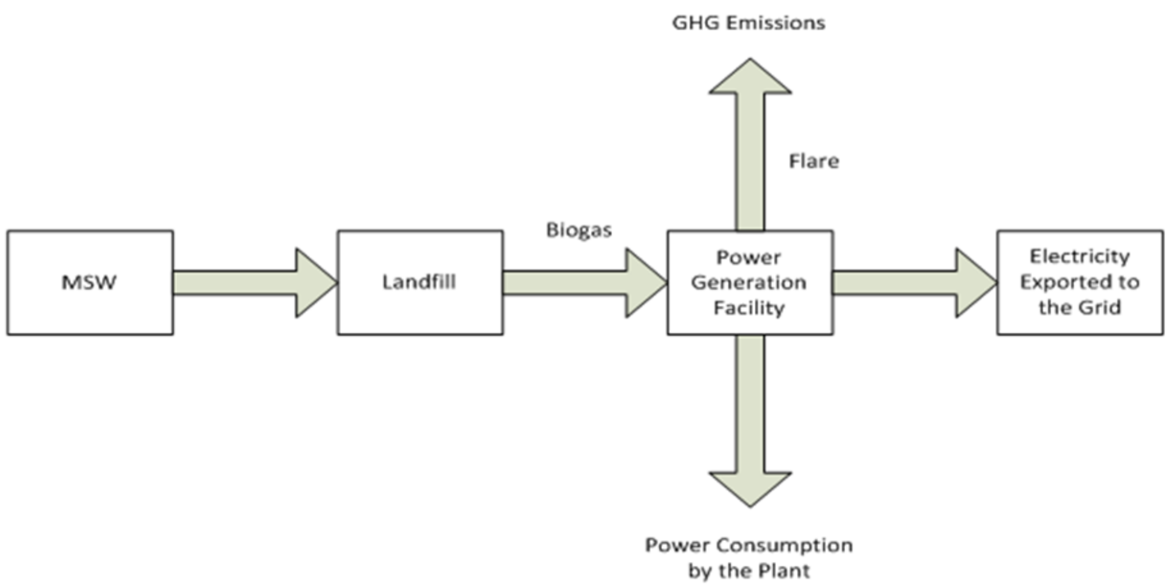

Figure 8 Schematic representation of a power generation facility utilizing biogas from landfills

Pure methane gives a lower heating value (LHV) of approximately 33906 kJ/m^3 [57] while CO_2 associated with biogas is incombustible. With this much of heating value, Pakistan has the potential to generate 25.10 MW_t (202.38 GWh) of thermal power *'P_t'* from landfill waste per year. Density of methane is taken as 0.66 kg/m^3 at room temperature [48]. Figure 8 shows the schematic diagram of a power generation facility employing biogas from landfill sites. Almost 70% of the landfill power projects employ internal combustion engines due to higher efficiency and relatively lower cost. Other than internal combustion engines, gas turbines and micro turbines are also used for the purpose depending upon the size of landfill. Gas turbines require greater flow rates of gas; hence suitable for large systems. Micro turbines are usually employed where either the flow rate of biogas is low or the methane content in biogas is in lower percentage but higher operational costs are associated with this technology [58]. Electrical power *'P_e'* potential can be determined by the following equation:

$$P_e = P_t \times r \times \eta_e \tag{7}$$

where *'r'* is the recovery rate and is taken as 75% [58] while *'η_e'* is the electrical efficiency. Table 12 shows the comparison of costs to generate 5.20 MW_e, 4.16 MW_e and 7.28 MW_e with an average electrical efficiency of 30%, 24% and 42% [58,59] from internal combustion engines, gas turbines and micro turbines respectively if any of the aforementioned three technologies are employed for power production depending upon the size of the landfill site. It is to be noted that in above power generation projects typically 2% parasitic load are frequently included in calculations for adjustments like lost generation, equipment downtime and other parasitic load (equipments) [59]. Other than above energy convertors, fuel cells can also be operated by utilizing biogas from landfills.

The electricity shortfall is 6000 MW as mentioned in the previous sub-section and present operational landfills in Pakistan can only contribute up to ~0.1% in the total deficit which does not make any huge difference. In spite of having low potential of landfills to overcome energy shortage, the fact cannot be ignored that it can at least provide significant energy to the vicinities around those landfill sites from which biogas will be captured plus GHG reduction.

Table 12 Comparison of costs to generate power by different technologies

Technology	Avg. Elect. Efficiency (%) [58,59]	Power Generation (MW)	Cost of Engine/Turbine ($/kW) [58]	Annual O&M Cost ($/kW) [58]	Overall Gen. Cost ($/yr)
Combustion Engine	30	5.20	1700	180	9,776,000
Gas Turbine	24	4.16	1400	130	6,364,800
Micro Turbine	42	7.28	5500	380	42,806,400

Non-recyclable waste can be converted to energy by various processes including gasification, pyrolyzation, anaerobic digestion and direct combustion [60]. Following the EfW approach, Pakistan can exploit its huge amount of MSW also for power generation. To landfill 50% of the total waste generated by a developing country is reasonably a good practice from the management point of view [45]. Following the general code of conduct to keep the cities clean, if 75% of the total waste generated today is collected and landfilled 50%

of it then Pakistan has the potential to produce ~83.17 MW of power that can contribute up to ~1.4% to overcome the current power shortage as shown in Table 13.

Table 13 Power generation potential from waste landfills emissions

	Waste Disposal in Landfills (%)	Collection of Waste Generated (%)	Total Methane Production (Gg/year)	Power Gen. Potential (Approx.) (MW)	Share in Current Deficit (%)
Scenario 1	5	50	14.18	5.55	0.1
Scenario 2	50	75	212.74	83.17	1.4

Table 14 shows the calorific values and potential contribution of power of each combustible component present in the MSW generated in Pakistan. On the basis of these calorific values, if the amount of waste which is intended to be landfilled is incinerated or burned, it can generate up to 9.29 MW and 139.40 MW of power in scenario 1 and 2 respectively with 22% electrical efficiency [61]. Although power generation potential from incineration is relatively more than the average potential of landfilling, the environmental issues associated with the incineration plants makes landfilling more viable due to its controlled setting and overall high efficiency EfW plants under this setting.

Table 14 Power generation potential by incineration from MSW generated in Pakistan (sample calculations for scenario 1)

Waste Stream /MSW Component	MSW Composition (%)	MSW Generated (kg/yr)	Calorific Value (MJ/kg) **[62]**	Power Generation (MW_e)
Food Waste	17.26	53277899.93	5.49	2.04
Paper	2.58	7963903.93	7.07	0.39
Cardboard	1.74	5371004.98	17.41	0.65
Wood	1.46	4506705.32	10.55	0.33
Textiles	5.54	17100785.96	14.56	1.74
Yard Waste	13.38	41301176.19	6.33	1.83
Plastic	5.34	16483429.06	20.14	2.32
			Total	9.29

8. POTENTIAL REDUCTION IN GREENHOUSE EFFECT

As stated earlier, the estimated amount of methane (CH_4) emissions from waste landfills is 14.18 Gg per year. When CH_4 is released to the atmosphere, it commendably traps the radiated heat from the earth and has a 23-fold greater greenhouse effect than CO_2. Therefore, it is vital to keep low levels of CH_4 emissions as much as possible from various sources [56]. Let's assume the period of interest is 100 years then the equivalent amount of CO_2 that need to be curtailed is 326.19 Gg. If the estimated amount of CH_4 is captured in the form of biogas and directed towards combustion engines for power generation, 39 Gg of CO_2 will be added to the atmosphere annually. Hence it is evident from the calculations that by combusting biogas collected from landfills as a waste management scheme can reduce greenhouse effect up to ~88%. Also, same percentage of greenhouse effect reduction is observed as shown in Table 15 when we apply the same analysis over the potentially improved practice (scenario 2) discussed in the previous section. Therefore, utilization of landfill waste to produce energy is not only an environmentally viable option but it will also be a positive move towards the promotion of renewable energy technologies by utilizing available resources for sustainable future.

Table 15 Estimate of greenhouse effect reduction by recovering energy from waste landfills

	Waste Disposal in Landfills (%)	Collection of Waste Generated (%)	Total Methane Production (Gg/year)	Greenhouse Effect Equivalent of CO_2 (Gg/year)	Greenhouse Effect Reduction (%)
Scenario 1	5	50	14.18	326.19	88
Scenario 2	50	75	212.74	4892.91	88

9. CONCLUSION AND RECOMMENDATIONS

Although landfills represent the largest source of GHGs as compared to other methods but still landfills remain the leading waste disposal method in most parts of the world especially in developing countries. The biogas collection projects over landfills have established a strong point to introduce and ripen activities in the renewable energy sector in developing countries. Such projects will also help in achieving greenhouse effect reduction, environmental protection, energy security and decline in dependency over conventional fossil fuels. For the aforementioned objective, FOD model developed by IPCC to estimate the landfill GHG emissions is a viable tool that gives modest results if used properly. Results of this study show that if MSW generated by Pakistan is managed appropriately by various schemes especially landfilling, it cannot only support Pakistan’s energy sector to deal with its severe energy crises but can also help in improving the environment by reducing carbon emissions. Future estimates of solid waste production indicate that the current situation could worsen unless a dedicated national policy framework and an integrated action plan is adopted along with a concerted effort to improve the collection and disposal system.

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