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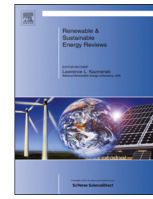

Evaluation of energy potential of Municipal Solid Waste from African urban areas

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A B S T R A C T

Energy is a critical issue for Africa, where large number of people do not have access to energy. Energy recovery from waste can play a role in minimising the impact of Municipal Solid Waste (MSW) on the environment with the additional benefit of providing a local source of energy. This study was carried out to assess, at the African level, the role which waste could play in providing energy to citizens and provides an estimate of the total potential of energy from waste incineration and from landfill gas (LFG). The results show an energy potential of all waste generated in Africa of 1125 PJ in 2012 and 2199 PJ in 2025. Nevertheless, if energy recovery through LFG is considered, about 155 PJ could be recovered in 2012 and 363 PJ in 2025 if waste actually collected, or projected to be collected, is considered. The electricity generation could reach 62.5 TWh in 2012 and 122.2 TWh in 2025, in case of full waste collection, compared with electricity consumption in Africa of 661.5 TWh in 2010. If waste actually collected is considered, these estimates decrease respectively to 34.1 TWh in 2012 and 83.8 TWh in 2025. Apart from continental estimates, the study provides detailed information at the country level and a vision of the spatial distribution of energy from waste based on the city population in major African cities.

Contents

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1. Introduction

There is a growing understanding, at global level, about the negative impacts that waste can have on the local environment (air, water, land) and human health etc. The increasing complexity, costs and coordination implied by proper waste management require multi-stakeholder involvement at every stage of the process. Waste management is usually one of the most complex and cost-intensive public services, even when well organised and operated properly. In developing countries, waste management has the highest share in municipalities' budgets, spending from 20% to 50% of their available budget on solid waste management. A significant part (up to 80–90%) of the solid waste management budget is used for waste collection. Services typically cover, however, only about 40–70% of all urban solid wastes, with the remainder being uncollected and less than 50% of the population being served [1–4].

Population growth, urbanisation and economic development are expected to produce increasing quantities of waste that are overburdening existing waste-management systems. Many cities in Africa face significant difficulties related to waste management, collection and disposal of Municipal Solid Waste (MSW). Increasing city size poses great problems linked to increasing population and city area as well as lack of infrastructure development [2,5,6].

The poor waste management in Africa has important consequences for the disposal of uncollected waste in dumps and the associated severe environmental and health related problems. An integrated approach to solid waste management is required in order to enable local/ national authorities to reduce the overall amount of waste generated and to recover valuable materials for recycling and for the generation of energy.

Despite all efforts to reduce, recycle and reuse waste, there is a growing amount of waste that needs to be disposed in landfills. Several options are available and the choice of the most adequate should consider the local specific conditions [3]. Waste incineration might be an option for waste disposal, but technical and economic problems are preventing large scale deployment of waste to energy plants, especially in developing countries. Landfill gas (LFG) recovery could be a solution, an opportunity for energy recovery and a potential source of energy in areas with low access to energy, such as Africa.

This paper addresses the issue of waste management in Africa and investigates the potential of energy production from waste, contributing to energy supplies and alleviating energy poverty. It focusses on the assessment of the potential of MSW to produce energy. Several studies relate to the use of MSW for energy production and provide estimates of the energy potential of MSW. However, the data about the waste generation, collection and the use of waste for energy production for the African continent is very scarce and covers only few cities or countries.

The study makes GIS spatial explicit analysis of the energy potential MSW in Africa using the best available data related to MSW from the United Nations, World Bank, Food and Agriculture Organisation (FAO). This study provides a complete overview and wider perspective of this potential for the whole African continent, while providing detailed information at country and city level.

2. Energy recovery from waste at global level

2.1. Challenges and opportunities for energy recovery from waste

The world population grew from 3.1 billion in 1960 to almost 7 billion in 2010 and it is projected to increase to 8 billion by 2025 and to 9.3 billion by 2050. World urban population also sharply increased from 1 billion in 1960 to 3.5 billion in 2010 and it is projected to reach 4.5 billion in 2025 and 6.4 billion in 2050 accounting for a population share increasing from 30% in 1960 to 68% in 2050 [7].

As the world's population grew and became more urban, global solid waste generation is estimated to have increased tenfold in a century from 110 million tonnes in 1900 to 1.1 billion tonnes in 2000 [8]. Currently, the global MSW generation is estimated at about 1.3 billion tonnes per year, and it is expected to increase to approximately 2.2 billion tonnes per year by 2025. A significant increase of the waste generation rates per capita has been also projected, from the current 1.2 kg per person per day to 1.42 kg per person per day until 2025 [1].

Africa faced a particularly rapid population growth, from 294 million in 1960 to 1.0 billion in 2010 and it is expected to increase to 1.4 billion by 2025 and 2.2 billion by 2050. The urban population grew from 56 million in 1960 to 409 million in 2010 and it is projected to further increase to 672 million in 2025 and 1364 million in 2050. In 2010, more than 42% of the population in Africa lived in urban areas, increasing from 20% in 1960, and could reach 47% in 2025 and 62% in 2050 [7]. Even if waste generation rates per capita are lower than in developed countries, developing countries produce large amounts of waste. These amounts are expected to rise with increased population, urbanisation and improved lifestyle; this is would result in additional challenges to waste management systems and in an additional pressure on the environment.

Improvements in waste management are needed, especially in Africa, where current waste management is often in a poor state; the use of the energy content of waste could be one of the leading ideas for such progress. The energy content of waste can be recovered by means of either thermo-chemical processes (combustion, pyrolysis or gasification) or biological processes (anaerobic digestion). The global energy potential of waste can be estimated at 8–18 EJ/year in 2010, which could increase to 13–30 EJ in 2025, if a heating value of municipal waste ranging from 6 to 14 MJ/kg is considered, with a best estimate moving from 12 EJ in 2010 to 20 EJ in 2025, for an average heating value of 9 MJ/kg for waste [9,10].

Currently (2010 data), there are more than 600 waste-to-energy facilities worldwide, most of them in Europe (472 in EU, Switzerland and Norway), Japan (100) and the US (86) [11,12]. In the European Union (EU), energy recovery by incinerating Municipal Solid Waste produced more than 8.0 million tonnes of oil equivalent in 2010, with 73 million tonnes of waste treatment capacity. This capacity is expected to rise to 85 million tonnes by the end of 2016 and 94 million tonnes by 2020 [13].

The International Solid Waste Association (ISWA) reports that on a global scale, landfilling still represents the main disposal method for Municipal Solid Waste [14]. In particular, Low and Middle Income countries are still almost exclusively depending on

List of acronyms

CDM	Clean Development Mechanism
GHG	Green House Gas
GW	Gigawatt
GWh	Gigawatt-hour(s)
LFG	Landfill Gas
LI	Low Income
LMI	Lower Middle Income
UMI	Upper Middle Income
HI	High Income
MSW	Municipal Solid Waste
TPES	Total Primary Energy Supply

Measurement units

kgoe	kilogram oil equivalent
ktoe	kilo tonnes oil equivalent
kWh	kilo Watt hour
MJ	mega Joule
Mt	million tonnes
Mtoe	million tonnes oil equivalent
PJ	peta Joule
TWh	terra Watt hour

landfilling or dumping of waste. The European Union has approved a strategy aiming at reducing waste disposal focusing on waste prevention, reuse, recycling and recovery aimed at achieving recycling rates of 50% by 2020, as compared to the current rate of 25%. These goals have been integrated into the European environmental policy, notably the European Commission's Roadmap [15] for a resource efficient Europe (2011/571/COM) and the EU's Waste Framework Directive 2008/98/EC. The Directive 1999/31/EC on landfilling in the European Union requires Member States to cap the biodegradable municipal waste disposal in landfills to 35% of their 1995 level by 2016 and requires appropriate measures to control landfill gas emissions and to recover the landfill gas. This approach encourages waste incineration instead of landfilling, provided that strong environmental standards on pollutant emissions in waste-to-energy power plants are met. Primary energy production of gas recovery from landfills reached 117 PJ (2.8 Mtoe) in 2010, representing more than 25% of the biogas production in the European Union [13]. Due to the policy target of reducing waste landfilling, the potential landfill gas generation from landfills is expected to decrease in the European Union in the longer term.

Waste landfilling is declining in developed countries due to advanced regulations encouraging waste reduction and recycling. Developing countries are expected to face an increase of waste generation and thus an increase of waste landfilling can be expected at least in the short term. This will lead, among other environmental impacts, to an increase of methane generation and subsequent emissions, if proper technologies are not put in place.

2.2. Landfill gas generation and global methane emissions from landfills

The global greenhouse gas emissions were estimated at 50 $GtCO_{2e}$ in 2010, with CO_2 contributing for 76%, CH_4 for about 16%, N_2O for about 6% and other gases for about 2% [16]. The total anthropogenic methane emissions were estimated at 373 Mt in 2010, of which 46 Mt were released in Africa. On a global level, major sources of CH_4 were: agriculture (43%), energy (38%) and waste (17%) from landfills and wastewater. The global annual CH_4 emissions from landfilling of solid waste were estimated at 29 Mt CH_4, accounting for approximately 8% of estimated global emissions. This is equivalent to emissions of about 735 Mt CO_{2e}. Methane emissions from landfills in Africa were estimated at 1.3 Mt CH_4, equivalent to 32 Mt of CO_{2e} emissions in 2010 [17].

Table 1
Methane potential from landfill (L_0) (Source: [21]).

	L_0 (Nm^3/tonne waste)	Half-time (years)
IPCC model	88	4–23
TNO-model	84	7
GasSim	71	6–15
Landgem (conventional)	171	14
Landgem (arid)	101	35

When waste is deposited in landfills, the organic matter in the waste decomposes to LandFill Gas (LFG). Complex chemical and biological decomposition processes occur resulting in the production of landfill gas, a mixture of methane (45–60%), carbon dioxide (40–55%) and trace components. The LFG production rate steadily increases while MSW accumulates in the landfill. The time scale of the gas generation depends on waste composition, landfill management and climate, but generally, CH_4 and CO_2 are generated within 25 years from landfilling, whereas emissions from the landfill site may continue for up to 50 years [18]. The various models available for the estimation of methane emissions from landfills show various generation rates, or methane generation potential (Table 1). Methane generation in landfills depends on the extent of anaerobic decomposition and the type of landfill and is influenced by waste composition and climate (temperature and precipitations) [20,21]. The anaerobic degradation of one tonne of wet MSW, supposed to contain 60% organic matter and 40% moisture, could generate theoretically 200 Nm^3 of methane (150 kg of methane). Various studies showed an actual rate of generation of landfill gas ranging from 54 to 140 Nm^3 methane or (39–100 kg methane) per tonne of waste [12,18]. A methane generation rate of about 50 Nm^3 of methane per tonne of MSW landfilled was considered to be a conservative estimate, which can be used with confidence [18]. If this estimate is coupled with a global estimate of landfilled MSW of about 1.3 billion tonnes per year [1], global methane generation can be evaluated at around 65 billion Nm^3 (46 Mt) per year.

As methane is oxidised by methanotrophic bacteria in the aerobic zone of the landfill cover into CO_2, methane oxidation depends on the top-layer and climate conditions and ranges between 10% and 30% for landfills in exploitation and 10 – 60% for closed landfills, with a 10% default value proposed by IPCC [22], and 25% by the GasSim model [21]. Considering the methane oxidation in the top layers of the landfills of 10%, according to IPCC [22], the global landfill emissions reach about 42 million tonnes CH_4, in accordance with the other estimates of CH_4 emissions from waste landfilling of 32 million tonnes CH_4 [17].

LFG can be captured and used for energy generation or flared on-site to reduce GreenHouse Gas (GHG) emissions. The LFG collection is technically feasible starting from some years after landfill opening and can continue after landfill closing (typically 25 years) (Fig. 1). The practice of methane recovery from landfills started in 1975 at Palos Verdes, Los Angeles in the United States [23]; its relatively low cost and cost effective technology that is

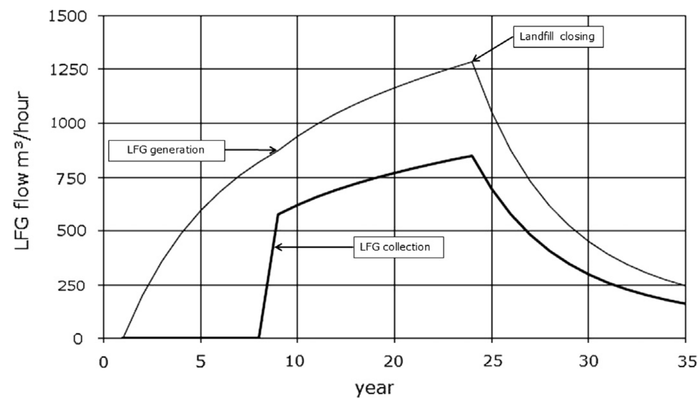

Fig. 1. Landfill life cycle, LFG generation vs. LFG collection.
(*Source*: [19])

implemented nowadays in many developed countries and in particular the EU and the US [20]. However, only a small share of the entire global potential (about 5 Mt per year) are captured worldwide, about half of which in the European Union [13,18].

LFG is used as fuel in internal combustion engines, gas turbines and steam boilers for electricity or heat generation. LFG uses may include upgrading to methane gas quality. Prior to use, some treatment is required to remove certain trace gases and impurities. Using LFG for energy generation provides also some additional “side benefits“: it helps to reduce odours and harmful emissions, undesired methane emissions contributing to local pollution and global climate change. For these reasons, the Clean Development Mechanism (CDM) developed under the Kyoto Protocol could be a useful tool for the funding and for the implementation of such projects in Africa[2].

LFG use in small to medium size internal combustion engines can be a good option for local production of electricity in Africa. At the moment only a few CDM projects (about 35) have been reported for methane capture from landfill sites in the continent [25,26] and the large majority of landfills in Africa do not have any system for gas collection installed.

A study conducted in Uganda to explore the viability of electricity generation from landfill gas in Kampala assessed the electricity potential of the landfill at 31,000 MWh in 2009 and 26,600 MWh in 2011. This study concluded that this project is not viable under current economic conditions, without improved incentives, feed-in-tariffs, or carbon credits [27]. South Africa is currently considering the option of generating electricity from landfill gas collected from landfill sites. The study conducting an economic assessment of electricity generation at the landfill site in Cape Town proved that grid-connected or stand-alone systems using turbines appear to be economically viable [28].

[2] The Clean Development Mechanism was defined in the Kyoto Protocol, as a way to (1) assist parties not included in Annex I in achieving sustainable development and in contributing to the GHG emission reduction goals and (2) to assist parties included in Annex I in achieving compliance with their GHG emissions reduction commitments [24]. Its first commitment period started in 2008 and ended in 2012.No new treaty to reduce greenhouse gases emissions was established as planned. In the United Nations Climate Change Conference of 2012 held in Doha, Qatar, an agreement was reached to extend the Kyoto protocol until 2020. A successor of the Kyoto Protocol is set to be developed by 2015 and implemented by 2020. The future of the CDM mechanisms will depend on the new treaty to be agreed on GHG emissions.

3. Approach and methodology

3.1. Objectives

The goal of this study is the quantification of the potential of waste for energy production in Africa and for such an evaluation, two main options, waste incineration and landfill gas recovery, were investigated. This paper provides the maximum theoretical potential of energy that can be recovered from waste, if adequate waste to energy plants could be built, and the potential landfill gas for energy production. The energy potential is estimated for 2012 and for 2025, for which either data or projections on waste generation, collection rates, waste composition, and other relevant parameters were available.

3.2. Methodology

The estimations provided in this study consider waste production and collection in urban areas only, since no waste management systems are generally available for rural areas in Africa. Data on waste generation and composition for 2012 were made available by World Bank [1], which also provided predictions depending on urbanisation and perspectives for economic development, based on the current solid waste management practices. Data on urban population for 2012 and 2025 was used with the additional assumption that individual city population increases with the same rate as provided for the UN national urban population at country level.

Considering the poor data availability on waste management in Africa, the average data at country level was taken into account for the purpose of assessing the energy potential, although there are large variations from city to city in terms of waste generation and collection. For countries for which no data was available (e.g. Equatorial Guinea, Djibouti, Guinea Bissau, Libya and Somalia) estimates were made considering the regional data from other countries and the level of income.

Although waste incineration in most of Africa is probably not realistically viable at present from the financial and technical points of view as well as on short to medium-term, waste incineration was investigated as providing the maximum theoretical potential of energy recovery from waste. For this option, the energy potential of waste generated was established at country level for the whole Africa, considering a lower heating value of waste of 9 MJ/kg, representing a total energy which can theoretically be recovered from waste.

Landfill gas recovery has been considered to represent the most appropriate way for energy production from waste in African conditions, at least on short term, entailing fewer technical difficulties and lower investment costs in comparison with waste incineration. For the methane generated and recoverable from landfills a CH_4 net heating value equal to 35.8 MJ/Nm³ was considered [39]. The potential amount of methane from landfills was established using the relevant IPCC default methodology based on waste generation rates, waste collection rates, waste composition and the potential gas recovery rate from managed landfills as key parameters. This energy potential of waste however, strongly depends on the actual rate of waste collection and this theoretical potential could be significantly reduced if waste is not collected or it is collected just to a small extent.

The potential electricity production from waste in incineration plants and of landfill gas was also estimated. An electricity production efficiency of 20% was considered for waste incineration plants. This is a conservative assumption, due to the fact that efficiencies of 20–25% can be easily achieved and state of the art waste to energy plants can reach even up to 30–32% efficiency [14,40].

The electricity potential obtained from using methane from landfill in internal combustion engines was determined, considering an efficiency of 30%. This potential electricity production was calculated under both the assumptions of waste fully collected and landfilled, or using actual waste collection rates, detailed at country level. To put the potential electricity production in a proper context, the additional electricity production from waste was compared with the actual electricity consumption in each country.

3.2.1. Calculation of methane generation in landfills

In general, only a fraction of organic material can be converted into landfill gas in anaerobic conditions, depending also on specific conditions. The maximum amount of methane that may be generated during anaerobic decomposition can be determined from the approximate, simplified molecular formula of organic material degradation:

$$(CH_2O)_n \rightarrow \tfrac{1}{2}nCH_4 + \tfrac{1}{2}nCO_2 \quad (1)$$

Several models are available for calculating the actual amount of landfill gas produced by waste decomposition in landfills, such as IPCC, TNO, GasSim, LandGem, Afvalzorg, EPER and Scholl Canyon [20,21]. The IPCC has formulated guidelines and provided two methods for estimating methane emissions from solid waste disposal. The IPCC default method is a mass balance method which estimates the amount of CH_4 emitted from landfills based on the theoretical gas yield and assumes that methane is released the year the waste is disposed. This default method produces reliable estimates of the yearly emissions if the total amount of waste and its composition does not change over time.

The IPCC Guidelines also introduce the First Order Decay model (FOD), which provides estimates of the actual annual methane emissions, but requires long time-series data over the lifetime of the landfill site (20–25 years) [22]. Therefore, for the specific conditions in Africa, where data available on waste management and disposal is very scarce, the default method has been considered more appropriate and it has been applied in the present study. The methane generation from waste degradation in landfills was then established in this study with the following formula:

$$Q = W \cdot DOC \cdot DOC_f \cdot MCF \cdot F \cdot s \ (\text{kg } CH_4/\text{kg waste/year}) \quad (2)$$

where $Q = L_0$ = methane generation (kg CH_4/kg waste/year), W = waste amount deposited per year (kg/year), MCF = Methane Correction Factor (dimensionless), DOC = Degradable organic carbon in waste under aerobic conditions (dimensionless), DOC_f = fraction of DOC decomposing under anaerobic conditions (dimensionless), F = Fraction of CH_4 in the landfill gas (dimensionless), $s = 16/12$ is the stoichiometric factor to convert carbon into CH_4 (dimensionless).

The methane correction factor (MCF) accounts for the fact that landfills actually produce less CH_4 than theoretically possible, because a fraction of waste decomposes aerobically in the top layers. Depending on the type of landfill, this factor ranges between 0.4 for unmanaged, shallow sites to 1.0 for managed sites. As this study aimed to provide the potential for energy of methane generated from managed landfills, a methane correction factor of 1.0 was assumed.

Since not all the organic matter can decompose, the fraction of the Degradable Organic Carbon (DOC) considers the fraction of organic carbon that is accessible to biochemical decomposition, depending on the composition of waste. The variability of the waste composition data, as well as the ranges for the Degradable Organic Carbon content of waste were taken into account in this study.

$$DOC = 0.4A + 0.2B + 0.15C + 0.43D \quad (3)$$

where A = share of carbon content in paper and textiles in waste (%), B = share of carbon content in garden and park waste (%), C = share of carbon content in food waste (%), D = share of carbon content in wood and straw waste (%).

In a real landfill, only a fraction of DOC actually decomposes under anaerobic conditions (DOC_f) and is converted to CH_4 and CO_2. The rest is stored in the landfill site as stable organic matter or degrades through other processes. In this study a default value of DOC_f of 0.5 as recommended by IPCC on the basis of several experimental studies, is considered.

Landfill gas consists mainly of methane (CH_4) and carbon dioxide (CO_2). The CH_4 fraction (F) in the landfill gas can vary between 0.4 and 0.6, depending on several factors including again waste composition. In this study the default value in the IPCC Guidelines of 0.5 is applied, in consistency with other studies [21]. Finally a share of CH_4 generated from landfill is oxidised in the top layers of landfills and an Oxidation Factor (OX) of 0.1 was considered here, as recommended by the IPCC to estimate the avoided emissions of CH_4 into the atmosphere [22].

In practice, the various landfill gas collection systems cannot recover the whole amount of methane. The efficiency of landfill gas recovery can vary between 40% and 90% with an average of 75% [21,41]. EPA has estimated that landfill gas collection efficiency varies between 67% and 90% [19] depending on the type of landfill cover and the type of LFG collection system employed. In this study a collection efficiency of 75% was considered appropriate in African conditions.

3.2.2. Spatial allocation of energy potential from waste

The present study also has made a GIS spatial explicit analysis of the energy potential from waste and the LFG generated in landfills. Such detailed spatial information is crucial for evaluating landfill constraints such as neighbourhood (distance from residential areas and water bodies); geological and hydrogeological conditions; risk of flooding and landslides; and infrastructure (e.g., access roads, power grids, etc.). This provides a useful tool for deciding on the implementation of a landfill gas recovery project, a decision requiring a spatial analysis of the previously cited factors and the need for additional infrastructure.

The amount of waste generated and its potential energy, calculated at national level, have been spatially allocated into African major cities, according to FAO City location and Population in Africa [42]. The GIS data layer (shape file points) displays major cities in Africa, including cities with populations above 50000 inhabitants estimated for 2008. For 2012 and 2025, it was assumed

Table 2
Energy supply in Africa in 2010.

Country	Income	TPES (PJ)	TPES (GJ/capita)	Electricity (GWh)	Electricity kWh/cap
Algeria	LMI	1690	47.7	42,988	1212
Angola	LMI	572	30.0	4993	262
Benin	LI	153	17.3	1085	123
Botswana	UMI	95	47.2	3442	1715
Burkina Faso	LI	137	8.3	905	55
Burundi	LI	98	11.7	231	28
Cameroon	LMI	298	15.2	5443	278
Cape Verde	LMI	62	124.1	309	622
Central African Rep.	LI	995	226.0	158	36
Chad	LI	120	10.7	182	16
Comoros	LI	5	6.1	41	56
Congo, Dem. Rep.	LI	995	15.1	7115	108
Congo	LMI	62	15.2	966	239
Cote d'Ivoire	LI	401	20.3	5482	278
Djibouti	LMI	11	12.6	270	304
Egypt	LMI	3067	37.8	144,099	1776
Equatorial Guinea	HIC	67	95.4	100	143
Eritrea	LI	31	5.9	296	56
Ethiopia	LI	1390	16.8	4315	52
Gabon	UMI	89	59.4	1755	1166
Gambia	LI	20	11.3	239	138
Ghana	LI	390	16.0	9232	378
Guinea	LI	179	17.9	785	79
Guinea-Bissau	LI	9	6.1	32	21
Kenya	LI	819	20.2	6840	169
Lesotho	LMI	37	17.1	896	413
Liberia	LI	99	24.7	333	83
Libya	UMI	802	126.1	27,793	4373
Madagascar	LI	274	13.2	1340	65
Malawi	LI	134	9.0	2000	134
Mali	LI	135	8.8	510	33
Mauritania	LI	63	18.1	942	272
Mauritius	UMI	59	45.4	2650	2040
Mayotte	UMI	0	0.0	0	0
Morocco	LMI	691	21.6	26,750	837
Mozambique	LI	427	18.3	11,742	502
Namibia	LMI	67	29.4	3743	1640
Niger	LI	170	10.9	798	51
Nigeria	LI	4733	29.9	25,373	160
Rwanda	LI	111	10.5	338	32
Réunion	HIC			2646	3127
Saint Helena	HIC			9	2150
Sao Tome	LI	3	18.2	57	347
Senegal	LI	142	11.4	2552	205
Seychelles	UMI	10	116.1	295	3388
Sierra Leone	LI	114	19.5	169	29
Somalia	LI	225	24.1	327	35
South Africa	UMI	5730	114.3	253,720	5061
Sudan	LMI	676	15.5	7816	179
Swaziland	LMI	94	79.3	1455	1227
Tanzania	LI	841	18.7	4492	100
Togo	LI	113	18.7	839	139
Tunisia	LMI	403	38.5	15,247	1455
Uganda	LI	660	19.7	2053	61
Western Sahara	LI			80	151
Zambia	LI	340	26.0	10,476	800
Zimbabwe	LI	402	32.0	13,010	1035
Total Africa		29,308	28.7	661,749	647
Sub-Saharan Africa		22,654	26.5	404,792	473

that cities' populations increase with the same rate as provided for the UN national urban population at country level. The spatial allocation process applied in this study implies the assumption that waste generated in urban areas is collected and deposited in landfill sites located in the vicinity of major cities. Spatial allocation of energy from waste to major cities only is a limitation introduced by the lack of data on the population of all African cities and their spatial position. The spatial distribution of waste could be better allocated to the place where it is really generated, if all data on cities' locations and their populations would be available.

Table 3
Waste management systems in various countries in Africa (Source: [1]).

Country	Income level	Dumps (%)	Landfills (%)	Recycled (%)	Other (%)
Algeria	UMI	96.8	0.2	2	1
Cameroon	LMI	95	–	5	–
Madagascar*	LI	–	96	–	4
Mauritius	UMI	–	91	2	–
Morocco	LMI	95	1	4	–
Niger	LI	–	64	4	32
Tunisia	LMI	45	50	5	0
Uganda	LI	–	100	–	–

* Percentages might not add up to 100% because some residues from incineration and composting are landfilled.

4. Overview of energy situation and waste management in Africa

4.1. Energy supply in Africa

Access to energy and electricity in particular, is an indispensable condition to develop economic activities and to improve the quality of life. The use of electricity is a key factor to make agricultural and industrial processes more efficient. Electricity is needed for households (cooking, lighting, refrigeration, and home-based activities) but is also needed for essential facilities such as hospitals, schools, and for industry. Energy consumption and energy access is an important issue directly related to income and poverty, as limited and unreliable energy access translates into poverty, limited employment opportunity and poor economic performance, and it is a major impediment to economic growth [29].

Africa has consumed on average 685 ktoe per capita in 2010, which is only one third of the global average energy consumption per capita (1881 kgoe/capita), using a mix of hydropower, fossil fuels and biomass, mostly in traditional uses. Energy consumption in Sub-Saharan Africa was even smaller, just 632 kgoe/capita, while, if excluding South Africa, this figure drops down to 501 ktoe per capita in 2010 [30,31]. African countries often have to rely on diesel power generation to meet their electricity needs, which costs some African economies between 1% and 5% of GDP annually. Africa, with 15% of world population has produced 662 TWhe, representing only 3.1% of world electricity and only 647 kWe/capita. In South Saharan Africa, however, the electricity consumption per capita was even smaller, only 473 kWe/capita, compared to the world average of 2981 kWe/capita in 2010 [31,32].

Nearly 1.3 billion people globally, almost one-fifth of the Earth population, did not have access at all to electricity in 2010. The highest share of the people without electricity lives in Africa: about 590 million people, representing around 57% of the African population. Some small progress has been made in Africa and the electrification rate increased from about 35.5% in 2002 to almost 43% in 2010. The urban electrification rate has reached 72.1% in 2010 while the rural electrification rate was still only 23.6% in 2010 [29,30].

Nevertheless, regional differences are huge: while in North Africa only 1% of the population does not have access to electricity, the average electrification rate for Sub-Saharan Africa was only 31.8% in 2010. For Sub-Saharan Africa this share varies across countries between 50% and 85% [29,30]. The average urban electrification rate was 64.2% in 2010 and the rural electrification rate was only 12.9% in Sub-Saharan Africa; a high share of people (around 57.8%) lived in rural areas in Africa [7,30].

It has been estimated that the African continent will need to add around 250 GW of capacity by 2030 in order to meet the demand growth, while Africa's installed power capacity was just 135 GW in 2010 [32]. In particular, it was also estimated that Uganda alone needs an additional installed power capacity of 2 GW to meet its own electricity needs against 549 MW installed in 2010 [27,32]. National data on the Total Primary Energy Supply (TPES) and electricity consumption in Africa in 2010 are presented in Table 2.

Presently, biomass is widely used for cooking and industrial use and to a little extent for power generation. Bagasse residue was in 2011 the most important source of energy for Africa, corresponding to 94% of the 860 MW of installed bioenergy power generation capacity and could be further developed. Fuel wood and charcoal as well as agricultural residues are widespread energy sources used in households across Sub-Saharan Africa. Around 2.6 billion people relied worldwide on the traditional use of biomass for cooking in 2010 (49% of the population) while the traditional use of biomass for cooking in Africa covers 698 million people (68% of the population), of which 696 Million people live in Sub-Saharan Africa; accounting for a population share ranging between 75% and 96% in different African countries [30]. Agricultural residues are also potential resources to be used for energy production through combustion (dry biomass) or anaerobic digestion (wet biomass). The co-firing of biomass in coal-fired power plants could also provide a contribution to energy supply.

A number of initiatives to increase access to energy across various regions have been launched in the last decade such as the UN Sustainable Energy for All initiative (SE4All), the Global Lighting and Energy Access Partnership (Global LEAP) and Global Alliance for Clean Cookstoves. For these reasons, the present paper addresses specifically the issue of possible electricity generation from waste and from landfill gas generated from Municipal Waste.

4.2. *Waste management and energy recovery options in Africa*

Solid waste management collection and disposal are key challenges that all cities in the world have to face, but that are particularly difficult in Africa where most towns and cities lack regular waste collection and disposal services. Poor financial resources, limited technical capacity and poor infrastructure are important challenges for planning and management of solid waste [5,33] and the increase in population puts additional pressure on waste management? [27]. Additional issues are related to the lack or weak enforcement of environmental legislation, as well as a limited environmental awareness? [34,35]. Several other factors influence the MSW management, including economic development, technology access and population size, and waste management activities, which vary significantly across countries.

The energy content of waste and landfill gas generation both depend on waste composition. Waste composition, on the other hand, is influenced by many factors, such as culture and traditions, economic development and climatic conditions. The waste composition shows higher fractions of organic material in low and middle-income countries, while more developed countries have a higher share of paper, plastic and other inorganic materials, such as glass and metal [1,36]. For this reason, the composition of waste is expected to change with the increase of living standards [20].

4.2.1. *Waste management services in Africa: current situation*

Waste management services in Africa are provided mainly to large cities [2,26]. Nevertheless, a limited share of waste is generally recovered and reused (Table 3). No waste management systems are generally available for rural areas where waste is traditionally deposited in uncontrolled areas or subject to some extent to reuse, recycling and composting [34]. Most of the MSW in Africa is burned on site or deposited in open dumps or semi-controlled landfills with no groundwater protection, leachate recovery, or treatment systems and usually without soil cover. Waste dumps are located on the edges of urban areas, sometimes in ecologically sensitive areas with potentially negative impacts on water sources [5,27,33]. Waste deposited in these areas contaminates the surface and ground water and poses major health hazards. If not properly controlled, waste disposal has important negative impacts on the local environment, e.g. soil, pollution and air pollution (odours, emissions), health risks (pathogens) and climate change (methane emissions) [3,35].

When disposed in dumps or open landfills, waste degrades in aerobic conditions generating higher CO_2 emissions and lower methane emissions. Improving waste management and extending access to waste collection will result in more waste being disposed in managed landfills. Sanitary landfills offer conditions favourable for anaerobic degradation. This leads to higher LFG generation and potentially more GHG emissions from landfills that can be reduced through LFG collection and utilisation for energy purposes, with better impacts on the environment, health and energy supply.

4.2.2. *Waste management services in Africa: options and challenges*

In principle, several practices are possible for MSW management, which includes waste reduction, recycling and recovery, and for energy recovery from waste [3]. Several technologies are commercially available for energy recovery from waste, such as incineration, biochemical conversion (e.g. anaerobic digestion), which can bring other additional benefits (e.g. fertiliser from anaerobic digestion) and LFG collection. Some technologies entail certain technical and economic difficulties (incineration) or are still not proven at the commercial scale (gasification, pyrolysis). All those options need dedicated supply chain management to be set up at local level and some pathways for Africa, all relevant from both the technological and economical point of view, are shown in Fig. 2.

Waste incineration is common practice in the developed countries (EU, US, Japan) where waste-related policies limit waste disposal on land. Even using waste minimisation, recycling and recovery practices as it is the case in the EU or US, some non-recoverable waste will remain, making landfills necessary. Recovering the energy embedded in waste is considered preferable to landfilling assuming emission control is adequately addressed. Open burning of waste is particularly discouraged due to harmful emissions and severe air pollution.

In developing countries, the high capital and maintenance and operation costs of waste incineration plants have prevented the large scale application of this technology as an energy recovery option, making it an option even less attractive for Africa [3,4]. Moreover, the highly variable composition and high moisture content of waste make continuous and optimal plant operation difficult to achieve, requiring additional fuel support as well. Without proper controls, waste incineration can be highly polluting, generating harmful emissions, such as dioxins and heavy metals [4,35].

Additional options for MSW management include, for example, *biochemical conversion* through fermentation and anaerobic digestion to produce alcohols and methane and aerobic processes for waste stabilization and composting. Anaerobic digestion has become an attractive method in Europe for the biodegradation of organic fractions derived from MSW. Utilisation of the organic fraction of MSW for biogas production has a large potential and

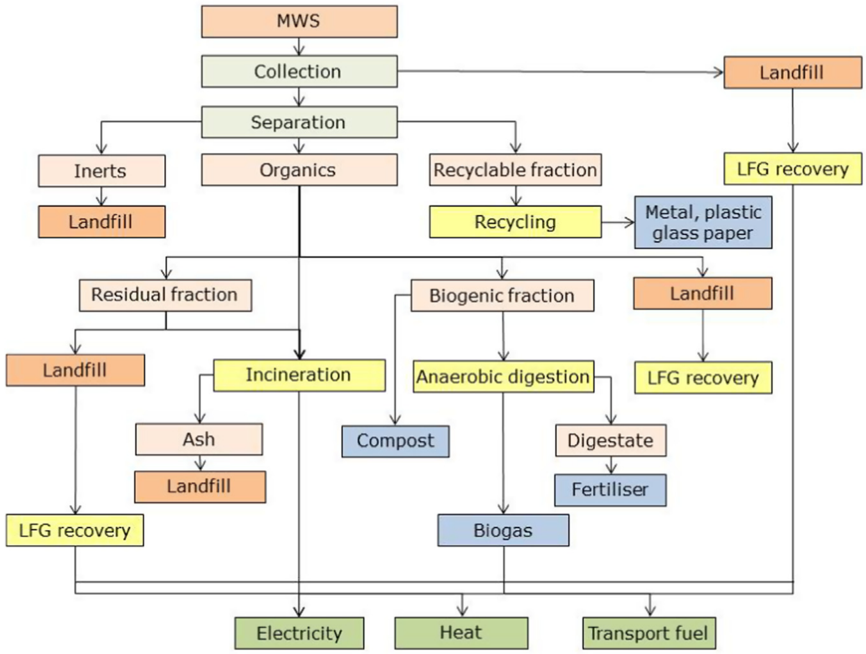

Fig. 2. Pathways for energy generation from waste.
(*Source*: adapted from [34,37])

Table 4
Present waste generation rates by region.
(*Source*: [1])

Region	Range (kg/capita/year)	Average (kg/capita/year)
Sub-Saharan Africa	33–1095	237
North Africa	296–533	442
OECD	400–1351	803
Latin America	40–1945	402
East Asia and Pacific	160–1570	347
South Asia	44–1862	164

many AD plants are in operation around the world. Anaerobic digestion as a pretreatment prior to landfill disposal or composting offers several advantages, such as minimization of the waste disposed in landfills and could contribute to recycling. Anaerobic digestion offers the opportunity to produce renewable energy and a higher quality of treatment but requires technical know-how and brings financial burdens.

Landfilling offers a simpler and more affordable solution and has been the common practice for long time, but poses significant challenges in the African context. Although landfilling of waste should be avoided as far as possible, this practice will continue especially in Africa due to financial reasons. Proper *landfilling*, in modern sanitary landfills, is also often lacking, especially in developing countries due to complex logistics, the lack of financial capabilities and technical know-how, coupled with poor environmental policies. Building sanitary landfills with leachate and gas recovery may be too expensive for most African cities [36] and few landfill sites, such as in Namibia and South Africa, comply with minimum standards. Some countries, including Egypt, Uganda, Ghana, Nigeria, South Africa, Tunisia, and Zambia, have started to develop upgraded landfills and the few existing sanitary landfills are limited to major cities [2,33,35]. Landfill gas recovery systems are currently available in few places in South Africa [26].

Since the power grid in Africa covers essentially the urban areas, according to the AICD (Africa Infrastructure Country Diagnostic) [38], the presence of landfill sites in the vicinity of urban areas creates good opportunities for producing electricity from

Table 5
Waste collection in several African countries in the present ().
(*Source*: [1])

Country	Income	Collection (%)
Algeria	LMI	92
Benin	LI	23
Cameroon	LMI	43
Chad	LI	20
Comoros	LI	20
Egypt	LMI	63
Ghana	LI	85
Madagascar	LI	18
Mali	LI	40
Mauritania	LI	30
Mauritius	UMI	98
Morocco	LMI	86
Senegal	LI	21
Seychelles	UMI	95
Sierra Leone	LI	44
South Africa	UMI	50
Tanzania	LI	48
Togo	LI	42
Tunisia	LMI	95
Uganda	LI	39
Zambia	LI	20

landfill sites with low cost for grid connection. A stand-alone system can also be installed when the community surrounding the plant is able to use the electricity generated, thus creating opportunities for electricity access for remote areas without electricity grids.

5. Results

5.1. Waste generation and collection

Solid waste generation rates and composition vary across Africa in relation to local economy, industrial development, local conditions and cultural traditions, estimated to range from 33 kg/capita/

Table 6
Waste generation and collection in Africa.

Country	2012			2025		
	Generation (kg/capita)	Generation (10^3 t/year)	Collection (10^3 t/year)	Generation (kg/capita)	Generation (10^3 t/year)	Collection (10^3 t/year)
Algeria	442	10,905	10,032	529	16,490	15,171
Angola	175	2126	914	256	4897	2938
Benin	197	792	182	274	1796	898
Botswana	376	483	208	511	820	492
Burkina Faso	186	892	357	274	2698	1619
Burundi	201	205	82	292	540	324
Cameroon	281	3448	1483	365	6601	3961
Cape Verde	183	58	55	274	109	104
Central African Rep.	183	329	132	256	675	405
Chad	183	620	124	256	1571	628
Comoros	814	210	42	767	303	151
Congo, Dem. Rep.	183	4640	1856	274	11,897	7138
Congo	193	515	222	274	1045	627
Cote d'Ivoire	175	1878	751	256	4232	2539
Djibouti	183	129	55	274	252	151
Egypt	500	18,350	11,560	657	31,899	25,519
Equatorial Guinea	281	84	36	365	169	101
Eritrea	183	230	92	256	599	360
Ethiopia	110	1615	646	237	5550	3330
Gabon	164	223	96	256	455	273
Gambia	193	211	84	274	471	282
Ghana	33	444	377	183	3756	3192
Guinea	164	627	251	256	1646	988
Guinea-Bissau	164	79	31	256	186	111
Kenya	110	1071	429	219	3834	2301
Lesotho	183	115	49	292	279	168
Liberia	164	339	135	256	814	489
Libya	438	2219	954	529	3225	1935
Madagascar	292	1984	357	402	4749	2375
Malawi	183	604	253	292	2039	1223
Mali	237	1449	580	347	3876	2326
Mauritania	183	278	83	292	671	335
Mauritius	840	462	452	803	503	493
Mayotte	840	60	57	803	93	88
Morocco	533	10,326	8880	675	16,384	14,745
Mozambique	51	500	210	183	2963	1778
Namibia	183	169	73	329	450	270
Niger	179	518	218	274	1509	905
Nigeria	204	17,451	7329	292	40,438	24,263
Rwanda	190	416	175	310	1233	740
Réunion	840	687	652	803	750	713
Saint Helena	840	2	2	803	2	2
Sao Tome	179	20	19	329	51	49
Senegal	190	1070	225	310	2743	1371
Seychelles	1088	53	51	913	53	50
Sierra Leone	164	394	173	310	1113	712
Somalia	110	412	173	219	1436	862
South Africa	730	23,214	11,607	730	27,064	18,945
Sudan	288	5481	2357	383	11,891	7135
Swaziland	186	48	23	310	104	62
Tanzania	95	1237	519	201	4988	3242
Togo	190	535	508	310	1341	805
Tunisia	296	2154	840	420	3663	3480
Uganda	124	605	182	237	2233	1340
Western Sahara	183	85	17	274	178	89
Zambia	77	385	162	201	1747	873
Zimbabwe	193	989	490	256	2010	1206
Total Africa	284	124,994	68,150	362	244,303	167,525
Sub-Saharan Africa	234	80,955	35,865	310	172,465	106,587

year to 1095 kg/capita/year. Several studies showed that waste production is linked to the income: the higher the GDP, the greater the waste production [2,26,35]. The data available shows that the average waste production from South African countries is around 237 kg/capita/year, well below the waste production of 803 kg/capita/year in OECD countries, as shown in Table 4 [1,26].

A first result of the present study consists in estimations of the urban MSW generation and collection for all African countries for 2012 and 2025, based on estimated 2012 data and projections for urban population for 2025 produced by the World Bank for each African country [7]. It is worth noting that the analysis has been possible for average values at the country level, and a detailed assessment of differences within each country and between cities from the same country has been not possible.

Since a large share of the African population lacks access to waste management, waste collection rates are well below the generation rates. The waste collection rates vary significantly by national income and by region. Higher income countries have higher collection rates, averaging 98% in high-income countries and 40% in low-income countries. There are significant differences

Table 7
Methane generated and recovered from waste landfilling in Africa in 2012 and 2025.

Country	2012			2025		
	Potential (10^6 Nm^3)	Waste generated (10^6 Nm^3)	Waste collected (10^6 Nm^3)	Potential (10^6 Nm^3)	Waste generated (10^6 Nm^3)	Waste collected (10^6 Nm^3)
Algeria	916	687	632	1308	981	903
Angola	179	134	58	389	291	175
Benin	63	47	11	143	107	53
Botswana	43	32	14	69	52	31
Burkina Faso	71	53	21	214	161	96
Burundi	16	12	5	43	32	19
Cameroon	290	217	93	524	393	236
Cape Verde	5	4	3	9	6	6
Central African Rep.	26	20	8	54	40	24
Chad	49	37	7	125	93	37
Comoros	17	12	2	24	18	9
Congo, Dem. Rep.	368	276	110	944	708	425
Congo	43	32	14	83	62	37
Cote d'Ivoire	149	112	45	336	252	151
Djibouti	11	8	3	20	15	9
Egypt	1541	1156	728	2531	1898	1518
Equatorial Guinea	7	6	2	15	11	7
Eritrea	18	14	5	48	36	21
Ethiopia	128	96	38	440	330	198
Gabon	20	15	6	38	29	17
Gambia	17	13	5	37	28	17
Ghana	35	26	22	298	223	190
Guinea	50	37	15	131	98	59
Guinea-Bissau	6	5	2	15	11	7
Kenya	85	64	25	304	228	137
Lesotho	10	7	3	22	17	10
Liberia	27	20	8	65	48	29
Libya	197	148	63	271	203	122
Madagascar	157	118	21	377	283	141
Malawi	48	36	15	162	121	73
Mali	115	86	34	308	231	138
Mauritania	22	17	5	53	40	20
Mauritius	41	31	30	42	32	31
Mayotte	5	4	4	8	6	6
Morocco	867	651	559	1300	975	877
Mozambique	40	30	13	235	176	106
Namibia	14	11	5	36	27	16
Niger	41	31	13	120	90	54
Nigeria	1384	1038	436	3208	2406	1444
Rwanda	33	25	10	98	73	44
Réunion	61	46	43	67	50	47
Saint Helena	0	0	0	0	0	0
Sao Tome	2	1	1	4	3	3
Senegal	85	64	13	218	163	82
Seychelles	5	4	3	4	3	3
Sierra Leone	31	23	10	88	66	42
Somalia	33	25	10	114	85	51
South Africa	2058	1544	772	2273	1705	1194
Sudan	486	364	157	999	749	449
Swaziland	4	3	2	9	7	4
Tanzania	110	82	35	419	314	204
Togo	42	32	30	113	84	51
Tunisia	191	143	56	308	231	219
Uganda	54	40	12	188	141	84
Westyern Sahara	8	6	1	15	11	6
Zambia	34	26	11	147	110	55
Zimbabwe	88	66	33	169	127	76
Total Africa	10,496	7872	4304	19,677	14,758	10,118
Sub-Saharan Africa	6776	5082	2264	13,945	10,459	6473

between collection rates in Sub-Saharan region, ranging between 18% and 48%, with the exception of South Africa, as shown in Table 5. These collection rates are much lower than other developing countries, especially in comparison with Northern Africa [1,20,36]. Moreover, significant differences between cities and also between rural and urban areas are also known to exist.

In general, only major cities or capital cities in Africa have waste management systems collecting waste; data on waste generation and collection are generally available at country level and several studies provided some data for large cities, such as Yaounde or Kampala [1,27,33,43], while data for smaller cities appears to be very limited. This leads to uncertainties in the assessment of the amount of waste which might be available and deposited in landfills, as the main cities could have higher waste generation and collection rates per capita compared to smaller ones. Some cities face faster increases in waste

Table 8
Waste composition by income level and in Africa (Source: [1]).

Income	Organic average/ range (%)	Paper average/ range (%)	Plastic average/ range (%)	Glass average/ range (%)	Metal average/ range (%)
LI	64 (18–22)	6 (2–21)	9 (1–20)	3 (1–8)	3 (1–12)
LMI	59 (20–76)	10 (3–34)	13 (2–18)	4 (1–9)	2 (1–20)
UMI	54 (5–70)	15 (7–37)	12 (3–36)	4 (1–13)	3 (1–8)
HI	25 (4–56)	30 (4–68	11 (1–24)	7 (1–13)	6 (1–16)
Africa	57 (18–88)	9 (2–21)	13 (1–20)	4 (1–5)	4 (1–5)

generation rates compared to collection rates, as it was the case for Yaounde [43].

Depending on the improvements in waste management practices, on the economic development and income improvement, the waste collection rates could increase in the future. On these bases, the amounts of waste generated and collected for 2012 and expected for 2025 from urban areas in Africa were estimated and presented in Table 6. This table shows how large the difference is between from the waste generated and the amounts that are really collected, especially for Sub-Saharan countries. A large increase in the amount of waste produced can be expected until 2025 and while some increase in the collection was also projected, there will be large amounts of waste which probably will not be collected.

5.2. *Methane generation from landfills*

Table 7 shows the potential amount of methane generated and recovered from waste landfilling in different countries in Africa in 2012 and 2025, based on the World Bank projections for the increase of urban population and waste generation rates. The table provides the potential amounts of methane generated if all LFG produced could be captured and used for energy recovery (columns 1 and 4). However, as only a share of it can actually be recovered, Table 7 also provides the potential amount of methane recovered, assuming that all the waste generated is landfilled (columns 2 and 5) and also considering the waste actually collected, based on current figures and expected levels for 2025 (columns 3 and 6).

Although providing reliable estimates, the results of this study, as reported in Table 7, should be interpreted in light of the large uncertainties affecting some critical parameters. For instance, waste composition, a critical parameter for properly assessing LFG production is not generally available for African cities, with some exceptions. The little existing data shows that the organic matter content of waste in Africa ranges significantly between 18% and 88% of the waste, across the continent. The organic matter of Sub-Saharan waste is around 58%, which is higher than the typical content of about 50% in developed countries [1,26]. This fraction could be converted to compost or used to generate biogas in anaerobic digestion plants. Table 8 shows the variability of waste composition by income level worldwide and in Africa.

Such a high organic matter content of waste, as well as the lack of recycling, composting and treatment leads to a high amount of methane generated from waste. The calculations made in this study, following the IPCC default methodology, show that the methane generation rates from landfills in Africa range between 79 and 89 Nm^3 CH_4/t waste) or 57 and 63 kg CH_4/t waste[3]. This is in accordance with the data provided from different models available, as shown in Table 3.

[3] The use of the IPCC default methodology is adequate for the estimation of the amount of methane generated from landfills in the specific conditions in Africa, where data available on waste management and waste disposed in landfills is very scarce.

The calculations show that methane potentially recoverable from managed landfills in Africa could have reached 7.7 billion Nm^3 in 2012 and 14.8 billion Nm^3 in 2025, if all waste generated would be collected. In real conditions, however, with much lower collection rates, the potential recovered methane from managed landfills could have reached only 4.3 billion Nm^3 in 2012 and 10.1 billion Nm^3 in 2025.

It is also worth noticing that the future set up of landfills in Africa is expected to induce a significant increase of methane emissions, in comparison with the current methane emissions from landfills in Africa (as mentioned above, estimated at of about 1.3 Mt CH_4 for 2010) [17]. If deposited in managed landfills, waste can release significant amounts of CH_4 into the atmosphere that could be avoided by installing proper LFG recovery systems.

5.3. *Energy recovery from waste*

The energy content of waste provides good opportunities for energy generation, as a cheap, available source, which can contribute to increasing energy access and energy consumption and reduce energy poverty in Africa. This study also provides an estimate of the potential energy recovery from waste generation through incineration (as a theoretical potential) or from landfill gas recovery in managed landfills. As a general rule, waste incineration provides the maximum potential of energy which can be recovered, if adequate waste-to-energy plants could be built.

5.3.1. *Country and regional results*

The results of this study show that the energy potential of waste would have amounted to 1125 PJ for the whole of Africa in 2012 and can reach 2198 PJ in 2025, if all the waste generated is supposed to be collected. Only waste generated in urban areas was considered, where waste management is generally available or could realistically be established in the near future. Table 9 shows the potential energy recovery from waste generated and collected through incineration and landfill gas recovery in 2012 and for 2025 for the whole continent and as total for Sub-Saharan countries. The data considers only the energy recovered from waste and does not include the energy from additional fuel support in waste-to energy plants.

However, as already stated, the collection rates of waste in Africa are quite low overall, with significantly higher values in North Africa and South Africa (see Table 5). Considering the actual collection rates for 2012 and projected for 2025, the energy potential of waste was estimated at 613 PJ for the whole of Africa in 2012 with a possible increase to 1508 PJ in 2025. In comparison, the primary energy supply in Africa was about 29,308 PJ in 2010. Thus, the share of energy from waste is relatively reduced, due to the low amount of waste generated, but especially due to the low rate of waste collected per capita.

Nevertheless, since this potential comes only from waste from urban areas, the extension of waste management systems to rural areas could change the whole picture, adding a considerable energy potential on the market, especially in some countries with limited access to energy.

Compared to the total energy potential of waste of 1125 PJ in 2012, about 283 PJ could be recovered from the LFG from landfills in the whole African continent, if all waste from urban areas is collected. From the total 2198 PJ of waste expected to be generated in 2025, around 530 PJ can be recovered from the LFG from landfills, also assuming a complete collection of generated waste. Considering the total energy potential of waste actually collected of 613 PJ in 2012, only about 155 PJ could be recovered from the LFG from landfills and from the overall 1508 PJ of waste generated

Table 9
Potential energy recovery from waste (incineration and landfill gas recovery) [TJ/year].

	2012				2025			
	Waste generation		Waste collected		Waste generation		Waste collected	
	Incineration	Landfills	Incineration	Landfills	Incineration	Landfills	Incineration	Landfills
Algeria	98,143	24,663	90,292	22,690	148,409	35,223	136,536	32,405
Angola	19,133	4808	8227	2067	44,075	10,461	26,445	6276
Benin	7128	1692	1639	389	16,167	3837	8084	1919
Botswana	4344	1152	1868	496	7377	1854	4426	1112
Burkina Faso	8028	1905	3211	762	24,285	5764	14,571	3458
Burundi	1843	437	737	175	4859	1153	2916	692
Cameroon	31,034	7799	13,345	3353	59,413	14,101	35,648	8461
Cape Verde	519	130	493	124	981	233	932	221
Central African Rep.	2965	704	1186	281	6078	1442	3647	865
Chad	5581	1325	1116	265	14,135	3355	5654	1342
Comoros	1890	449	378	90	2725	647	1362	323
Congo, Dem. Rep.	41,761	9911	16,704	3965	107,072	25,412	64,243	15,247
Congo	4638	1166	1994	501	9409	2233	5645	1340
Cote d'Ivoire	16,906	4013	6763	1605	38,087	9039	22,852	5424
Djibouti	1158	291	498	125	2264	537	1359	322
Egypt	165,149	41,502	104,044	26,146	287,088	68,137	229,670	54,510
Equatorial Guinea	754	200	324	86	1521	403	913	242
Eritrea	2074	492	830	197	5395	1280	3237	768
Ethiopia	14,535	3450	5814	1380	49,946	11,854	29,967	7112
Gabon	2006	532	863	229	4091	1028	2454	617
Gambia	1896	450	758	180	4235	1005	2541	603
Ghana	3997	949	3397	806	33,803	8023	28,732	6819
Guinea	5644	1340	2258	536	14,813	3516	8888	2109
Guinea-Bissau	708	168	283	67	1672	397	1003	238
Kenya	9642	2288	3857	915	34,510	8191	20,706	4914
Lesotho	1033	260	444	112	2515	597	1509	358
Liberia	3048	723	1219	289	7329	1739	4397	1044
Libya	19,970	5297	8587	2278	29,022	7293	17,413	4376
Madagascar	17,852	4237	3213	763	42,744	10,145	21,372	5072
Malawi	5432	1289	2281	541	18,351	4355	11,011	2613
Mali	13,040	3095	5216	1238	34,887	8280	20,932	4968
Mauritania	2502	594	750	178	6037	1433	3018	716
Mauritius	4156	1102	4072	1080	4524	1137	4434	1114
Mayotte	544	144	517	137	838	211	796	200
Morocco	92,934	23,354	79,923	20,085	147,452	34,996	132,707	31,497
Mozambique	4504	1069	1892	449	26,669	6330	16,002	3798
Namibia	1523	383	655	165	4053	962	2432	577
Niger	4662	1106	1958	465	13,578	3223	8147	1934
Nigeria	157,056	37,275	65,963	15,656	363,941	86,377	218,365	51,826
Rwanda	3743	888	1572	373	11,094	2633	6656	1580
Réunion	6180	1639	5871	1557	6750	1791	6,13	1701
Saint Helena	15	4	14	4	14	4	14	4
Sao Tome	177	42	168	40	461	109	438	104
Senegal	9633	2286	2023	480	24,683	5858	12,342	2929
Seychelles	480	127	456	121	476	120	453	114
Sierra Leone	3545	841	1560	370	10,019	2378	6412	1522
Somalia	3712	881	1559	370	12,924	3067	7754	1840
South Africa	208,926	55,420	104,463	27,710	243,576	61,211	170,503	42,847
Sudan	49,326	13,084	21,210	5626	107,020	26,894	64,212	16,136
Swaziland	436	116	209	55	935	235	561	141
Tanzania	11,131	2953	4675	1240	44,892	11,281	29,180	7333
Togo	4814	1142	4573	1085	12,068	3033	7241	1820
Tunisia	19,390	5143	7562	2006	32,968	8285	31,320	7871
Uganda	5447	1445	1634	433	20,095	5050	12,057	3030
Western Sahara	765	203	153	41	1601	402	801	201
Zambia	3462	918	1454	386	15,721	3951	7860	1975
Zimbabwe	8902	2361	4411	1170	18,088	4545	10,853	2727
Total Africa	1,124,946	282,602	613,346	154,520	2,198,725	529,813	1,507,728	363,244
Sub-Saharan Africa	728,596	182,439	322,785	81,275	1,552,184	375,476	959,280	232,385

in 2025, 363 PJ could be recovered from the LFG from landfills. The data shows large variations between countries, depending on the waste generation and waste collection rates as well, which have a large impact on the waste potentially available for energy. Moreover, it needs to be pointed out that these results depend on the future options applied to waste management in Africa (reducing, recycling, reusing, composting, etc.) and to an extent to which the collection rates could increase, an aspect for which a simple "business as usual" approach is taken in this study.

5.3.2. Geographical allocation

The energy potential of waste and the methane potential reported in the Table 9 have been spatially allocated into African

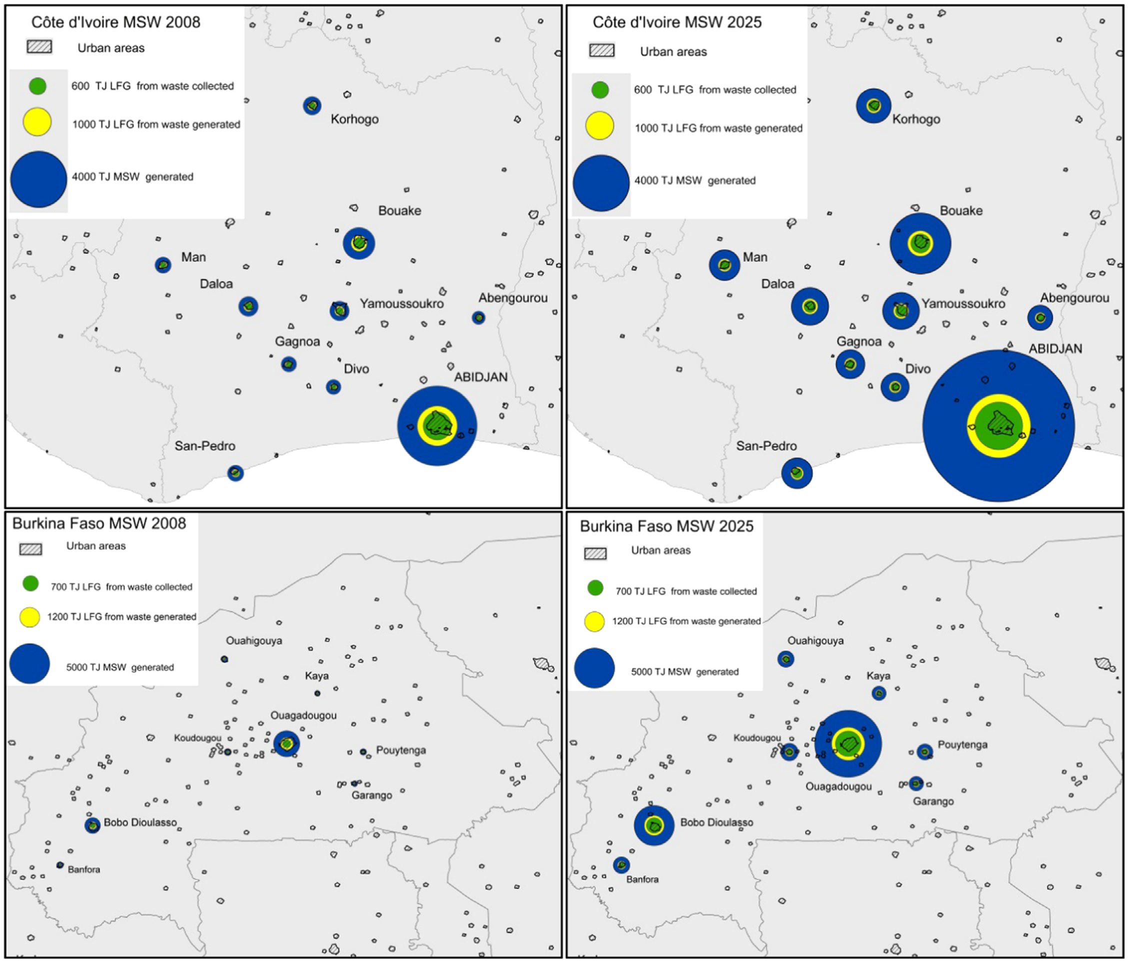

Fig. 3. Spatial distribution of energy potential of waste in 2008 (left column) and 2025 (right column); exemplification for Burkina Faso and Côte d'Ivoire.

major cities, according to FAO "City location and Population in Africa" [42]. The potential locations of the landfill sites were supposed to be chosen in the vicinity of the urban areas, where they are actually typically placed. The amount of the waste deposited in each location was estimated on the basis of the waste generated or collected in that specific urban area.

Fig. 3 shows the exemplification for Burkina Faso and Côte d'Ivoire of the spatial distribution of energy potential of waste. Several major cities were considered in this analysis (8 cities for Burkina Faso and 11 cities for Côte d'Ivoire) where the waste could be collected and its energetic potential could be used. This figure gives a closer view of the potential at country level for the year 2008 (using data from FAO on major city population in 2008) and the projections for 2025.

Figs. 4 and 5 show the spatial distribution of the energy potential from waste generated and collected in Africa and from LFG recovery in 2012 (top lines) and 2025 (bottom lines) visually emphasizing the differences among countries. The figures also illustrate specific locations where this energy could be exploited in the neighbourhood of major cities. For each year, the differences between the assumptions of full waste collection (left columns) and actually collected waste (right columns) appear to be significant in Sub-Saharan Africa countries.

Although all these figures provides a broad and accurate overview at country level, considering the fact that in this study a unique national average value for the waste collection was applied, there is an uncertainty about the exact amount of energy that could be made available at each location. This needs to be further refined, depending on the availability of data on waste management at the city level.

5.4. *Potential electricity generation from waste*

The potential of electricity production from waste was calculated for incineration in waste-to-energy plants and the use of landfill gas in internal gas combustion engines, which are best suited options for electricity generation in Africa, being able to be installed on a modular basis and having low installation costs. In the calculations, as mentioned above, an electricity efficiency of 20% was considered for waste incineration and an efficiency of 30% was considered for the landfill gas use in internal combustion engines.

The potential electricity production through incineration from all waste generated was estimated for the whole of Africa at 62.5 TWh in 2012 and 122.2 TWh in 2025. However, due to lower collection rates, electricity production by waste incineration from waste actually collected was assessed at 34.1 TWh in 2012 and 83.8 TWh in 2025. Table 10 provides detailed information on the electricity production from waste at country level, for Sub-Saharan Africa and for the whole continent. If, on the contrary, electricity is supposed to be produced from LFG recovered from all waste generated, the electricity production was estimated at 27.5 TWh in 2012 and 51.5 TWh in 2025. For LFG recovered from waste actually collected, the electricity production was estimated at 12.9 TWh in 2012 and 30.3 TWh in 2025. These results have to

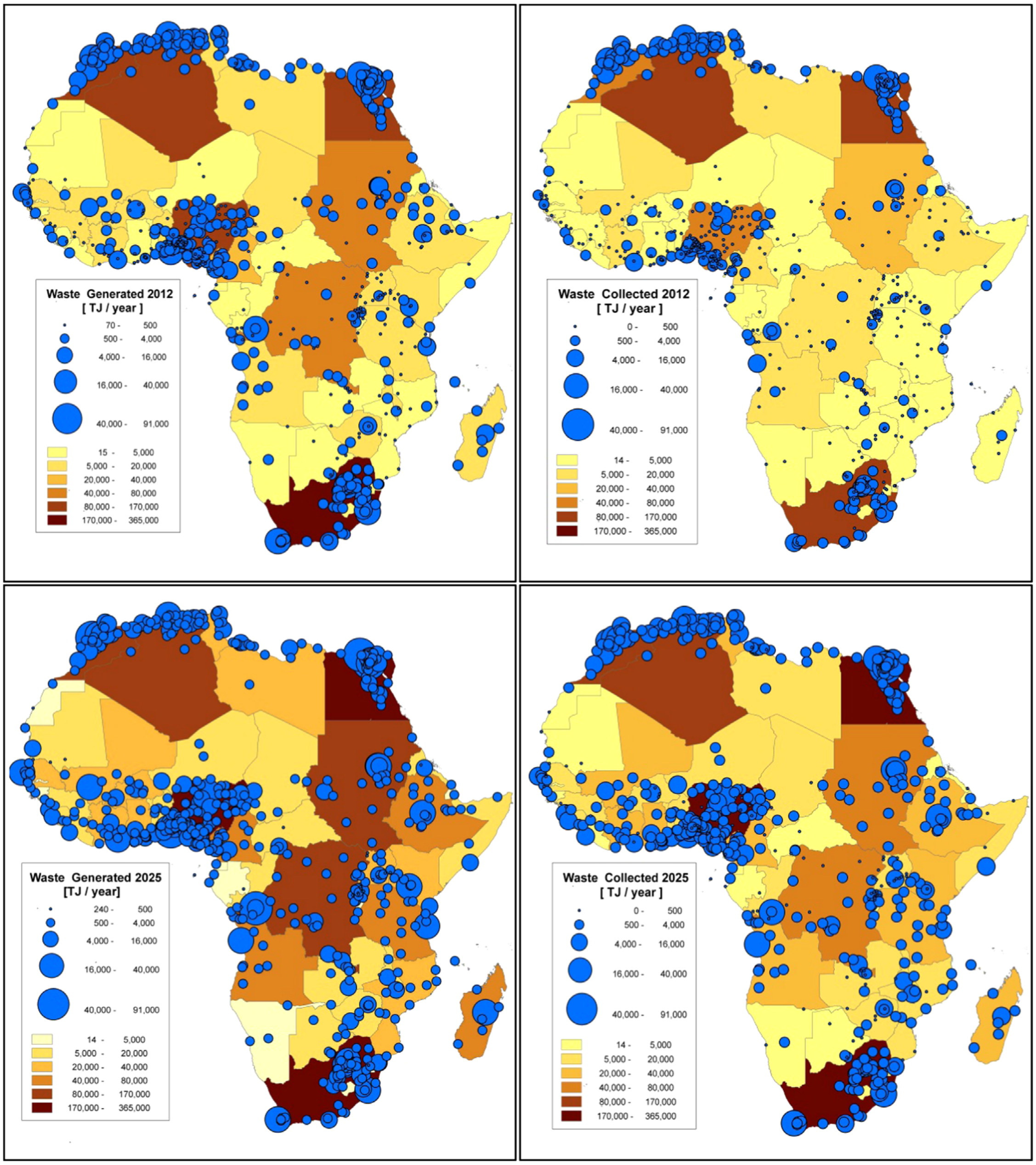

Fig. 4. Energy potential from waste generated (left column) and collected (right column) in Africa in 2012 (top line) and 2025 (bottom line).

be compared with a total electricity use of 662 TWh in 2010 in Africa.

The per capita amount of waste electricity for 2012 and 2025 was also determined and expressed in reference to the total country population and compared to the current (2010) value of electricity use in each country (Table 11). The results show that additional electricity production from all generated waste could be significant. At continental level, waste could produce, through incineration, about 58 kWh/capita/year in 2012 and 86 kWh/capita/year in 2025. In comparison, the electricity consumption in Africa was estimated at 618 kWh/capita in 2010. The contribution of electricity production from waste actually collected is however, much lower, due to the low collection rates in many countries: about 32 kWh/capita/year in 2012 and 59 kWh/capita/year in 2025. Landfill gas could produce about 26 kWh/capita/year in 2012 and 36 kWh/capita/year in 2025 from all waste generated while the electricity from landfill gas generated from waste actually collected could reach about 12 kWh/capita/year in 2012 and 21 kWh/capita/year in 2025. A large variation of the possible contribution of waste from urban areas to electricity supply in different countries is noticeable.

6. Discussion and conclusions

An assessment of the total potential of energy from waste and from methane generated from Municipal Solid Waste from urban areas for 2012 and its projection to 2025 has been provided for each African country on the basis of the most updated and robust available data and projections. The analysis has shown that waste, and in particular MSW, is a renewable energy resource that could in principle provide an interesting share of both gross energy consumption and electricity in the African continent, if compared with current needs. The potential contribution of waste to energy is even more important considering how critical energy is for

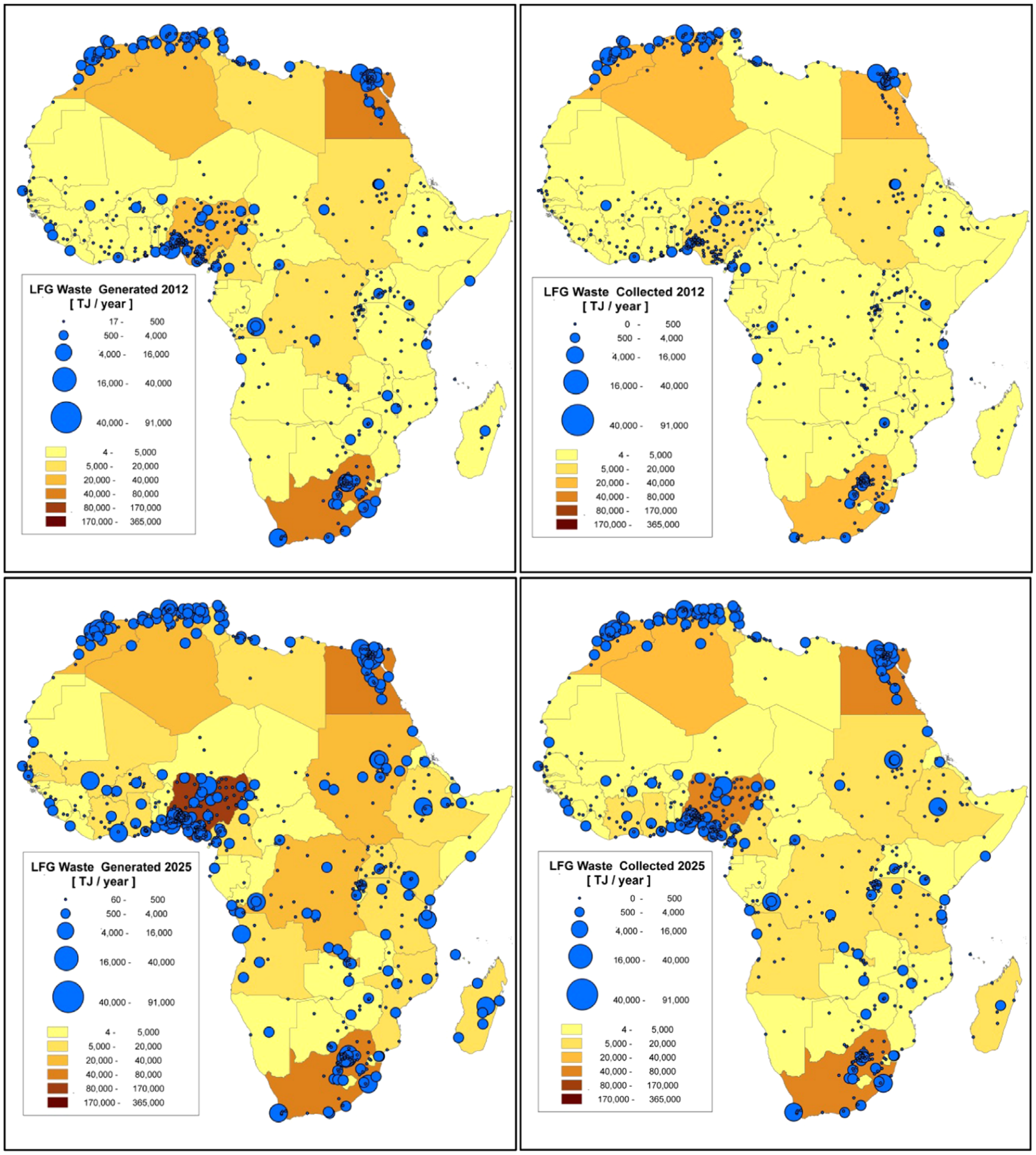

Fig. 5. Energy potential of LFG from waste generated (left column) and collected (right column) in Africa in 2012 (top line) and 2025 (bottom line).

Africa, where large a number of people do not have access to energy and rely on the traditional use of biomass.

Moreover, given the increase of both the overall African population and its urban share, the amount of waste generated in the continent is expected to increase in the next decades, providing an even more interesting resource for energy production. It is also worth noticing that the same growth of waste is also expected to result in an increasingly urgent pressure on the quality of the environment in the continent and that setting up proper waste energy recovery infrastructures will help in better handling such an issue.

This study shows that the energy potential of generated waste could have provided 1125 PJ of energy for the whole Africa in 2012 and this could reach 2199 PJ in 2025. Nevertheless, considering that the actual collection rates in African cities are quite low, the energy potential of waste actually collected was estimated to be about 613 PJ in 2012 and 1508 PJ in 2025. As a reference, the primary energy supply in Africa was about 29,308 PJ in 2010.

If all waste that is generated is also collected and deposited in managed landfills, about 283 PJ could have been recovered from the LFG in 2012 and 530 PJ can be recovered in 2025. Considering the waste actually collected, about 155 PJ could have been recovered from the LFG in 2012 and 363 PJ in 2025.

The potential electricity produced from waste and its contribution to electricity consumption was estimated both at country and continental level. The electricity production from the total waste generated could reach 62.5 TWh in 2012 and 122.2 TWh in 2025, in comparison with a total electricity consumption of 661.5 TWh at continental level in 2010. This can be considered as a theoretical potential of electricity from waste incineration in Africa. The electricity production from waste actually collected was estimated at 34.1 TWh in 2012 and 83.8 TWh in 2025. If using LFG, the electricity production from all generated waste was estimated at 27.5 TWh in 2012 and 51.5 TWh in 2025 while the electricity production from waste actually collected was quantified at much lower levels, 12.9 TWh in 2012 and 30.3 TWh in 2025.

Table 10
Potential electricity generation from waste (incineration and landfill gas recovery) [GWh].

	2012				2025			
	Waste generation		Waste collected		Waste generation		Waste collected	
	Incineration	Landfills	Incineration	Landfills	Incineration	Landfills	Incineration	Landfills
Algeria	5452	2398	5016	1891	8245	3424	7585	2700
Angola	1063	467	457	172	2449	1017	1469	523
Benin	396	164	91	32	898	373	449	160
Botswana	241	112	104	41	410	180	246	93
Burkina Faso	446	185	178	64	1349	560	810	288
Burundi	102	43	41	15	270	112	162	58
Cameroon	1724	758	741	279	3301	1371	1980	705
Cape Verde	29	13	27	10	54	23	52	18
Central African Rep.	165	68	66	23	338	140	203	72
Chad	310	129	62	22	785	326	314	112
Comoros	105	44	21	7	151	63	76	27
Congo, Dem. Rep.	2320	964	928	330	5948	2471	3569	1271
Congo	258	113	111	42	523	217	314	112
Cote d'Ivoire	939	390	376	134	2116	879	1270	452
Djibouti	64	28	28	10	126	52	75	27
Egypt	9175	4035	5780	2179	15,949	6624	12,759	4542
Equatorial Guinea	42	19	18	7	84	39	51	20
Eritrea	115	48	46	16	300	124	180	64
Ethiopia	808	335	323	115	2775	1152	1665	593
Gabon	111	52	48	19	227	100	136	51
Gambia	105	44	42	15	235	98	141	50
Ghana	222	92	189	67	1878	780	1596	568
Guinea	314	130	125	45	823	342	494	176
Guinea-Bissau	39	16	16	6	93	39	56	20
Kenya	536	222	214	76	1917	796	1150	410
Lesotho	57	25	25	9	140	58	84	30
Liberia	169	70	68	24	407	169	244	87
Libya	1109	515	477	190	1612	709	967	365
Madagascar	992	412	179	64	2375	986	1187	423
Malawi	302	125	127	45	1020	423	612	218
Mali	724	301	290	103	1938	805	1163	414
Mauritania	139	58	42	15	335	139	168	60
Mauritius	231	107	226	90	251	111	246	93
Mayotte	30	14	29	11	47	20	44	17
Morocco	5163	2271	4440	1674	8192	3402	7373	2625
Mozambique	250	104	105	37	1482	615	889	316
Namibia	85	37	36	14	225	94	135	48
Niger	259	108	109	39	754	313	453	161
Nigeria	8725	3624	3665	1305	20,219	8398	12,131	4319
Rwanda	208	86	87	31	616	256	370	132
Réunion	343	159	326	130	375	174	356	142
Saint Helena	1	0	1	0	1	0	1	0
Sao Tome	10	4	9	3	26	11	24	9
Senegal	535	222	112	40	1371	570	686	244
Seychelles	27	12	25	10	26	12	25	9
Sierra Leone	197	82	87	31	557	231	356	127
Somalia	206	86	87	31	718	298	431	153
South Africa	11,607	5388	5804	2309	13,532	5951	9472	3571
Sudan	2740	1272	1178	469	5946	2615	3567	1345
Swaziland	24	11	12	5	52	23	31	12
Tanzania	618	287	260	103	2494	1097	1621	611
Togo	267	111	254	90	670	295	402	152
Tunisia	1077	500	420	167	1832	805	1740	656
Uganda	303	140	91	36	1116	491	670	252
Western Sahara	43	20	9	3	89	39	44	17
Zambia	192	89	81	32	873	384	437	165
Zimbabwe	495	230	245	98	1005	442	603	227
Total Africa	62,497	27,475	34,075	12,877	122,151	51,510	83,763	30,270
Sub-Saharan Africa	40,478	17,737	17,933	6773	86,232	36,505	53,293	19,365

In a number of countries, the use of waste to generate electricity could have a significant impact, both in the electricity generation per capita and as a share of electricity consumption. Waste can have a very high contribution to providing electricity to citizens and alleviate energy poverty especially in countries with low access to electricity and reduced electricity consumption per capita (Central African Republic, Burundi, Guinea-Bissau, Mali, Sierra Leone, Rwanda, Somalia, etc.).

Nevertheless, some caveats need to be clearly stated in order to guide the use of the results contained in this study.

– Data about the waste sector for the Africa continent are generally scarce in number and not always reliable. In the study the most complete and robust data bases have been used; nevertheless consistent uncertainties have to be associated with final results.

– The study assesses theoretical and technical potentials of energy and electricity from waste. The evaluation of these potentials are based on assumptions such as the setting up of an adequate system for waste management covering all urban areas, which are unlikely to be fulfilled, even in the 2025 time horizon investigated here.
– The real energy potential of waste can increase, depending on the total amount of waste generated and on the extent to which waste will be collected. The actual energy use of landfill gas will depend on the building of sanitary landfills and the implementation of LFG recovery systems.
– There is an intrinsic risk in waste energy recovery that is to be considered and that is beyond the scope of the present study: waste energy recovery projects are complex, their success depending on optimal plant location and size and the landfill logistics. The use of LFG from landfill sites could entail smaller

Table 11
Potential contribution of waste to electricity consumption [kWh/capita].

	Current use	2012				2025			
		Waste generation		Waste collected		Waste generation		Waste collected	
		Incineration	Landfills	Incineration	Landfills	Incineration	Landfills	Incineration	Landfills
Algeria	1178	149	66	137	52	196	81	180	64
Angola	248	53	23	23	9	88	37	53	19
Benin	116	42	18	10	3	69	29	34	12
Botswana	1676	118	55	51	20	180	79	108	41
Burkina Faso	52	26	11	10	4	53	22	32	11
Burundi	26	12	5	5	2	25	10	15	5
Cameroon	266	84	37	36	14	125	52	75	27
Cape Verde	611	57	25	54	20	96	40	91	32
Central African Rep.	34	36	15	14	5	58	24	35	12
Chad	15	26	11	5	2	48	20	19	7
Comoros	53	136	56	27	10	145	60	73	26
Congo, Dem. Rep.	102	33	14	13	5	62	26	37	13
Congo, Rep.	228	61	27	26	10	94	39	56	20
Cote d'Ivoire	266	46	19	18	6	78	32	47	17
Djibouti	293	70	31	30	11	108	45	65	23
Egypt	1716	109	48	69	26	158	66	126	45
Equatorial Guinea	135	57	26	24	10	84	39	51	20
Eritrea	53	21	9	8	3	39	16	24	8
Ethiopia	50	9	4	4	1	25	10	15	5
Gabon	1122	71	33	31	12	115	50	69	26
Gambia	131	58	24	23	8	93	39	56	20
Ghana	361	9	4	7	3	56	23	48	17
Guinea	75	30	12	12	4	58	24	35	12
Guinea-Bissau	20	25	10	10	4	45	19	27	10
Kenya	160	13	5	5	2	32	13	19	7
Lesotho	404	26	11	11	4	56	23	34	12
Liberia	78	40	17	16	6	70	29	42	15
Libya	4296	172	80	74	29	216	95	130	49
Madagascar	61	45	19	8	3	76	32	38	14
Malawi	126	19	8	8	3	42	17	25	9
Mali	31	44	18	18	6	82	34	49	18
Mauritania	260	38	16	12	4	71	29	35	13
Mauritius	2016	176	82	172	69	182	80	178	67
Mayotte		139	65	132	53	153	67	145	55
Morocco	821	158	70	136	51	225	93	203	72
Mozambique	480	10	4	4	2	46	19	27	10
Namibia	1583	36	16	15	6	79	33	47	17
Niger	48	16	6	7	2	29	12	17	6
Nigeria	152	52	22	22	8	88	37	53	19
Rwanda	30	18	8	8	3	39	16	23	8
Réunion	3058	397	184	377	150	385	179	366	146
Saint Helena	2150	210	97	199	79	201	93	191	76
Sao Tome	333	57	24	54	19	118	49	112	40
Senegal	195	41	17	9	3	76	32	38	14
Seychelles	3388	306	142	291	116	291	128	276	104
Sierra Leone	28	32	13	14	5	71	29	45	16
Somalia	33	21	9	9	3	51	21	30	11
South Africa	5001	229	106	114	46	252	111	176	66
Sudan	171	60	28	26	10	98	43	59	22
Swaziland	1193	20	9	10	4	37	16	22	8
Tanzania	94	13	6	5	2	35	15	23	9
Togo	134	43	18	40	14	84	37	50	19
Tunisia	1424	101	47	39	16	154	68	146	55
Uganda	58	8	4	3	1	21	9	13	5
Westyern Sahara	141	75	35	15	6	116	51	58	22
Zambia	755	14	6	6	2	42	18	21	8
Zimbabwe	1000	38	18	19	7	60	27	36	14
Total Africa	618	58	26	32	12	86	36	59	21
Sub-Saharan Africa	450	45	20	20	8	71	30	44	16

technical and economic difficulties than waste incineration and provide a clean fuel for electricity generation for local use. Nevertheless, LFG is not released instantaneously, but over long time periods. For each landfill site it is crucial at local level to evaluate the optimal plant size considering the waste composition and quantity, local environment and infrastructure available.

– It has also to be emphasized that the issue of cost evaluation was not in the scope of the present study. Cost is a major driver for decision making in the field of energy systems, nevertheless, adding the cost issue to the present analysis would have introduced a large number of additional variables also affected by large uncertainties and would have blurred the overall picture.

The methodology developed and the results shown here can provide guidance to policy makers in evaluating the potential advantages arising from a modern waste management systems including energy recovery and can provide an estimate of the potential energy production from the waste sector to be, for instance, benchmarked with other options when setting energy strategies.

In particular, the spatial distribution of energy potential of waste and landfill gas, provided by this study, is one of the parameters to be used by decision makers when deciding on the energy recovery from waste. This spatial layer could be combined with other geospatial data on infrastructures, soil, and water resources in order to evaluate the most suitable options for energy recovery in the investigated areas.

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