METHANE IN AFRICA

A high-level assessment of anthropogenic methane emissions in Africa with case studies on potential evolution and abatement

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Carbon Limits works with public authorities, private companies, finance institutions, and non-governmental organisations to reduce emissions of greenhouse gases from a range of sectors. Our team supports clients in the identification, development, and financing of projects that mitigate climate change and generate economic value, in addition to providing advice on the design and implementation of climate and energy policies and regulations.

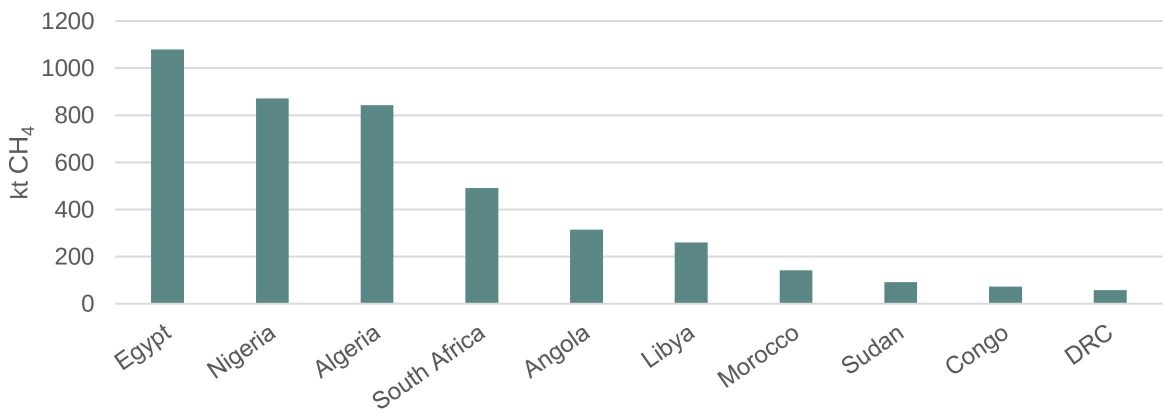
Executive Summary

As a potent greenhouse gas with a high global warming potential, assumed to be 34 times that of CO_2 over a 100-year period, methane is responsible for more than one-fifth of total global greenhouse gas (GHG) emissions. Reducing anthropogenic methane emissions would have a drastic mitigation effect on climate change but requires an understanding of the largest sources of emissions to target abatement interventions more effectively. This report considers the four main sectors that dominate anthropogenic methane emissions, including oil and gas, municipal solid waste management, coal mining, and wastewater management, with reference also being made to GHG emissions from livestock in the annex, assessing each source's contribution to methane emissions in Africa. The report outlines a methodology for quantifying methane in Africa to develop a 2020 baseline for each country and sector, before exploring possible sectoral abatement options and costs through specific country case studies.

The four sectors mentioned above were chosen as these were identified as the sectors which make the most significant anthropogenic contributions of methane on a global basis. Within each sector, total methane emissions by country were calculated by multiplying activity data (AD) by emission factors (EF) per country and per sector. Activity data differed according to the sector, but examples include oil and gas production data or total municipal solid waste (MSW) production, and these were sourced from a variety of sector specific and publicly available reports. Emission factors describe the amount of methane emitted per unit of activity data (e.g., tonnes of methane per $1000m^3$ gas produced), and were mainly sourced from the UNFCCC or IPCC. Emissions were then estimated on a per country and sector basis. For a set number of relevant countries, the most cost effective and likely abatement options were analysed and consequently evaluated on their overall suitability for the continent, based on a review of available research and reports.

Annual methane emissions for the four primary sectors in Africa, excluding livestock, total 4.7 million tonnes CH_4, equivalent to 160 million tonnes CO_2e. Oil and gas is the highest emitting sector (48 %), followed by municipal solid waste (35 %), wastewater (16 %), then coal (1 %). Egypt is the highest emitting country with over one million tonnes CH_4. Together with Nigeria and Algeria, these three countries generate over half of continental emissions. Adding South Africa and Angola, these five countries are responsible for three-quarters of all continental methane emissions (Figure 1).

Figure 1: Total methane emissions by country across analysed sectors



Total sectoral emissions for Africa (Figure 2) follow almost the same order of significance as global CH_4 emissions for the four highest emitting sectors yet diverge in their respective share of total continental emissions from the global pattern.

Figure 2: Estimated African anthropogenic methane emissions sources (inset chart shows estimated global anthropogenic CH_4 emission sources for the same sectors, for comparison)

The most methane-intensive sector generating just under half of all analysed anthropogenic methane emissions is oil and gas, despite just 17 of 54 African countries operating in this sector. This shows the sector's significant methane mitigation potential, which would only need to be addressed in less than half of countries. Methane reduction in the sector is often synonymous with additional revenues from gas sales, generating economically appealing mitigation projects for operators. Algeria and Nigeria are the largest emitters of methane from oil and gas. An estimated 74 % of annual emissions from the Algerian gas sector could be abated, nearly half at no net cost, through leak detection and repair (LDAR), replacement of thermic engines and turbines with electric motors, or blowdown capture, for example. Nigeria, with the highest oil production in Africa, could abate an estimated 71 % of its oil and gas operations, about half also at no net cost, through measures such as LDAR or vapor recovery units (VRUs) with negative abatement costs.

Municipal solid waste management is the next largest sectoral emitter, with a larger proportional role in Africa than globally due to the prevalence of waste burning. The report reviewed abatement options in two countries, Egypt and Nigeria, where the MSW sector is a major contributor to methane emissions largely due to their larger populations producing higher total waste volumes. Half of all municipal waste is collected in Egypt, of which half is sent to anaerobic methane-emitting landfills; in Nigeria, only 20-30% of waste is collected while open and indiscriminate dumping or waste burning are the dominant practices. Though these simpler waste management practices emit significantly less methane than landfilling, the latter is a far more sanitary disposal method. A potential abatement option for both countries is therefore the construction of landfill gas (LFG) collection systems for flaring or for recovery and use in energy production. Estimated reductions of sector emissions for this abatement option are over 85% for Egypt and 86% for Nigeria, increasing by a further 2% for both countries if gas recovery is implemented.

Though accounting for less than half of the emissions from the MSW management sector in Africa, wastewater is the third-largest methane-intensive sector considered. The best alternative to open wastewater discharge that benefits both sanitation and health while reducing methane emissions is the improved management of wastewater treatment plants and sewage systems. Taking Angola as one case study, which already has a small amount of existing centralised wastewater treatment, the report found that the country could reduce its emissions from this sector by 31% through improving management of wastewater treatment plants and sewage systems. The Democratic Republic of Congo, meanwhile, has limited wastewater management and instead discharges mostly into the environment (rivers and ocean). The DRC would face costs twice as high as Angola by implementing this centralised abatement option, largely due to its high population and current lack of wastewater piping infrastructure. Other explored intermediary methods such as septic tanks would however increase methane emissions.

The waste and wastewater sectors demonstrate an important issue related to future economic and social development in Africa, namely that some development options may lead to greater emissions of methane than the current practices. As mentioned, collection of wastewater in septic tanks undoubtedly has positive sanitation, environmental and health outcomes, but leads to greater emissions of methane compared to discharge to local water courses. The same can be said of centralized landfilling compared to open burning of waste, due to the anaerobic conditions created in the landfill sites. In this latter example, methane emissions would only be reduced if the landfill gas is collected and either flared or used for energy production.

Coal mining is a significant global contributor to methane emissions yet represents a minor share of African methane due to its presence in only two countries—South Africa and Zimbabwe. As Africa's largest coal producer and eighth largest worldwide coal mine methane (CMM) emitter, South Africa has significant potential to abate half of its CMM emissions through accessible, established, and profitable methods of gas drainage for recovery and use.

Methane from livestock is also an important contributor to greenhouse gas emissions worldwide. However, estimating these is less straightforward than for other sectors; the topic was instead reviewed through an assessment of existing datasets. More details on the methodology and results, with reference to two case studies in Ethiopia and Niger, is included in the annex of this report.

Though abatement potential varies according to sector and country, overall, there are considerable possibilities for methane emissions reductions across Africa. While this study analyses abatement options for only a few countries more precisely, chosen to exhibit the highest potential or most significant impacts, the actions explored are likely to have major effects on any country if implemented, albeit with varying efficiencies. Given that abatement potential and cost analyses rely on country-specific information, the evaluations for each sector were not extrapolated to the entire continent as not all measures are applicable to each country. Further assessment would be required to investigate abatement potential at a country level.

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Abbreviations

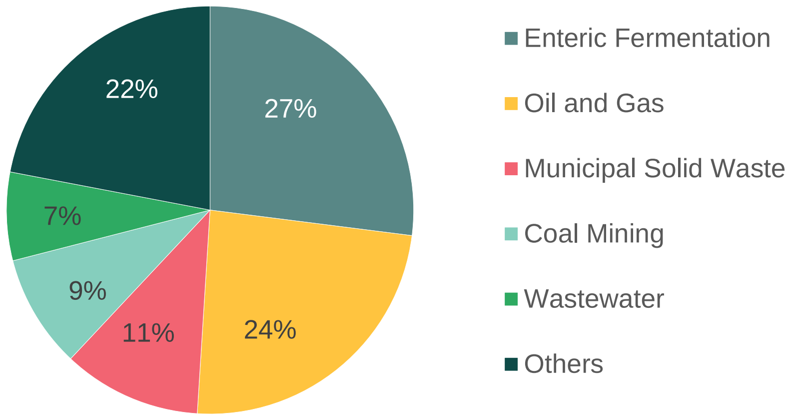
AfDB	African Development Bank
AD	Activity Data
BOD	Biochemical Oxygen Demand
CAS	Conventional Activated Sludge
CH_4	Methane
CMM	Coal Mine Methane
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalent
COP26	United Nations Climate Change Conference 2021
DRC	Democratic Republic of Congo
EF	Emission Factor
GHG	Greenhouse Gas
GMI	Global Methane Initiative
GWP	Global Warming Potential
IEA	International Energy Agency
LFG	Landfill Gas
MSW	Municipal Solid Waste
VAM	Ventilated Air Methane

1 Study background

Methane (CH_4) is the second most abundant anthropogenic greenhouse gas after carbon dioxide (CO_2). It is responsible for more than 20 % of total global emissions. Largely a result of human activity, methane concentrations in the atmosphere have more than doubled over the last two centuries. Due to the relatively short atmospheric lifetime of CH_4, about 12 years, and its global warming potential (GWP) of 34 over a 100-year horizon (i.e., 34 times the GWP of CO_2), undertaking significant reductions to methane emissions would have a rapid and significant effect on global atmospheric warming.[1]

According to the Global Methane Initiative (GMI), 2020 global anthropogenic methane emissions were dominated by enteric fermentation (27 %), followed by oil and gas (24 %), municipal solid waste management (11 %), coal mining (9 %), and wastewater management (7 %) (**Error! Reference source not found.**). By 2030, global emissions of methane are likely to increase by a further 9 %.[2] While Africa's contribution to total global GHG emissions is limited, totalling only around 4 % in the year 2020, the potential for abatement is substantial. According to the International Energy Agency (IEA), 75 % of current methane emissions from the oil and gas sector are entirely avoidable and, more significantly, 40 % could be avoidable at no or negative abatement cost, representing much of Africa's CH_4 emission sources in this sector.[3] Although recognition of anthropogenic methane sources in Africa is gaining traction, major uncertainties remain, especially concerning the specific sources and abatement options in each country.

Figure 3: Estimated global anthropogenic CH_4 emission sources[4]



The purpose of this project is thus to improve knowledge around the most significant sources of methane emissions in Africa, as well as to explore major cost-effective abatement options on a per-sector basis.

This project is linked to the African Development Bank's Climate Change and Green Growth Framework, recently presented at COP26. A joint US–EU led coalition of more than 100 countries pledged to reduce 2030 methane emissions by 30 % below 2020 levels. To be equitably involved in global methane abatement activities, the bank requested the development of a methodology to quantify methane emissions by sector

[1] EPA, Importance of Methane, 2021, https://www.epa.gov/gmi/importance-methane. For the purposes of this report the GWP of methane has been assumed to be 34, and this figure has been used whenever stated volumes of methane emissions are converted to carbon dioxide equivalent (CO_2e)

[2] Global Methane Initiative, Global Methane Emissions, 2020,https://www.globalmethane.org/documents/gmi-mitigation-factsheet.pdf

[3] IEA, Methane Tracker, 2020, https://www.iea.org/reports/methane-tracker-2020

[4] Global Methane Initiative, Global Methane Emissions, 2020, https://www.globalmethane.org/documents/gmi-mitigation-factsheet.pdf.

and country in Africa, as well as a 2020 baseline against which to periodically assess progress in the light of the US–EU led initiative.

2 Methodology and results

This study focuses on the four main globally contributing sectors for anthropogenic methane emissions according to GMI (i.e., oil and gas production, coal mining, municipal solid waste management, wastewater management). For the purposes of comparison, Africa wide data on methane emissions from livestock is also presented, although the data for this sector was not obtained by the consultant or processed or controlled to the same level of detail as for the other four sectors, and therefore is included in this report under the

Annex section.

Activity data (AD) and emission factors (EF) per country and per sector from various reports were taken as a starting point for the analysis. Emissions were then estimated on a per country and sector basis. For a set number of relevant countries, the most cost effective and likely abatement options were analysed and consequently evaluated on their overall suitability for the continent.

As per IPCC guidance, the final magnitude of emissions can be estimated by combining the activity data and emission factors as follows:

$$Emission_i = Activity\ Data_i * Emission\ Factor_i$$

- Activity data (AD) refers to the economic and social activity (e.g., volume of production)
- Emission factor (EF) refers to the coefficient for emissions per unit of activity (e.g., kg CH_4 / m^3 wastewater)

Where country specific AD was unavailable for specific sectors, assumptions were made on a case-by-case basis and together with the sources are specified below in the corresponding sectoral methodology description. All emission factors come from the UNFCCC, IPCC, or GLEAM except for emission factors for coal mining in South Africa, which come from South Africa reporting to UNFCCC.

The following paragraphs will go more into methodological detail and discuss the results by individual sector, including the top 10 emitting countries and total emissions for each.

2.1 Oil and gas

Methane emissions can occur across the entire oil and gas value chain. These can come from unintended leaks, venting (conducted as part of typical operations or safety procedures), or from incomplete combustion of natural gas in flares and other combustion devices.

To estimate the emissions from the oil and gas sector, the most significant segments on the continent were considered: upstream oil (including associate gas production); upstream gas; and gas transmission. There are very little emissions associated with the transport of oil whilst the downstream segment, mainly gas distribution, was assumed to be negligeable in Africa.

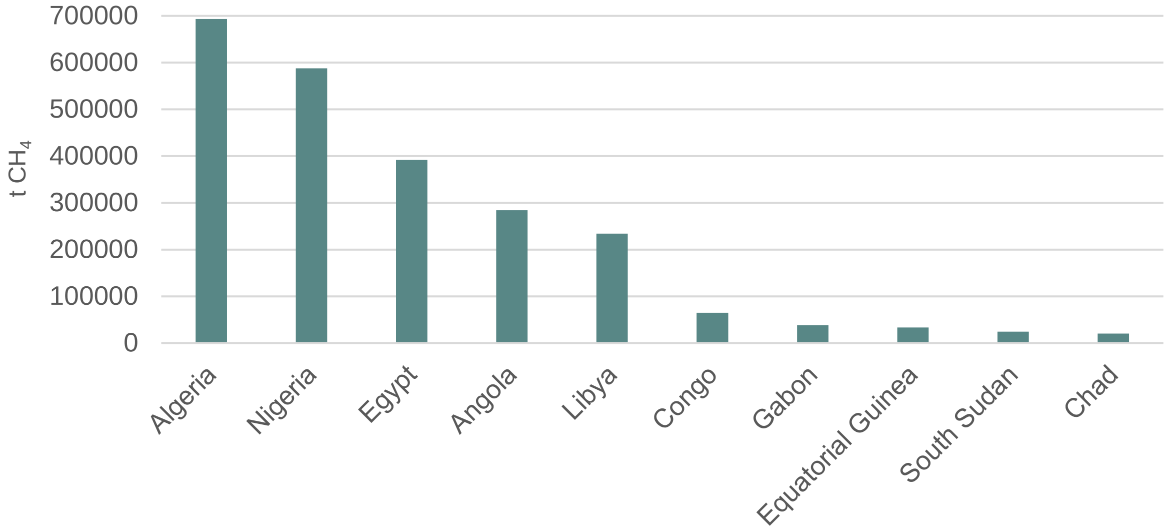
For the upstream segment of both oil and gas, production data was taken from the BP Statistical Energy review 2019 (2018 data) after which the IPCC[5] throughput-based emission factor was applied to the activity data. For gas transmission, the length of gas pipeline in a country better reflects potential methane emissions. Therefore, the IPCC emission factor accounting for emissions per length of pipe was applied to the length of gas transmission pipes per country.[6] Conservative EFs, accounting for limited Leak Detection and Repair (LDAR) and higher emitting practices, were used for this analysis.

Based on this data, the annual CH_4 emissions from the oil and gas sector in Africa were estimated at around 2.4 Mt CH_4 (81.6 Mt CO_2e), with nearly 60 % coming from oil production. As seen in Figure 4, Algeria has the highest emissions for the sector overall (0.7 Mt CH_4), as well as for gas production and transmission specifically (0.4 Mt CH_4), whilst Nigeria is the main contributor to emissions from oil production (0.4 Mt CH_4).

[5] IPCC 2019 refinements

[6] ChartsBin, *Total Length of Pipelines for Transportation by Country,* varying years (depending on the country, typically 2010)

Figure 4: Total annual CH_4 emissions and top 10 emitting countries for oil and gas



2.2 Municipal solid waste

Globally, solid municipal waste management (MSW) is responsible for over 10 % of all methane emissions, with methane-producing bacteria during the anaerobic decomposition phase of organic waste being the primary contributor.[7] To estimate methane emissions from MSW in Africa, activity data per country needed to be consulted first. Total MSW production was available for a total of 44 African countries.[8] Production data for the remaining countries was substituted by the per-capita production rate of economically similar countries (i.e., GDP per capita), as a function of the country's population. After total MSW production volumes per country were established, waste management practices needed to be investigated.

Due to different management practices leading to different emission factors (e.g., landfilling favours CH_4 production due to prevalent anaerobic decomposition, while burning predominantly results in CO_2 emissions), attributing waste production to management practices is key in understanding main CH_4 sources and areas for abatement potential. For 30 countries, MSW management practices could be found and were divided into 4 main categories (Dumped, Landfilled, Burned, Recycled).[9,10] For countries with missing data, data was substituted by the average waste management practices for a multitude of African countries with a similar GDP per capita.

After the AD has been established for all countries, the EF needed to be attributed to each management practice. For recycling, a methane EF of 0 has been assumed. Based on past Africa-specific reports from the UNFCCC, [10] an EF could be established for dumping and burning practices. As for landfilling, the EF was chosen as being a function of the EF for dumping. According to the IPCC,[11] managed anaerobic dumpsites, in this case assumed to be landfills, show 1.7x the methane emission intensity of uncategorised solid waste disposal sites, hereby assumed to be dumpsites. As such, the EF for landfills were assumed to be 1.7x the

[7] EPA, Basic Information about Landfill Gas, 2022, https://www.epa.gov/lmop/basic-information-about-landfill-gas

[8] Hoornweg & Bhada-Tata, A Global Review of Solid Waste Management, 2012 http://hdl.handle.net/10986/17388

[9] Dladla et al. A review of factors associated with indiscriminate dumping of waste in eleven African countries, 2016, https://doi.org/10.1080/20421338.2016.1224613

[10] Federal Republic of Nigeria, Third National Communication, 2020, https://www4.unfccc.int/sites/SubmissionsStaging/NationalReports/Documents/187563_Nigeria-NC3-1-TNC%20NIGERIA%20-%2018-04-2020%20-%20FINAL.pdf

[11] IPCC, Solid Waste Disposal, 2006, https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/5_Volume5/V5_3_Ch3_SWDS.pdf

one of dumpsites. No semi-aerobic landfills were assumed because, according to Hoornweg and Bhada-Tata,[8] much of Africa's landfills likely belong to lower tier categories and as such represent a conservative approach to MSW management practices. After total MSW production per country was divided into management categories, results were multiplied with their respective EF, leading to total methane emissions per country for the MSW sector.

Total CH_4 emissions for the municipal solid waste management sector for the African continent are equal to 1.6 Mt (55.9 Mt CO_2e) per year. The top 10 emitting countries, including South Africa, Egypt, and Nigeria, are responsible for close to 80 % of total continental emissions (Figure 5). In terms of per capita emissions (Figure 6), the top of the list is lead, as expected, by countries with a higher-than-average GPD per capita.

Figure 5: Total annual CH_4 emissions and top 10 emitting countries for municipal solid waste

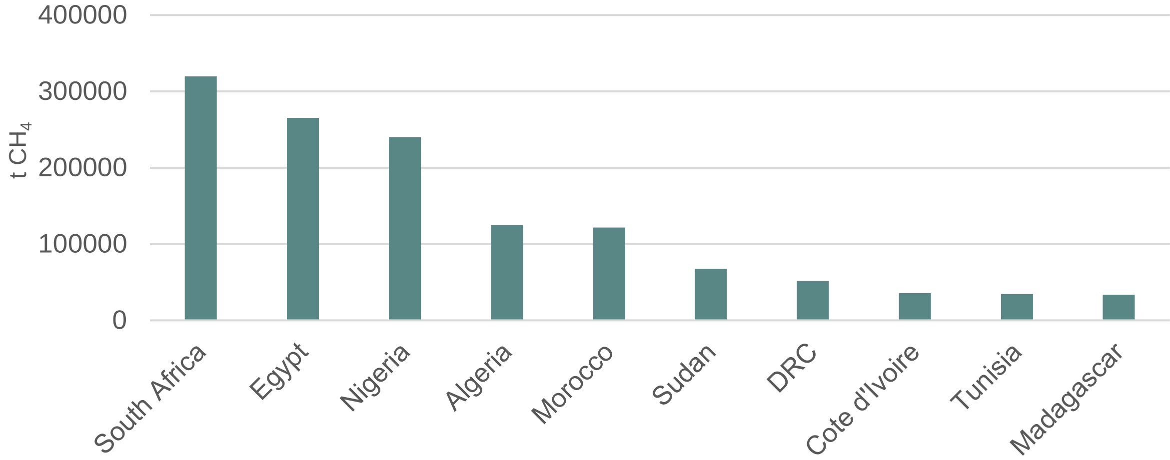
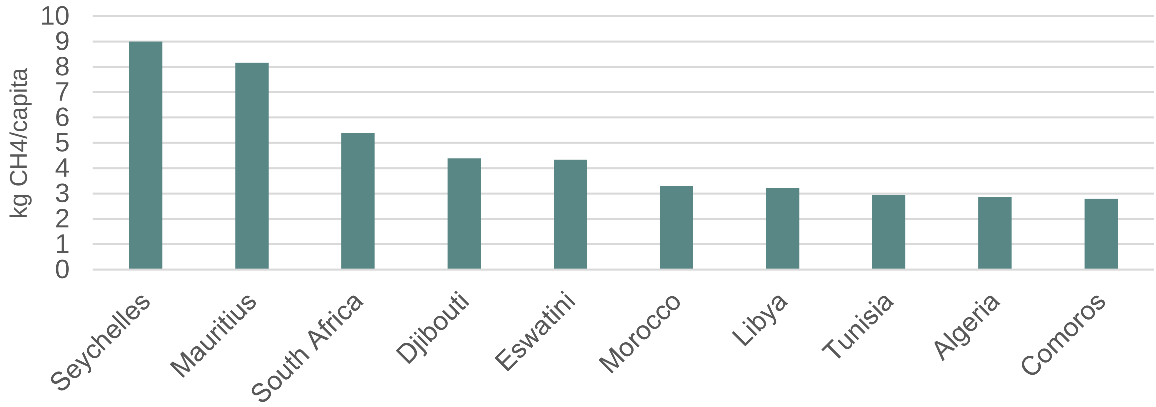


Figure 6: Per capita annual CH_4 emissions and top 10 emitting countries for municipal solid waste



2.3 Wastewater

While global methane emissions from wastewater management are smaller than for MSW, they are still significant, representing 7 % of total emissions. Just as for MSW, the main reason for methane emissions in the wastewater management sector is the anaerobic decomposition process.

Initial African AD for wastewater production were found for all but 2 countries,[12] for which data was substituted by the per-capita production rate of economically similar countries, multiplied by their respective population. After total production rate per country were established, wastewater management practices needed to be investigated.

The same dataset used for production gives information about the total amount of wastewater collected as well as treated per country. While this already enables a first division into categories with different EF (i.e., treated and untreated), further categorisation enhances the accuracy of the analysis and enables a more in-depth abatement methods analysis later on. To further subdivide untreated wastewater, data concerning sanitation practices per country was consulted.[13] This allowed for a final division of wastewater management into 4 different categories: treated, untreated, latrines and septic tanks. Wastewater in the 'treated' category was assumed to be treated in a wastewater treatment plant, while 'untreated' wastewater was assumed to drain to sea, rivers, and lakes. Due to differing collection and storage processes for latrines and septic tanks, their respective EFs differ as well.

The original EFs were taken from UNFCCC reports.[10] While the UNFCCC specifies EFs related to CH_4 emissions per kg biochemical oxygen demand (BOD), with BOD indicating the amount of organic matter in water, they needed to be translated into kg CH_4/m^3 wastewater in accordance with the AD. To do so, it was assumed that 1 kg CH_4/kg BOD is equivalent to 0.25 kg CH_4/ m^3 wastewater.[14] Based on this transformation, EFs for each wastewater management category were created, except for wastewater treatment plants. The wastewater treatment plant EF was chosen as a function of the EF for open water discharge. According to the IPCCC,[15] aerobic treatment plants (assumed for the treatment plant type of choice in this study) result in 3x the methane emission intensity of open water discharge. When faced with the choice between well managed and less well managed treatment plants, the same rationale as for landfills applies, and the conservative, non-perfectly managed option was chosen.

Finally, after total wastewater production per country was divided into management categories, results were multiplied with their respective EF, leading to total CH_4 emissions per country for the wastewater sector.

Total CH_4 emissions for the wastewater management sector for the African continent are equal to 0.74 Mt (25 Mt CO_2e) per year. With 0.4 Mt CH_4 per year and over 4 kg per person, Egypt is the top emitting country, responsible for over 50 % of total continental wastewater emissions, followed by South Africa with 0.1 Mt CH_4 (**Error! Reference source not found.**7 & 8). The significant contribution from Egypt is explained by the f act that this country has a significant urban population and that the wastewater from urban centres are collected and treated in centralized wastewater treatment plants, which as mentioned above have 3x the methane emission intensity of open water discharge.

[12] Edward et al, Country-level and gridded estimates of wastewater production, collection, treatment, and reuse, 2020, https://doi.org/10.5194/essd-13-237-2021

[13] Washdata, Sanitation, 2020, https://washdata.org/data/downloads#WLD

[14] Paredes et al. Methane emissions from stabilization ponds for municipal wastewater treatment in Mexico, 2015, https://doi.org/10.1080/1943815X.2015.1110185

[15] IPCC, Wastewater and discharge, 2016, https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/5_Volume5/V5_6_Ch6_Wastewater.pdf

Figure 7: Total annual CH_4 emissions and top 10 emitting countries for wastewater

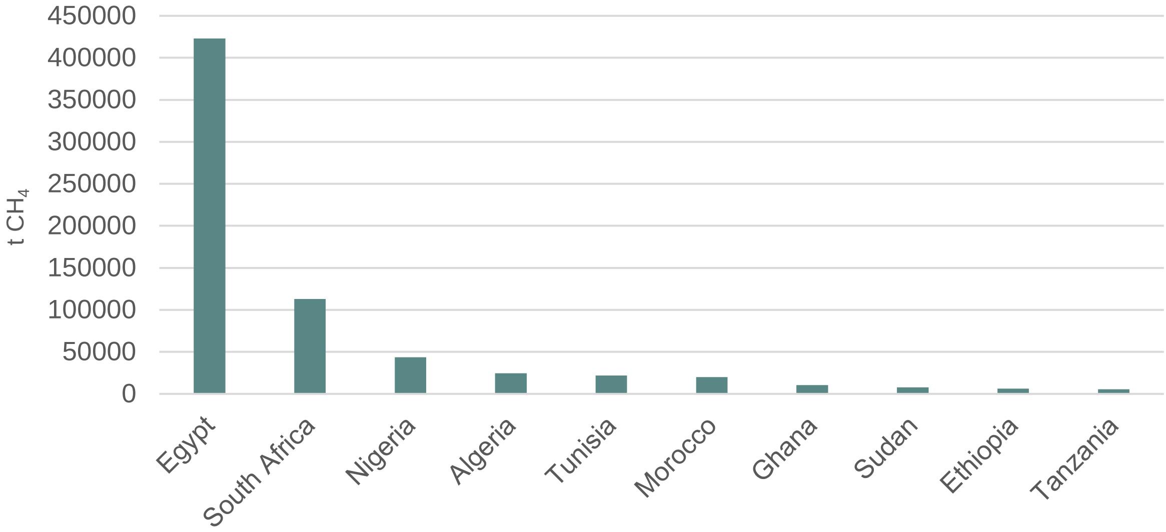
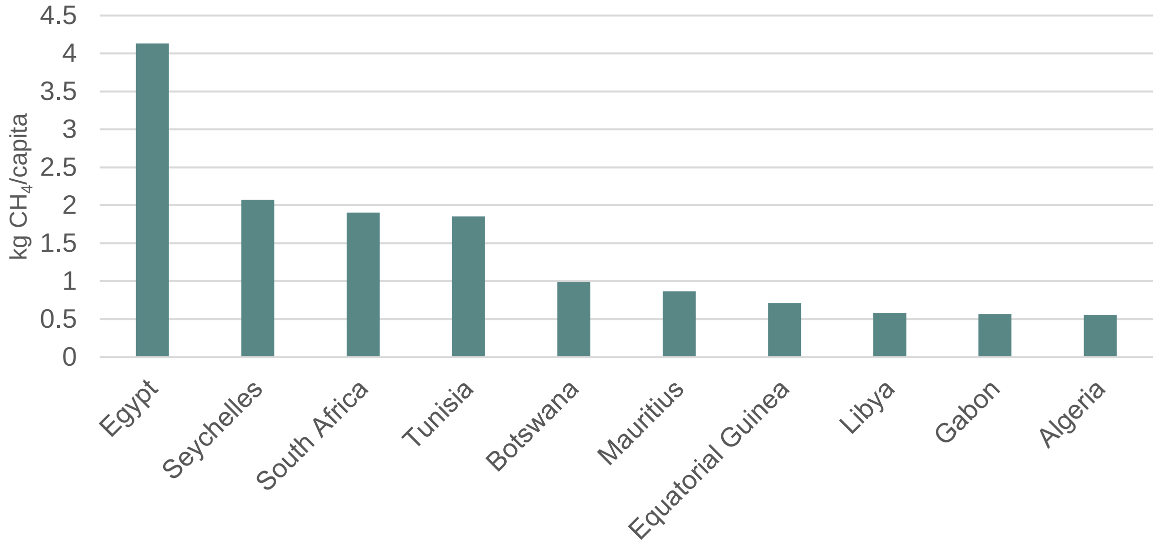


Figure 8: Per capita annual CH_4 emissions and top 10 emitting countries for wastewater



2.4 Coal

Coalbed methane emissions, released during coal mining operations, is also an important global contributor to anthropogenic methane emissions. There is a significant difference between the methane intensity of underground coal mining and surface coal mining. The latter tends to have much more limited methane emissions associated with its activities.

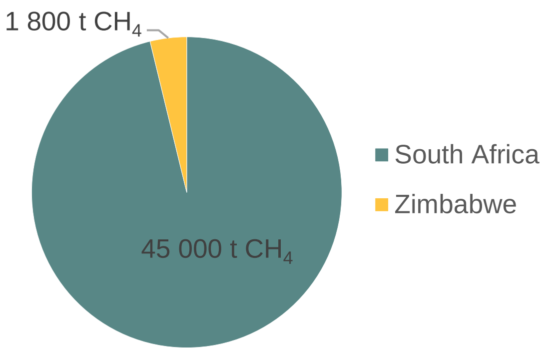
In Africa, only 2 countries, South Africa and Zimbabwe, have significant coal mining activities. Coal production for these two countries was taken from the BP Statistical Energy review 2019 (2018 data). The share of coal produced from underground and surface mines was calculated for South Africa based on the production data presented in the South African BUR.[16] In Zimbabwe, it was assumed that all the coal was

[16] South Africa BUR 4, UNFCCC, 2021, https://unfccc.int/documents/307107

produced in underground mines, as a conservative assumption. The emission factor was taken from South Africa's NIR.[17] The value of the emission factor is lower than the emission factor suggested by the IPCC for underground coal mining. This is linked to the characteristics of the coal in the region, which contains little coalbed methane.

Overall, annual CH_4 emissions from coal in Africa were estimated at around 47 000 t (1.6 Mt CO_2e), the vast majority of which was emitted by South Africa, by far the largest coal producer on the continent, with emissions estimated at about 45 000 t CH_4 (Figure 9).

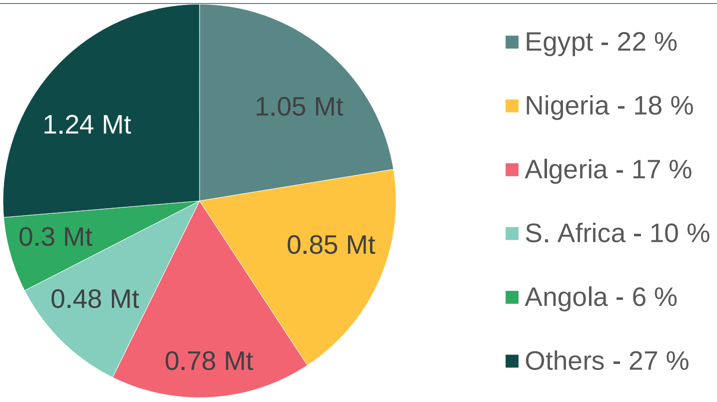
Figure 9: Total annual CH_4 emissions for the two relevant countries for coal production



2.5 Results summary

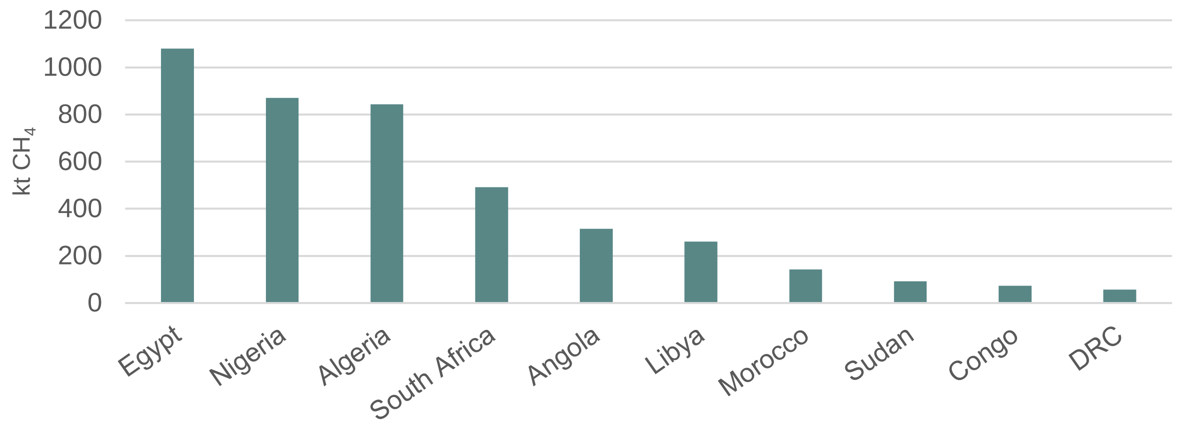
Applying the methodology above, total annual CH_4 emissions for Africa for all four sectors (excluding livestock) amount to 4.7 Mt (160 Mt CO_2e). Just three countries (Egypt, Nigeria, Algeria) are responsible for over half of total CH_4 emissions and, including the fourth and fifth largest emitters (South Africa and Angola), this rises to 75 % of total continental emissions (Figure 10 and 11). The highest emitting country overall is Egypt, with over 1.05 Mt of CH_4 emissions representing over one-fifth of total continental emissions.

Figure 10: Total annual CH_4 emissions for all sectors combined (excluding livestock)



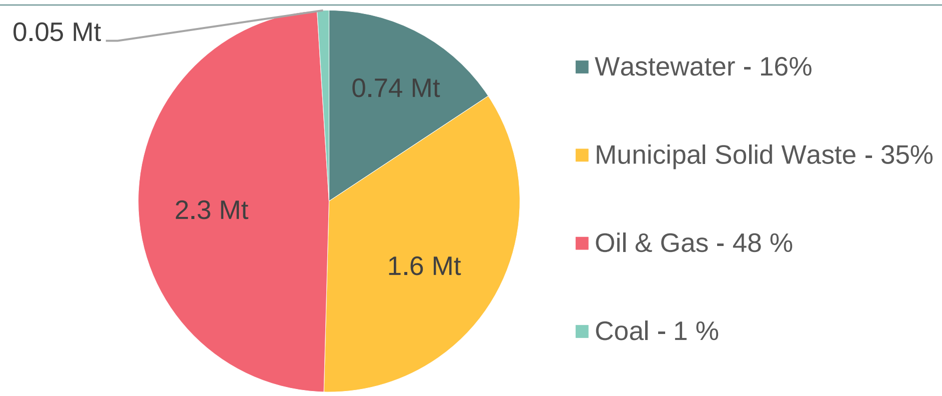
[17] South Africa NIR, UNFCCC, 2017

Figure 11: Total annual CH_4 emissions and top 10 emitting countries for all four sectors combined



In terms of sectoral emissions, the most emitting sector (excluding livestock) is oil and gas, with nearly 48 % of total emissions (**Error! Reference source not found.**Figure 12). With just 12 oil producing countries and 16 gas producing countries (19 total), less than half of all African countries produce nearly half of the continent's CH_4 emissions from one sector.

Figure 12: Total annual CH_4 emissions per sector (excluding livestock)



3 Case study countries for abatement potential and cost

After establishing total emissions per sector and country, it is valuable to investigate possible methane abatement measures and technologies for each, including what their potential mitigation potential is and where the biggest impact can be achieved. Possible measures are also evaluated according to their implementation cost, allowing for a marginal abatement cost calculation per tonne of mitigated CO_2e.

The following sections will each consider one sector for which methane emissions have previously been established, introduce up to three different methane emissions abatement options per sector and demonstrate mitigation potential and implementation costs for one or two African countries. Countries have been chosen to either demonstrate the greatest possible mitigation potential that abatement measures can have on total African methane emissions or to contrast each other in an informative way (e.g., choosing one country with high GDP per capita and one country with lower GDP per capita), as abatement options with substantial emission reductions or sanitary improvements for one country might be less impactful in another country.

3.1 Oil and gas – Algeria

Based on the methane emissions estimates presented in the previous section, Algeria is the largest contributor of methane emissions from natural gas production and transport, with annual emissions from the sector estimated at around 450 000 t CH_4 (15.3 Mt CO_2e). This stems from the fact that it is the largest gas producer on the continent and has an extensive pipeline network to transport the gas from the south of the country, where it is produced, to the coast for export to Europe. This case study will focus on methane abatement potential and cost for the gas sector more specifically.

According to IEA Global methane tracker 2022, the oil and gas sector in Algeria can reduce methane emissions in its oil and gas sector by 74 %, of which 49 % can be reduced at no net cost due to the increase in revenue from gas savings,[18] as natural gas is mostly composed of methane. The abatement options with the highest abatement potential in the country considered by the IEA methane tracker and linked to the gas sector more specifically are:

- Leak detection and repair (LDAR)
- Replacing thermic engines and turbines with electric motors
- Blowdown capture

The IEA methane tracker also considers replacing pneumatic equipment, such as controllers and pumps, with their electric equivalent as having a large abatement potential. However, this type of equipment is not common outside of North America. Therefore, this abatement option might be overestimated and was not further considered for this assessment. Other abatement options are also considered, but these do not provide significant abatement potential for the gas sector in Algeria.

In oil and gas installations, LDAR identifies leaking components for repair, which can occur at any point along the value chain and at any point in time. As methane is an odourless and colourless gas, specialised equipment is necessary to detect leaks, as they tend also to emerge over time. Therefore, for LDAR to be effective, campaigns need to be conducted at regular intervals as part of routine practices for oil and gas operators. LDAR is typically more cost effective for larger, centralised facilities than for distributed assets that require more time to inspect and have more challenging logistics around repairs. Production facilities therefore tend to benefit more from LDAR campaigns than transmission and distribution networks. For facilities with no LDAR in place, implementing the practice routinely can reduce methane emissions from leaks by up to 80 % if performed monthly.[19] For Algeria, assuming LDAR is currently performed annually and using the IPCC split to quantify methane emissions from leaks (called "fugitive emissions" under IPCC), increasing LDAR frequency to quarterly campaigns could reduce methane emissions by over 25 000 t (850 000 t CO_2e) per year for an estimated cost of 7.5 USD/t CO_2e.[20] Gas savings from the LDAR campaigns, if a market is available, could generate revenues for oil and gas operators, thereby reducing the cost to around 1.3 USD/t CO_2e compared to assumed current practice,[21] meaning LDAR is profitable across the oil and gas sector in Algeria. As the cost of LDAR is influenced by the frequency at which it is performed, if LDAR is performed more frequently than once a year, the abatement potential increases along with the abatement cost. Monthly LDAR could allow for a further reduction in emissions but would be less profitable for operators.

However, leaks are not the only source of methane emissions in the gas sector. Natural gas operations are also subject to methane emissions from vents and incomplete combustion. Gas venting is part of the normal

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[18] IEA, Methane Tracker Data Explorer, 2022, https://www.iea.org/articles/methane-tracker-data-explorer

[19] Methane Guiding Principles, Methane Cost Model – Fugitives, https://methaneguidingprinciples.org/methane-cost-model/

[20] Calculated based on the following assumptions: 6 000 USD/day of LDAR campaign (CL internal data), 2 days per site, 3 campaigns per year, 200 facilities (CL assumptions)

[21] Calculated based on the following assumptions: wellhead gas price 4.7 USD/MMBtu, value given for Russian exports to Europe, IEA methane tracker 2022 documentation

functioning of certain equipment used in the industry. It typically occurs when gas pressure is used as an energy source or to allow to avoid over-pressure of equipment. In these types of equipment, methane emissions are expected as gas is emitted by design. Incomplete combustion is also an important source of methane emissions. It corresponds to the uncombusted methane that is released to the atmosphere, either from combustion devices used for energy and heat production or from gas flares.

Some solutions exist to reduce methane emissions from vents, such as replacing the equipment with lower-emitting alternative technology and design or, where emissions are unavoidable, capturing the vented gas to send to a pipeline, putting it to productive use on site or flaring it to control emissions. To reduce emissions from incomplete combustion and cover energy needs, thermic motors and turbines can be replaced by their electric equivalent. For both options, the IEA methane tracker 2022 assumes negative abatement costs thanks to additional revenues from gas and reduced fuel cost required to power gas facilities.

The oil sector in Algeria is less significant at the country level, but still one of the most important in Africa. Therefore, these gas abatement options could also improve methane emissions from the country's oil sector.

3.2 Oil and gas – Nigeria

Nigeria has the highest oil production in Africa, both onshore and offshore oil production facilities, and hence has the continent's highest methane emissions from the oil sector. The IEA methane tracker 2022 estimates that 71 % of emissions from the oil and gas sector in the country can be abated, of which about half can be abated at no net cost.

Similar to the gas sector in Algeria, the oil sector in Nigeria can reduce fugitive methane emissions through the implementation of regular LDAR. According to the IEA methane tracker 2022, implementing LDAR in Nigeria would have a negative abatement cost, and in some cases be highly profitable, across the entire value chain.

More specific to the oil sector in the country, other abatement options can be considered to reduce methane emissions from venting, including installing flares and vapor recovery units (VRUs). VRUs typically collect gas that builds up in tanks containing unstabilised hydrocarbons and compresses it for utilisation, where opportunities exist to sell the gas. When considering both onshore and offshore oil installations in the country, the IEA methane tracker estimates the abatement cost of installing VRUs to be on average around -2 USD/t CO_2e with emissions reductions from oil production estimated at around 20 %, corresponding with 75 000 t CH_4 (2.5 Mt CO_2e) using the emissions calculated as part of this analysis.

In some cases, there is no market for the gas produced, in which case, it is typically vented. This can be the case for operational venting but also the venting of associated gas. The latter is an important contributor to methane emissions in the oil and gas sector. An alternative to venting the gas is to install flares. Even though flaring generates CO_2 emissions, the climate impact of the combusted gas will be lesser than that of the uncombusted methane vented to the atmosphere. Flares are typically not an expensive technology to implement, but as there is no additional revenue from gas sales, their abatement cost is estimated by the IEA methane tracker to be on average 6.5 USD/t CO_2e for the country's oil production, considering both onshore and offshore installations. This would reduce oil and gas emissions in the country by 25 %, corresponding with around 95 000 t CH_4 (3.2 Mt CO_2e) if applied to the estimated emissions from the oil sector in Nigeria performed in the first part of this analysis.

Overall, reducing methane emissions in the oil and gas sector requires some initial investment but can often be profitable for oil and gas operators, provided there is a market to utilise or sell the recovered gas. Many international actors, some of whom operate facilities in Africa, have already made commitments to reduce their methane emissions, with initiatives such as the Oil and Gas Methane Partnership (OGMP) or the Oil and Gas Climate Initiative (OGCI). Governments can also further encourage the implementation of methane reduction technologies and practice, enforcing policy mechanisms adapted to the sector, as has been the case in countries such as Canada[22] or Colombia[23].

Table 1 presents a summary of the main abatement options reviewed for the oil and gas sector and their costs in the two case study countries.

Abatement option (CL assessment)	Algeria		Nigeria	
	Abatement cost (USD/t)	Abatement potential (t CO2e/y)	Abatement cost (USD/t)	Abatement potential (t CO2e/y)
LDAR	6.2 - 7.5 (i.e. without & with gas savings)	850 000	3.7 – 6.2	470 000
VRU	--	--	-2	2 500 000
Flaring	--	--	6.5	3 200 000

Table 1: Summary of abatement options and costs for the oil and gas sector

3.3 Municipal solid waste – Egypt

The Egyptian MSW management sector is a major contributor to CH_4 emissions in the country and, with over 265 000 t CH_4 (9 Mt CO_2e) per year, represents the second biggest emitter within this sector on the continent. The reason for this comes not only from the fact that Egypt has over 100 million inhabitants (i.e., >8 % of total African population) but is furthermore a middle-income economy, which often positively correlates with a country's total waste production,[24] whilst impacting on waste management procedures.[25] In the case of Egypt, this manifests in a total collection of municipal waste of just over 50 %, of which around half likely goes to landfills.[26] Due to the anaerobic characteristic of landfills, favouring a methane-producing decomposition process, methane emissions from landfills are estimated to be the third largest contributor to total global methane emissions.[27] In comparison, open and indiscriminate dumping as well as burning of waste produce significantly less methane emissions due to, respectively, aerobic decomposition processes and combustion processes, both favouring carbon dioxide (CO_2) production.

While basic landfilling potentially increases CH_4 emissions compared to more simple waste management practices, the advantages of modern sanitary landfills far outweigh the disadvantages. This includes the separation of waste from the environment and the human population, the concentration of waste in one single geographical area, and the opportunity to catch emissions from landfills.

[22] K. Konschnik and F. Reuland, Canada steps up its efforts to reduce methane emissions, 2020, https://www.iea.org/commentaries/canada-steps-up-its-efforts-to-reduce-methane-emissions

[23] CATF, A methane champion: Colombia becomes first South American country to regulate methane from oil and gas, 2022, https://www.catf.us/2022/02/methane-champion-south-america-colombia-becomes-first-south-american-country-regulate-methane/

[24] EPA, Economic Data and Indicators, 2013, https://www.epa.gov/sites/default/files/2016-01/documents/msw_task6_economicdataandindicatorsscopinganalysis_508_fnl.pdf

[25] NCBI, Waste Mismanagement in Developing Countries, 2019, https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6466021/

[26] Egypt Independent, Egypt disposes 80 million tons of garbage annually, 2018, https://www.egyptindependent.com/egypt-disposes-80-million-tons-of-garbage-annually-environment-minister/

[27] Global Methane Initiative, Global Methane Emissions, 2020,https://www.globalmethane.org/documents/gmi-mitigation-factsheet.pdf

With a theoretical abatement option of incorporating sanitary landfills as the sole potential waste management practice for the entire country—consequently abolishing the current high open and indiscriminate dumping prevalence—the construction of landfill gas (LFG) collection systems would allow for two major processing options, i.e., gas flaring and gas recovery for energy production.

LFG flaring generally represents the cheaper and easier to implement solution. Flaring is the process of combusting volatile gases, in this case landfill gas, to prevent their release into the atmosphere. In the case of LFG, flaring aims to transform the CH_4 share (+/- 50 % of total gas volume)[28] into CO_2, the latter being less environmentally damaging due to a lower GWP. For typically well managed flares under standard conditions, a flaring (e.g., methane destruction) efficiency of up to 98 % is expected.[29] In combination with average effective collection efficiencies for LFG collection systems around the world, the switch to country wide landfilling in combination with LFG flaring is able to reduce total CH_4 emissions from the MSW management sector by a minimum of 29 % in comparison to the current reference situation. The estimated installation cost for a combined LFG collection and flaring system is assumed to be around 60.000 USD per acre of landfill site. The LFG collection system itself is responsible for the bulk of the investment. As such, the marginal abatement cost is calculated at 5 USD/t CO_2e, yet this does not consider the multiple co-benefits of LFG collection systems such as reduced air pollution, odour, or health and safety benefits.[30]

LFG recovery for energy production (e.g., electricity, or combined heat and power) is an improvement from flaring as it employs the same collection system already embedded within the landfill site but ultimately makes use of the gas instead of combusting it. This is also where the biggest potential within the LFG collection system lies; it is not only a step up from flaring in terms of direct emissions reduction but also represents a further opportunity for local energy provision, economic income, and indirect reduction of CO_2 emissions through the potential replacement of natural gas in gas-fired power plants. As collection efficiencies from the LFG collection system do not change in this scenario, the main CH_4 emission reductions from flaring are a result of assuming no remaining CH_4 emissions after LFG is harnessed for energy production. Ultimately, LFG for energy recovery can reduce emissions from the MSW management sector by over 30 % in comparison to the current situation. It should further be noted that most LFG energy recovery systems are only economically lucrative for landfills of a certain minimum size and that have existed for 5 to 10 years, as the anaerobic decompositions process needs time to produce acceptable quantities of gas.[31] Due to the high initial investment costs of turbines, the estimated installation cost for a combined LFG collection and recovery system are around 50% more expensive per acre than for LFG collection & flaring systems alone. While this larger investment initially leads to a marginal abatement cost of over 7 USD/t CO_2e, this does not include the potential economic benefits of energy production through sales or a ripple effect, which likely decreases the marginal abatement cost further. An adapted marginal abatement cost includes the potential worth over the total energy production time (15-20 years),[32] which poses a temporal mismatch between the initial investment and potential return.

[28] EPA, Management of Low Levels of Landfill Gas, 2010, https://www.epa.ie/publications/compliance--enforcement/waste/EPA-_Management_Of_Low_Levels_Of_Landfill_Gas.pdf

[29] Caulton D. et al., Methane Destruction Efficiency of Natural Gas Flares Associated with Shale Formation Wells, 2014, https://pubs.acs.org/doi/10.1021/es500511w#:~:text=Flaring%20to%20dispose%20of%20natural,flare%20emissions%20have%20been%20reported.

[30] EPA, Benefits of Landfill Gas Energy Projects, https://www.epa.gov/lmop/benefits-landfill-gas-energy-projects

[31] LeRoi, Landfill Gas Recovery Process, https://www.gardnerdenver.com/en/leroi/industries/landfill-gas-recovery-process#:~:text=Landfill%20gas%20(LFG)%20recovery%20is,of%20non%2Dmethane%20organic%20compounds

[32] Rettenberger, G., Solid Waste Landfilling, 2019, https://www.sciencedirect.com/topics/earth-and-planetary-sciences/landfill-gas

3.4 Municipal solid waste – Nigeria

The Nigerian MSW management sector is, as for Egypt, a major contributor to the country's CH_4 emissions and the third biggest overall MSW methane emitter in Africa. Though Nigeria has more than double the inhabitants of Egypt, total waste production and landfilling percentages are lower, partly due to different consumption patterns explained by a 30 % lower GDP per capita than Egypt. Nonetheless, waste production is significant, creating over 240 000 t CH_4 (8 Mt CO_2e) per year. Total waste processing is limited; only 20-30 % is collected,[33] with high levels of indiscriminate disposal and significant proportions of burned waste.[34]

As landfilling has the highest CH_4 production rates of any MSW disposal method (see section 3.3), a country such as Nigeria that relies mostly on burning and open dumping of MSW would likely experience a drastic increase in CH_4 emissions from the waste sector by switching to a more sanitary disposal method (i.e., landfilling). To illustrate this, if Nigeria switched its entire MSW management system to landfills (without LFG collection systems), potential CH_4 emissions would increase by over 130 000 t CH_4 (4.4 Mt CO_2e) per year. This is an emission increase of over 55 % for the Nigerian MSW sector, demonstrating that, while simple landfilling will improve the sanitary situation for the local population and the overall environmental exposure to waste, in terms of CH_4 emissions alone, it leads to an overall deterioration of the situation.

For this reason, it is of utmost importance that landfills are constructed and retrofitted with LFG collection systems for either flaring or energy recovery (see section 3.3). In the case of LFG collection and flaring of *all* Nigerian MSW production, the country's CH_4 emissions would decrease by over 20 % from the current reference scenario, or by a total of over 50 000 t CH_4 (1.75 Mt CO_2e). Again, any remaining CH_4 emissions come from LFG collection and flaring efficiencies. At 7 USD/t CO_2e, the marginal abatement cost would be slightly higher for Nigeria than it is for Egypt (assuming the recovered gas is flared and not used for energy generation).

In the case of exchanging flaring towers for combustion or gas engines, remaining CH_4 emissions are exclusively characterised by LFG collection efficiencies, leading to total yearly CH_4 emission reduction of over 22 % from the current reference situation. Due to the installation costs of energy recovery systems, the marginal abatement costs for this scenario are over 10 USD/t CO_2e but could potentially again be reduced by the sale of produced energy.

Table 2 presents a summary of the main abatement options reviewed for the MSW sector and their costs in the two case study countries.

Abatement option	Egypt		Nigeria	
	Abatement cost (USD/t)	Abatement potential (t CO2e/y)	Abatement cost (USD/t)	Abatement potential (t CO2e/y)
LFG collection & flaring	5	2 500 000	7	1 750 000
LFG collection & energy recovery	7	2 750 000	10	2 000 000

[33] Bakare, W., Solid Waste Management in Nigeria, 2021, https://www.bioenergyconsult.com/solid-waste-nigeria/

[34] Federal Republic of Nigeria, Third National Communication, 2020, https://www4.unfccc.int/sites/SubmissionsStaging/NationalReports/Documents/187563_Nigeria-NC3-1-TNC%20NIGERIA%20-%2018-04-2020%20-%20FINAL.pdf

Table 2: Summary of abatement options and costs for the MSW sector

3.5 Wastewater – Angola

Wastewater management emissions for Angola only constitute around 1.5 % of total emissions, dwarfed by the oil and gas sector, yet still represent ample reduction opportunities. From a sanitary perspective, better managed wastewater poses fewer environmental and health related issues. Where the least well managed wastewater often goes straight from the source to the sea, rivers, and lakes (i.e., open water discharge), the most well managed wastewater is safely disposed of in situ or removed and treated offsite in either central or decentralised wastewater treatment plants. Between both extremes are septic tanks and pit latrines, with septic tanks being a sanitary improvement from pit latrines.

As Angola already possesses a small amount of centralised wastewater treatment and is, as such, assumed to have some experience in this sector, a potential high level abatement option would be the country-wide expansion of the existing wastewater treatment network. While unmanaged wastewater poses the biggest risk for health and the environment, it has potentially the lowest CH_4 emission factor; if wastewater concentration does not cross a certain threshold, anaerobic processes (responsible for the creation of methane) are limited in open areas. As such, the expansion of a basic wastewater treatment network to replace unmanaged wastewater flow to the environment would likely result in an increase in total methane emissions, despite improving sanitation. For Angola, replacing all current open water discharge, pit latrines, and septic tanks with sewage connections and basic wastewater treatment plants initially increases country wide CH_4 emissions to a total of 10 000 t CH_4 (340 000 t CO_2e) per year—up 157 % from the baseline.

In this basic abatement scenario, we assume the use of centralised conventional activated sludge (CAS) treatment plants that are running at a non-ideally managed (i.e., overloaded) state, impacting total CH_4 emissions as well as treatment costs.[35] While overloaded treatment plants can reduce treatment costs by operating at higher BOD loads,[36] this does not affect the initial investment required to connect households to treatment plants. While wastewater treatment costs are often dynamic and depend on the quality of the effluent, flow rates, or targeted purity,[37] the initial connection of a population to wastewater treatment plants is directly linked to total population and population density,[38] and is a major investment in its initial construction. Although wastewater could also be transported by truck instead of by pipelines, this is usually only done for sludge (e.g., from septic tanks) instead of for direct domestic wastewater use and would prove costly in the long run, especially at higher volumes.[39] In the case of assuming basic wastewater treatment and the construction of a currently non-existent wastewater sewage system for major parts of the country, total yearly costs could amount over 100 million USD for current wastewater production levels. This does assume the construction of the sewage system and treatment plants averaged over their expected lifetimes. As total CH_4 emissions increase for this scenario, no marginal abatement cost has been calculated.

To decrease Angola's total CH_4 emissions to a lower level than the current reference scenario while keeping to the best possible sanitation standards, we can build on the previous scenario by assuming the same level of sewage and treatment plant prevalence but assume better managed and, as such, more costly CAS

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[35] IPCC, Wastewater and discharge, 20116, https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/5_Volume5/V5_6_Ch6_Wastewater.pdf

[36] Wett et al., Load-flexibility of small activated sludge systems, 2000, http://www.hydro-it.com/extern/life/spezielle_untersuchung/belastung/load_flexibility.html

[37] Frankel, T., Treatment Systems Cost, 2021, https://www.ssiaeration.com/how-much-does-a-wastewater-treatment-system-cost/

[38] COWI, Appendix 3: Documentation of Expenditure Functions – Wastewater, https://www.oecd.org/env/outreach/36227787.pdf

[39] Marufuzzaman et al., Truck versus pipeline transportation cost analysis of wastewater sludge, 2015, https://www.sciencedirect.com/science/article/abs/pii/S096585641500018X#:~:text=Truck%20transportation%20is%20favored%20for,volumes%20and%20long%20travel%20distances

treatment plants. While well managed wastewater treatment plants operate on a narrower BOD load and are therefore more costly to run,[36] they are also significantly less likely to leak CH_4 emissions to the environment so pose the best alternative to open discharge for CH_4 management. While the total annual investment would increase to 122 million USD (including treatment plants and a sewage system), total emissions from the current reference scenario would decrease to 1 600 t CH_4 (55 000 t CO_2e) per year, a 31 % reduction from reference. As such, the marginal abatement cost for this measure would come to over 1 500 USD/t CO_2e, but could potentially be further reduced depending on the network length & type of the wastewater transport system as well as would decline in the future, once such as system is set in place.

3.6 Wastewater – Democratic Republic of Congo

In the Democratic Republic of Congo (DRC), wastewater management is limited, mostly consisting of discharge into the environment with no major centralised wastewater treatment plants. As the DRC does not possess major coal industries and only limited oil and gas, its main CH_4 emissions come from the MSW management sector, followed by the wastewater sector, which thus present attractive opportunities to not only lower exposure to human health and wellbeing risks but also to reduce CH_4 emissions.

From a sanitary perspective, septic tanks are a major improvement from open wastewater discharge or the use of latrines within communities or households.[40] Septic tanks are most used for domestic wastewater but can be used for distinct industrial process as well.[41] While septic tanks provide many benefits, including the separation of wastewater from the environment, low operating costs, and a long service life, they are also a major potential CH_4 source due to the creation of an anaerobic environment. In the DRC's case, as a country with no significant previous experience with centralised wastewater treatment systems, an interim sanitary step involving the country-wide development of anaerobic septic tanks for the entire population could potentially increase total emissions to over 26 000 t CH_4 (800 000 t CO_2e)—a 400 % increase from the reference year. While this is expectedly overestimated, as the DRC is likely to have more latrines (i.e., representing a similar or worse EF than septic tanks) than our dataset suggests, the increase would still be significant. Due to the initial financing costs of new septic tank systems, total annual investment costs would, averaged according to a tank's lifetime, be over 33 million USD for tank acquisition alone.

A less methane-intense alternative to anaerobic septic tanks are aerobic septic tanks. They offer near identical sanitary benefits to anaerobic septic tanks but possess a more complex ventilation system that introduces oxygen into the system, creating an aerobic phase in the decomposition process.[42] While the investment costs of aerobic septic tanks are expected to be triple the ones of the simpler anaerobic systems,[43] they are also expected to decrease emissions significantly in comparison. As the tanks cannot be assumed to operate always under ideal conditions, their EF are chosen conservatively yet remain significantly smaller than for anaerobic tanks. Though the country-wide distribution of aerobic septic tanks would increase total yearly investments to around 100 million USD a year, the lower emissions increase of a total 15 000 t CH_4 (500 000 t CO_2e) per year, a 200 % increase from reference scenario, is only half of the emissions increase calculated for anaerobic tank distribution. The option of distributing aerobic instead of anaerobic septic tanks would therefore result in an abatement cost of approximately 225 USD/t CO_2e based on the difference in cost of the former compared to the latter measure.

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[40] Washdata, Sanitation, 2020, https://washdata.org/data/downloads#WLD

[41] EPA, Large-Capacity Septic Systems, https://www.epa.gov/uic/large-capacity-septic-systems

[42] Mechanical Boost, What is an Aerobic Septic System, https://mechanicalboost.com/aerobic-septic-system/

[43] Lawnstarter, Pricing Guide: How Much Does a Septic Tank Cost, 2021, https://www.lawnstarter.com/blog/cost/septic-tank-price/#5-anaerobic-vs-aerobic-septic-system%C2%A0

The biggest leap towards both enhanced sanitation and reduced methane emissions would be the introduction of well-managed (centralised) wastewater treatment plants, foregoing an intermediate scenario that considers non-ideally managed wastewater treatment plants as this model is expected to yield total emissions similar to those of aerobic septic tanks. Although the introduction of country wide sewage system in the DRC is unlikely at present, its higher population density, over 50 % more than Angola, means the potential per capita costs could be significantly lower than for less dense countries.[38] Nevertheless, due to the DRC's high population and the currently insignificant wastewater piping infrastructure in the country, investment costs would be high, and would be expected to reach over 280 million USD a year for well-managed treatment plants at current wastewater production levels. While total emissions could be reduced to 2 600 t CH_4 (89 000 t CO_2e) per year, this would come at a cost of over 3 000 USD/t CO_2e.

Table 3 presents a summary of the main abatement options reviewed for the wastewater sector and their costs in the two case study countries.

Abatement option	Angola		DRC	
	Abatement cost (USD/t)	Abatement potential (t CO2e/y)	Abatement cost (USD/t)	Abatement potential (t CO2e/y)
Basic treatment plants		+ 200 000		+ 350 000
Improved treatment plants	1500	75 000	3000	90 000
Standard septic tanks		+ 400 000		+ 700 000
Aerobic septic tanks		+ 200 000		+ 350 000

Table 3: Summary of abatement options and costs for the wastewater sector

Note: The entries in red indicate an increase in emissions. Therefore, abatement cost becomes irrelevant for these options.

3.7 Coal – South Africa

Global coal mine methane (CMM) emissions represent about 8 % of global anthropogenic methane emissions.[44] South Africa is currently the eighth largest worldwide emitter of CMM, representing a significant opportunity to reduce methane emissions.[45] The country is Africa's largest producer of coal with about 3.5 % of the world's coal resources. Coal constitutes approximately 72 % of South Africa's total primary energy supply, mostly used for power generation and industry; more than 90 % of its electricity and 30 % of the liquid fuel are produced from coal.[46] The technologies to recover and use CMM are commercially accessible and established, making it an attractive near- to medium-term abatement solution for the coal industry.

[44] GMI, CMM Country Profiles: South Africa, 2015, https://www.globalmethane.org/documents/toolsres_coal_overview_ch31.pdf.

[45] IEA, *Methane Tracker Data Explorer,* 2022, https://www.iea.org/articles/methane-tracker-data-explorer

[46] Ratshomo, K. and R. Nembahe, South African Coal Sector Report, Department of Energy, www.energy.gov.za/files/media/explained/South-African-Coal-Sector-Report.pdf.

Underground mining is responsible for the vast majority of CMM emissions in South Africa, releasing an estimated 55 000 t CH_4 (1.9 Mt CO_2e) annually. The country's most common underground mining technique is 'bord and pillar', an ideal method for shallow deposits with low overlying rock pressure. This partial-extraction technique poses distinct challenges for ventilation due to the high volumes of air required and the difficulty of distributing it evenly. As such, gas can accumulate in closed off worked-out areas, which are ventilated less than the higher-risk working sections due to a limited supply of air. This is a significant safety risk due to methane's explosiveness when mixed with air in concentrations between 5 % to 17 %; government regulations thus stipulate that gas concentrations must be less than 1.4 %.

To dilute methane to safe concentrations to release as ventilation air methane (VAM), many South African mines improved ventilation practices through introducing auxiliary (secondary) ventilation, air velocity monitoring and gas detection schedules, and regular measurement and inspection. The large volume of ventilated air leads to significant annual methane emissions, despite the low methane concentration, as almost all VAM is emitted to the atmosphere. VAM is the single largest source of CMM emissions globally.[47]

Gas drainage was not initially regarded as viable due to the low gas content seams in many of South Africa's older mines, which are relatively shallow and not considered "gassy". In these instances, though, CMM could be collected for local heating purposes. South African gold mining companies have used recovered methane to fuel kitchen stoves and bath houses for over 20 years in the Free State province.[48] Many of the newer underground mines in South Africa are deeper and thus gassier, increasing the abatement potential opportunities through methane recovery and use. The primary underground mining systems employed in such cases are longwall mining and rib-pillar extraction.

South Africa has pursued only one CMM recovery project, as identified by the GMI International Database: a flaring project at the New Denmark colliery. The upfront project cost of 1.2 million USD allowed project developers to pursue carbon credits. Such carbon financing options may be a critical factor in making CMM use projects economically viable, providing a revenue stream for abatement-only projects such as VAM oxidation (without recovery) or CMM flaring. At South Africa's Beatrix Gold Mine, a 5.5 million USD flaring project to install underground pipeline drainage systems that capture methane from faults and fissures had an estimated emissions reduction of 2.6 Mt CO_2e over 7 years.[29]

Gas drainage and recovery is made profitable through various potential uses for CMM in South Africa, including electric power generation, boiler and transportation fuel, and feedstocks. CMM could also reduce gas import requirements as demand rises. In newer developments with deeper and gassier seams, gas drainage and subsequent commercial CMM would require infrastructure investments, installation of gas collection technologies, and construction of pipelines to move the methane to markets.[29] Estimated costs for extracting CMM from an underground longwall mine at a rate of 0.5 to 2.0 Mtpa, using in-seam pre-drainage techniques, range from 0.5 USD/t to 3.7 USD/t of coal. Post-drainage borehole techniques range between 0.1 USD/t to 1.9 USD/t of coal—two of the least costly gas drainage methods applicable in the South African context.[49] An achievable target in most cases is 50 % CMM capture from the entire mine; following current estimates, this puts the annual total cost of capturing underground South African mine emissions between 22 million to 162 million USD (in-seam pre-drainage techniques), or 4 million to 83 million USD (post-drainage borehole techniques), each method dependent on borehole diameter and length. This is equivalent to respective abatement costs of between 23 to 175 USD/t CO_2e or 2 to 90 USD/t CO_2e.

[47] UNECE, Best Practice Guidance for Effective Methane Drainage and Use in Coal Mines, 2016, https://unece.org/sustainable-energy/publications/best-practice-guidance-effective-methane-drainage-and-use-coal-0.

[48] GMI, CMM Country Profiles: South Africa, 2015, https://www.globalmethane.org/documents/toolsres_coal_overview_ch31.pdf.

[49] UNECE, Best Practice Guidance for Effective Methane Drainage and Use in Coal Mines, 2016, https://unece.org/sustainable-energy/publications/best-practice-guidance-effective-methane-drainage-and-use-coal-0.

Investment in effective gas drainage practices results in less downtime due to gas emission problems, safer mining environments, opportunities for reducing GHG emissions and using CMM, and reduced ventilation costs. The power consumed in operating underground ventilation is among the costliest operational expenses at a mine, therefore, introducing a drainage system is often a lower cost option than increasing ventilation air volumes.[50] Gas drainage also reduces the risks of methane explosions, outbursts, and related accidents, in turn reducing their associated costs—at a typical high-production longwall mine, a 10 % work stoppage due to a gas-related incident could cause 8 to 16 million USD per year in lost revenues.

South African coal production is expected to rise until at least 2026, and its National Development Plan (NDP) outlines the pivotal role of coal in supplying cheap and accessible energy for the foreseeable future as the backbone of its economy.[51] However, South Africa has made international commitments towards climate change mitigation, and the position of OECD countries to discontinue investments in coal-fired power stations, including the manufacture of machinery and equipment for their operations, presents a challenge towards financing new coal-fired power plants unless South Africa abates its coal mining emissions. Despite an initial opportunity cost for equipment and infrastructure, CMM recovery and use through gas drainage strategies may be necessary for continued coal mining as climate targets become increasingly stringent.

Table 4 presents a summary of the main abatement options reviewed for the wastewater sector and their costs in South Africa.

Abatement option	South Africa	
	Abatement cost (USD/t)	Abatement potential (t CO_2e/y)
Pre-drainage and directional long boreholes & flaring	23–175	950 000
Post-drainage and subjacent or guided horizontal boreholes & flaring	2–90	950 000

[50] UNECE, Best Practice Guidance for Effective Methane Drainage and Use in Coal Mines, 2016, https://unece.org/sustainable-energy/publications/best-practice-guidance-effective-methane-drainage-and-use-coal-0.

[51] Ratshomo, K. and R. Nembahe, South African Coal Sector Report, Department of Energy, www.energy.gov.za/files/media/explained/South-African-Coal-Sector-Report.pdf.

Table 4: Summary of abatement options and costs for coal mining

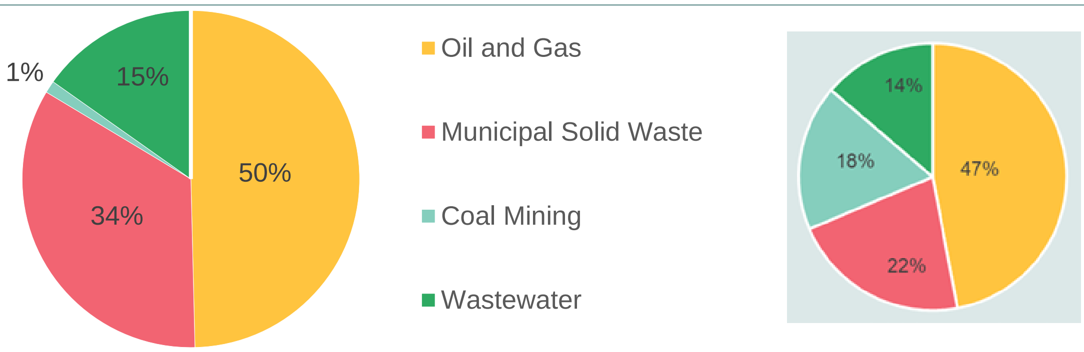
4 Conclusions

4.1 Total emissions

Total sectoral emissions for Africa (Figure 12) follow almost the same order of significance as global CH_4 emissions for the four highest emitting sectors yet diverge in their respective share of total continental emissions from the global pattern. The most methane-intensive sector responsible for just over half of analysed anthropogenic African emission sources comes from the oil and gas industry,[52] despite just 17 out of the 54 African countries operating in this sector. Though not necessarily surprising, this does show the very significant methane mitigation potential in the oil and gas sector, which would only need to be addressed in less than half of countries. In this sector, reducing methane emissions is often synonymous with additional revenues from gas sales, generating economically appealing mitigation projects for oil and gas operators.

Following in importance is the municipal waste sector, with a total emissions contribution one-third (34 %) of all analysed CH_4 emissions. As for global methane emissions sources, MSW is second for total emissions contributions, but it's role in Africa is more significant than at the global level. This might be explained by other methane-emitting sectors being less significant for Africa, as well as the prominence of open and indiscriminate dumping, leading to anaerobic decomposition conditions without proper management. Next is the wastewater management sector with 15 % of analysed African methane emissions, equivalent to less than half (40 %) of the emissions of the MSW sector. While the production and management of MSW and wastewater is often linked by GDP (i.e., consumption patterns, public spending) and country-specific infrastructure, globally the wastewater management sector is equivalent to over 60 % of the methane emissions of the MSW sector. Though the two numbers are too dissimilar, differences can often be explained by poor infrastructure decreasing potential methane emissions for the wastewater sector (i.e., open discharge) while increasing methane intensity from MSW (i.e., open dumping). Lastly, the coal sector is responsible for only 1 % of all analysed methane emissions, far below the share this sector represents globally. As there are only 2 significant coal producing countries in Africa (South Africa and Zimbabwe), this is not surprising on a continental scale, yet indicates important mitigation potential for the countries in question. An additional sector with a significant impact on continental methane emissions was livestock, which was not considered for the body of this analysis and is instead explored further in the annex.

Figure 13: Estimated African anthropogenic methane emissions sources (inset chart shows estimated global anthropogenic CH4 emission sources for the same sectors, for comparison)



[52] Note: No assumptions were taken for the 'others' (i.e., sectors not analysed in this study) of total African CH_4 emissions. Livestock was also excluded from analysis due to inconsistencies in the acquired datasets but is subsequently discussed in the annex.

Overall, this analysis demonstrates that it is largely the same major industries both in Africa and globally that that are responsible for most CH_4 emissions; it must be highlighted though, that despite Africa holding nearly 17 % of the global population, it is only responsible for around 1.7 % of global methane emissions.

4.2 Abatement potential

The abatement potential naturally varies according to sector, yet overall, there are considerable possibilities for emissions reductions in each field. While this study analyses abatement options for only a few countries more precisely, which were picked to showcase those with the highest potential or most significant effects depending on the abatement measure, the actions explored are likely to have major impacts on any African country (if the country has stakes in that respective sector), albeit with varying efficiencies. Given that abatement potential relied on country-specific information, the assessment for the different sectors was not extrapolated to the entire continent as not all measures are applicable or relevant for all countries. Further assessment would be required to evaluate abatement potential at a country level.

Generally, the sector with the highest total emissions should be a starting point for emission reduction due to potentially bearing the most significant results. For Africa, this is the oil and gas sector (see 4.1). Algeria and Nigeria are the most methane emitting countries in the gas and oil sectors, respectively, and as such serve as prime examples for mitigation strategies. With potentially 71 % of oil and gas emissions considered “abatable” in Nigeria alone,[53] there is a high mitigation potential in these sectors, as also partly confirmed by this analysis. Many of the abatement measures come at a relatively low cost (e.g., 2 to 3 USD/t CO_2e for LDAR and flaring) or even negative cost (-1.5/t CO_2e for VRUs), meaning that not only is the potential significant but the return on investment is the greatest from all analysed sectors.[54] Abatement options are typically decided upon and implemented by operators, but support can be provided to accelerate their implementation through specific policies targeted at the oil and gas sector.

For the municipal solid waste (MSW) sector, the abatement potential is high not only because it is the second largest contributor to Africa’s total methane emissions, but also due to the lower methane emissions involved in modern MSW management practices. An important first step for reduction in this sector involves the concentration of MSW in sanitary landfills. It should be noted here that landfilling MSW without gas recovery is likely to increase total emissions for this sector due to the creation of an anaerobic methane generating environment. As for the marginal abatement cost, measures to reduce methane emissions from sanitary landfills amount to between 5 to 10 USD/t CO_2e for flaring and gas recovery measures respectively (excluding potential economic gains from energy production), reducing total CH_4 emissions by up to 30 %.

The wastewater management sector, with 15 % of total continental emissions, has significant methane emissions reduction potential, yet is usually assessed from a sanitary perspective. Sanitary improvements are of utmost importance for mitigating direct human health implications, however, the methane emissions footprints of the various options differ. As open wastewater discharge generally only emits very limited amounts of methane, improved sanitation measures (e.g., latrines, septic tanks, and central wastewater treatment plants) emit more than no measures at all. While this is a general assumption and can indeed be observed in this study with an increase in methane emissions, actual changes in emissions always depend on the existing local infrastructure and climate (temperature and humidity both influence EF).[15] Applying the best-case scenario for both sanitation and methane emissions mitigation, country-wide connection to sewage systems and well-managed central wastewater treatment plants could reduce methane emissions from wastewater significantly. This comes, though, at a rather high investment cost of potentially several thousand USD per tonne of mitigated CO_2e. Despite there being more attractive methane abatement

[53] IEA, Methane tracker, 2022

[54] Note: This does not take into account co-benefits such as human health or well-being, which might be greater in other sectors.

choices that provide a greater return on investment, the wastewater management sector has some of the biggest co-benefits for human health and wellbeing and, as such, its contribution should not be dismissed.

Although the coal sector plays a lesser role in Africa's total continental CH_4 emissions, emissions reductions are important if only for South Africa's own footprint. Though coal mine methane (CMM) recovery and use is not widespread yet in the country, the current practice of venting CMM to the atmosphere in the form of ventilated air methane (VAM) is the sector's largest contributor to global methane emissions and would thus benefit from improvement. CMM recovery provides financial benefits beyond methane reuse (e.g., reduction of mining downtime due to gas venting complications) but, with marginal abatement costs ranging from 0.95 to 71 USD/t CO_2e, the investments generally exceed those of the oil and gas abatement measures.

In order to reduce Africa's methane emissions by 30% until the end of this decade, 2 sectors stand out the most when it comes to cost effectiveness. First, the potential of CH_4 emissions reduction is the most significant for the oil & gas sector. Although only 17 countries in Africa are significant oil and gas producers, 50% of methane emissions originate from the sector, from which more than half can be mitigated at a negative or low abatement cost, as seen in earlier paragraphs. While this study cannot draw a definitive conclusion for the entirety of Africa, the results are mostly in line with a previous IEA analysis, predicting major abatement possibilities in the oil and gas sector for the entire continent.[55] With the oil and gas abatement options presenting the lowest average marginal abatement cost and showing the biggest potential for reduction, it would be interesting to prioritize action in this sector, which can be prompted by adapted regulations.

The second most important sector in terms of total abatement as well as marginal abatement cost is the municipal solid waste sector. Based on current African waste management practices, improvements in municipal solid waste management are expected to have major impacts in all African countries and have shown to reduce emissions by 20–30% in the cases presented in this study. While reductions in all other sectors are also important, keeping in mind additional co-benefits that come with implemented abatement measures (e.g., sanitation, air quality, …), total abatement potential and marginal abatement costs are assumed to be overall higher for other sectors. A total, cost-effective reduction of 30% methane emissions by 2030 will likely only be possible by combining abatement measures in multiple high-impact sectors, and efforts in a single sector will not be sufficient to achieve the overall target.

5 Limitations and uncertainties

The assessment presented in this report was intended to provide a general picture of anthropogenic methane emissions in Africa and thus carries high levels of uncertainty. Individual situations in countries might not be precisely reflected by continent-wide emission factors and activity data. Hence, abatement potential and cost were evaluated at the country level through specific case studies, focusing on the specificities of the assessed countries, the results of which were not extrapolated to the entire continent because they are not necessarily applicable elsewhere due to the local climate, infrastructure, or economy.

On the other hand, this high-level assessment allows for an identification of interesting countries and sectors for further assessment of methane emissions and abatement potential. For example, South Africa is an important contributor to methane emissions across wastewater, coal, and MSW, displaying major abatement potential for total continental emissions. Further local assessment could help refine methane emissions assessment and identify, more specifically, interesting abatement options for these sectors.

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[55] IEA, Methane Tracker, 2020, https://www.iea.org/reports/methane-tracker-2020

Annex 1: Emissions from livestock

Emission from livestock in Africa - Results

The livestock sector is a significant contributor to greenhouse gas emissions, of which methane accounts for 50 %. This section collates and presents data on emissions emission from livestock as estimated by the Food and Agriculture Organization of the UN (FAO) [56], and considers only livestock methane emissions for Sub-Saharan Africa and not Africa overall, as FAO data does not disaggregate North Africa from countries categorised as Near East, including much of eastern Asia and the Middle East. Therefore, to ensure the data is only accurate to the African context and not conflated with data from other regions, this analysis excludes the North African countries of Algeria, Egypt, Morocco, Republic of Sudan, South Sudan, Libya, Tunisia, and Western Sahara.

Methane emissions from livestock originate from three main processes: enteric fermentation, manure management, and feed production. Enteric fermentation alone accounts for 44 % of the livestock sector's total GHG emissions, generating methane during the digestive process through anaerobic fermentation. These emissions are closely correlated with feed quality, as poorly digestible rations yield higher enteric methane. Methane also constitutes over half of all GHG emissions from manure management, which is responsible for about 10 % of total sector GHG emissions through the anaerobic decomposition of organic matter, dependent on the type of manure management system. Finally, feed production makes up 41 % of total livestock sector emissions, of which CH_4 emissions represent only 0.5 %, largely from rice crops.

Table 5 lists the aggregate CH_4 emissions of each species according to emissions source: feed, enteric fermentation, and manure management.

Table 5: Aggregate livestock species methane emissions (in Mt CO_2e) with breakdown by methane source

	Total CH_4 emissions	Feed	Enteric fermentation	Manure management
Cattle	215.6		209.4	6.18
Sheep	23.5		22.7	0.826
Goats	35.0		33.8	1.22
Pigs	6.73	0.557	0.687	5.49
Chicken	0.598	0.182		0.415
Total	281.4	0.738	266.6	14.1

In Sub-Saharan Africa, livestock emits over 281 million tonnes CO_2e of CH_4; the primary contributor being cattle, with nearly 216 Mt CO_2e, followed by goats, sheep, pigs, then chicken. Enteric fermentation is the main source of CH_4 emissions (95 %), largely from cattle with a smaller portion from other ruminants (sheep and goats). Methane emitted from enteric fermentation in cattle alone is responsible for 74 % of total Sub-Saharan African livestock methane emissions. The other large emitter is manure management, releasing over 6 Mt CO_2e from cattle, followed by 5.5 Mt CO_2e from pigs, 1.2 Mt CO_2e from goats, 0.8 Mt CO_2e from sheep, and 0.4 Mt CO_2e from chicken. Manure is the largest source of emissions from pigs and chicken, accounting for a respective 82 % and 70 % of their methane emissions yet represents only a small portion

[56] Global Livestock Environmental Assessment Model (GLEAM), 'Assessment of greenhouse gas emissions and mitigation potential', FAO, https://www.fao.org/gleam/results/en/#c303618.

for ruminants—3 % of methane emissions from cattle and goats and 4 % from sheep, the other 96–97 % arising from enteric fermentation. Only pigs and chicken generate CH_4 emissions from feed, releasing 0.56 Mt and 0.18 Mt CO_2e respectively.

Table 6 distinguishes between different livestock production systems in Africa, namely grassland and mixed for cattle, sheep, and goats; backyard, layers, and broilers for poultry; and backyard, intermediate, and industrial for pigs. This allows a more accurate analysis of CH_4 emissions within the sector. Just under two-thirds (64 %) of methane emissions from Sub-Saharan African cattle come from grassland production systems, over one-third (35 %) from mixed systems, and 1 % from feedlots. Grasslands also account for more than half of sheep (56 %) and goats (52 %) methane emissions, with the remaining portion coming from mixed systems. For pigs and poultry, backyard systems are the largest source of emissions at 86 % and 64 %, respectively. Layers account for nearly a quarter of methane emissions for poultry at 23 %, followed by broilers at only 14 %. For pigs, the remaining CH_4 is emitted through intermediate (7 %) and industrial systems (6 %). Across all species, grassland systems therefore account for 60 % of total livestock sector CH_4 emissions, followed by mixed systems with 37 %, and backyard systems with 2 %.

Table 6: Species methane emissions (Mt CO_2e) by production system

Animal species	Production system	CH_4 emissions (Mt CO_2e)
Cattle	Grassland	138.5
	Mixed	75.8
	Feedlots	1.4
Sheep	Grassland	13.1
	Mixed	10.4
Goats	Grassland	18.0
	Mixed	16.9
Pigs	Backyard	5.8
	Intermediate	0.5
	Industrial	0.4
Chicken	Backyard	0.4
	Layers	0.1
	Broilers	0.1

Case study – Ethiopia & Niger[57]

Emissions reduction from the livestock sector can be achieved by reducing production and consumption, by lowering emissions intensity of production, or by a combination of the two. Enteric fermentation is one of the most important sources of methane in Africa and therefore exhibits multiple opportunities for mitigation.

The following abatement potential considerations are based on enteric methane emissions with a specific focus on dairy production. In West Africa, enteric methane alone—excluding methane from manure and feed—accounts for 95 % of total dairy cattle emissions in Benin, 94 % in Burkina Faso, 87 % in Mali, and 97 % in both Niger and Senegal. Similarly, across East Africa, where milk accounts for four-fifths of total animal food supply, enteric methane constitutes 87 % of total dairy cattle emissions in Ethiopia, 88 % in Kenya, 92 % in Tanzania, and 79 % in Uganda—four countries which have the largest cattle herds in Africa with an estimated 121 million cattle, almost 40 % of the continent's total.

Although fully avoiding emissions of enteric methane is not achievable in the short-term due to the significant growth in demand, opportunities exist to substantially reduce emission intensity by, for example, improving the efficiency of production through implementing known practices or technologies that result in greater yields per animal and per unit of feed. Farming systems that are more productive have higher total methane emissions but much lower emissions intensity (emissions per unit of product). The emissions intensity (EI) of livestock is higher in regions where productivity is lower, yet demand is growing the fastest, such as West Africa, where demand for dairy products is projected to grow 370 % between 2012 and 2050. Thus, improving productivity and efficiency is key to mitigating livestock emissions whilst also improving rural livelihoods and food security.

In Ethiopia, the dairy cattle sector creates 116.3 Mt CO_2e, of which enteric methane accounts for 101.2 Mt—the largest of the nine studied African countries. This is expected to rise as urbanisation increases the demand for milk; per capita annual consumption in Addis Ababa is 52 litres compared to a national average of 19 litres. According to the FAO, the mitigation intervention with the greatest individual potential is artificial insemination, reducing national EI by 62 % and increasing production by 181 %. Employing a mitigation package that combines a variety of technical interventions (leguminous shrub supplementation, urea treated crop residues, trypanosomosis control, and artificial insemination) would have an even greater effect—halving national enteric methane EI from 24.5 kg CO_2e per kg of milk whilst more than tripling production—as farmers are then able to implement several changes simultaneously to achieve multiple goals.

Table 7 considers the effect of implementing the mitigation package on each production system in Ethiopia.

Table 7: Effect of mitigation intervention package on emissions intensity (EI) and milk production in Ethiopia

Production system	EI (kg CO_2e / kg milk)	% change in enteric CH_4 EI relative to baseline	New EI (kg CO_2e / kg milk)	% change in milk production relative to baseline
Rural mixed crop livestock	44.6	-68.3	14.1	206.8
Pastoral / agro-pastoral	18.9	-49.5	9.5	62
Small-scale commercial	8.7	-66.8	2.9	225.4
Medium-scale commercial	3.8	-44.1	2.1	66.9

[57] FAO: Food and Agriculture Organisation of the United Nations, 'Reducing Enteric Methane for improving food security and livelihoods', https://www.fao.org/in-action/enteric-methane/en/.

Rural mixed-crop livestock systems could reduce their EI by over two-thirds (68 %) whilst tripling production (207 %); pastoral and agro-pastoral systems by half (49.5 %) whilst increasing production by 62 %; small-scale commercial systems by two-thirds (67 %) whilst more than tripling production (225 %); and medium-scale commercial systems by 44 % whilst increasing production by two-thirds (67 %).

Combining interventions to target different areas of dairy cattle production through a mitigation package could also lead to significant EI reductions in Niger, averaging -34 % across both pastoral and agro-pastoral production systems. Though emissions intensity for agro-pastoral systems (responsible for 90 % of milk production in Niger) is the lowest of the five referenced West African countries, at 11.9 kg CO_2e per kg of milk, it has the largest dairy cattle sector. Niger produced 1.2 million litres of milk from 3.8 million cows in 2013, emitting a total of 16.3 Mt CO_2e, of which enteric methane accounted for 15.8 Mt CO_2e.

Table 8 considers the effect of various mitigation interventions on dairy cattle EI within both agro-pastoral and pastoral systems. Among various considered interventions, the use of improved breeds and forage tree cultivation showed the highest potential to reduce sectoral EI across both production systems. Other interventions also had high system-specific impact potential to reduce EI, such as cowpea hay making to improve feeding in agro-pastoral systems (-23.7 %) or conserved fodder use in pastoral systems (-23.1 %).

Table 8: Effect of different dairy cattle mitigation interventions on agro-pastoral and pastoral systems' EI and milk production in Niger

Current EI (kg CO_2 / kg): • agro-pastoral: 11.9 • pastoral: 21.1	% change in enteric CH_4 EI relative to baseline		New EI (kg CO_2e / kg milk)		% change in milk production relative to baseline	
Mitigation Intervention	Agro-pastoral	Pastoral	Agro-pastoral	Pastoral	Agro-pastoral	Pastoral
Conserved fodder use	-17.3	-23.1	9.8	16.2	19	23.6
Total mixed ration use	-17.2	-19	9.9	17.1	16	19.1
Silage making	-22.1		9.3		27.9	
Cowpea hay making	-23.7		9.1		30.9	
Urea treated straw supplementation	-19		9.6		30	
Forage tree cultivation	-18.6	-25.1	9.7	15.8	18.2	27.7
Water harvesting technologies	-14	-16.1	10.2	17.7	14.8	19.3
Superior genetics use (improved breeds)	-24.5	-22.3	9.0	16.4	33.1	29
Deworming	-15.4	-17.5	10.1	17.4	17.8	20.8

As methane emissions from enteric fermentation are directly linked to livestock species and volume, emission reduction that is achieved by reducing production and consumption must also account for population size and local conditions to be viable. As such, combining mitigation actions into packages helps not only to reduce emissions from this sector but also bears multiple co-benefits. These intervention packages would likely not only benefit system productivity and greenhouse gas emissions intensity, but also positively affect farmers' income and climate resilience through better management of fluctuations in seasonality and quality of resources as climate change aggravates seasonal and inter-annual variability in rainfall and the frequency of extreme events such as drought.

The strong observed correlation between enteric methane emissions reductions and animal productivity increases in both Ethiopia and Niger implies there are significant opportunities for mitigation that also have widespread social and economic benefits. Relative to other global greenhouse gas abatement techniques, reducing enteric methane in the livestock sector through productivity gains is one of the lowest cost options with direct economic gains for African farmers.

Annex 2: Input data

Sector	Activity data	Emission factors
Oil and gas	Oil and gas production: 2019 BP Statistical energy review (2018 data) Pipelines: ChartsBin, *Total Length of Pipelines for Transportation by Country,* http://chartsbin.com/view/1322	Oil and gas production: IPCC 2019 refinements, Table 4.2.4A - Onshore: most activities occurring with higher - emitting technologies and practices Pipelines: IPCC 2019 refinements, Table 4.2.4G - Limited LDAR or less than 50 % of centrifugal compressors have dry seals
Coal	Production data: 2021 BP Statistical energy review (2020 data) Share of underground/surface mining: South Africa BUR 4 2021, https://unfccc.int/documents/307107	South Africa BUR 4 2021, https://unfccc.int/documents/307107
Waste	Waste generation: Hoornweg and Bhada-Tata (2012) Share of waste treatment: Hoornweg and Bhada-Tata (2012); Dladla et al. (2016)	UNFCCC, IPCC
Wastewater	Wastewater generation: Edward et al. (2020) Share of wastewater collected/ share of wastewater treatment for collected: Edward et al. (2020), Washdata.org	Paredes et al. (2015), IPCC

Annex 3: Emissions estimates by country and sector

Table 9: Results of the emissions estimates by country and sector in t CH_4.

Country	MSW	Wastewater	Coal	Oil and gas
South Africa	319802.05	112842.64	54707	3723
Egypt	265220.534	423042.18	0	391472
Nigeria	240154.7211	43494.13	0	587541
Algeria	125121.7664	24407.82	0	693449
Morocco	121801.595	20069.84	0	0
Sudan	64970	7659.45	0	19314
Democratic Republic of Congo	51749.7	5259.76	0	152
Cote d'Ivoire	35773.65	2737.12	0	738
Tunisia	34653.465	21901.31	0	0
Madagascar	33527.586	1250.51	0	0
Cameroon	31634.0025	765.63	0	0
Ethiopia	28843.3585	6432.65	0	0
Libya	22101.20625	3997.56	0	234295
Zimbabwe	18058.74	4187.87	2060	0
Mali	16463.398	1866.35	0	0
Senegal	15839.686	4175.09	0	176
Kenya	13505	4032.79	0	0
Benin	11038.403	805.29	0	0
Mauritius	10380.965	1102.31	0	0
South Sudan	10063.05	869.88	0	24391
Guinea	9544.093	928.85	0	0
Uganda	8821.8675	3469.79	0	0
Burkina Faso	8368.136	986.45	0	0
Chad	8368.136	952.51	0	20199

Niger	8244.912	798.02	0	0
Malawi	7478.047	1074.94	0	0
Togo	6750.675	470.32	0	0
Congo	6700.67	837.79	0	65055
Ghana	6389.325	10555.37	0	4
Botswana	6107.18	2327.42	0	0
Sierra Leone	6005.272	434.99	0	0
Mozambique	5759.7	2107.52	0	3764
Central African Republic	5165.115	278.34	0	0
Eswatini	5028.678	420.62	0	0
Rwanda	4500.45	430.55	0	0
Zambia	4917.28	1793.39	0	0
Djibouti	4151.583	290.58	0	0
Mauritania	3851.6625	466.76	0	0
Gabon	3571.2987	1263.57	0	38173
Liberia	3433.64625	320.43	0	0
Somalia	3024.39	921.42	0	0
Eritrea	2845.686	590.51	0	0
Gambia	2845.686	207.89	0	0
Tanzania	2715.746	5316.65	0	1041
Angola	26703.4365	3808.23	0	284317
Comoros	2332.423	94.23	0	0
Equatorial Guinea	2268.9057	998.91	0	33308
Burundi	2179.488	806.48	0	0
Namibia	2176.495	1188.40	0	0
Lesotho	1494.31	295.10	0	0
Guinea-Bissau	1390.358	119.03	0	0

Seychelles	884.2563	203.97	0	0
Cape Verde	775.0775	86.97	0	0
São Tomé and Príncipe	240.9	40.14	0	0

Table 10: Results of the emissions estimates by country and sector in Mt CO_2e (GWP = 34).

Country	MSW	Wastewater	Coal	Oil and gas
South Africa	10.87	3.84	1.86	0.13
Egypt	9.02	14.38	0.00	13.31
Nigeria	8.17	1.48	0.00	19.98
Algeria	4.25	0.83	0.00	23.58
Morocco	4.14	0.68	0.00	0.00
Sudan	2.21	0.26	0.00	0.66
Democratic Republic of Congo	1.76	0.18	0.00	0.01
Cote d'Ivoire	1.22	0.09	0.00	0.03
Tunisia	1.18	0.74	0.00	0.00
Madagascar	1.14	0.04	0.00	0.00
Cameroon	1.08	0.03	0.00	0.00
Ethiopia	0.98	0.22	0.00	0.00
Libya	0.75	0.14	0.00	7.97
Zimbabwe	0.61	0.14	0.07	0.00
Mali	0.56	0.06	0.00	0.00
Senegal	0.54	0.14	0.00	0.01
Kenya	0.46	0.14	0.00	0.00
Benin	0.38	0.03	0.00	0.00
Mauritius	0.35	0.04	0.00	0.00
South Sudan	0.34	0.03	0.00	0.83
Guinea	0.32	0.03	0.00	0.00

Uganda	0.30	0.12	0.00	0.00
Burkina Faso	0.28	0.03	0.00	0.00
Chad	0.28	0.03	0.00	0.69
Niger	0.28	0.03	0.00	0.00
Malawi	0.25	0.04	0.00	0.00
Togo	0.23	0.02	0.00	0.00
Congo	0.23	0.03	0.00	2.21
Ghana	0.22	0.36	0.00	0.00
Botswana	0.21	0.08	0.00	0.00
Sierra Leone	0.20	0.01	0.00	0.00
Mozambique	0.20	0.07	0.00	0.13
Central African Republic	0.18	0.01	0.00	0.00
Eswatini	0.17	0.01	0.00	0.00
Rwanda	0.15	0.01	0.00	0.00
Zambia	0.17	0.06	0.00	0.00
Djibouti	0.14	0.01	0.00	0.00
Mauritania	0.13	0.02	0.00	0.00
Gabon	0.12	0.04	0.00	1.30
Liberia	0.12	0.01	0.00	0.00
Somalia	0.10	0.03	0.00	0.00
Eritrea	0.10	0.02	0.00	0.00
Gambia	0.10	0.01	0.00	0.00
Tanzania	0.09	0.18	0.00	0.04
Angola	0.91	0.13	0.00	9.67
Comoros	0.08	0.00	0.00	0.00
Equatorial Guinea	0.08	0.03	0.00	1.13
Burundi	0.07	0.03	0.00	0.00

Namibia	0.07	0.04	0.00	0.00
Lesotho	0.05	0.01	0.00	0.00
Guinea-Bissau	0.05	0.00	0.00	0.00
Seychelles	0.03	0.01	0.00	0.00
Cape Verde	0.03	0.00	0.00	0.00
São Tomé and Príncipe	0.01	0.00	0.00	0.00