III. Waste Sector

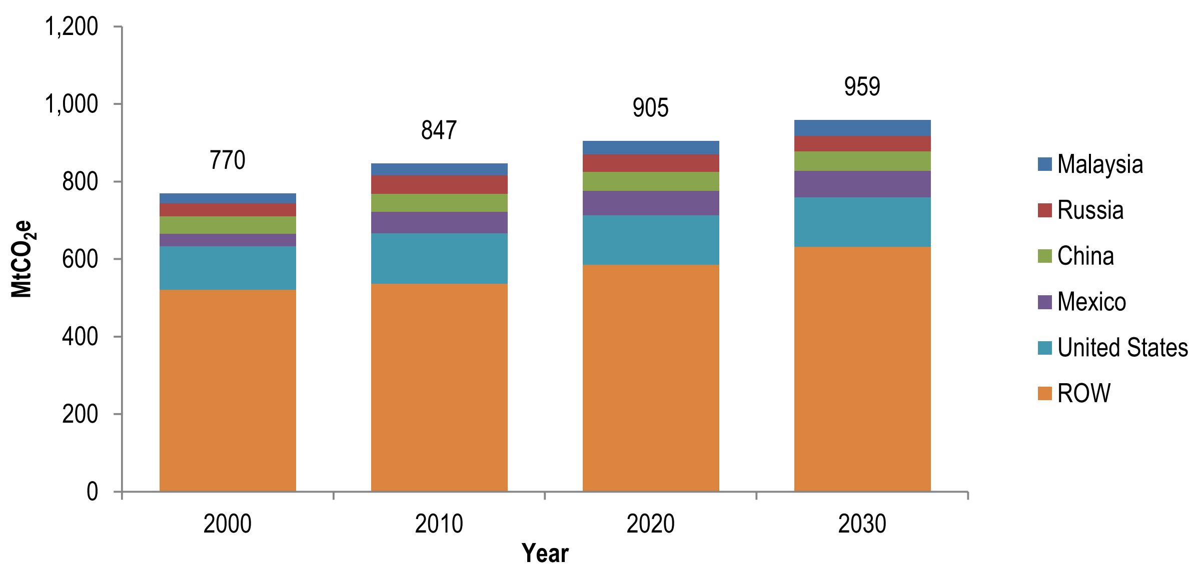
III.1. Landfill Sector

III.1.1 Sector Summary

Landfills produce methane (CH_4) in combination with other landfill gases (LFGs) through the natural process of bacterial decomposition of organic waste under anaerobic conditions. LFG is generated over a period of several decades, with gas flows usually beginning 1 to 2 years after the waste is put in place. CH_4 makes up approximately 50% of LFG. The remaining 50% is carbon dioxide (CO_2) mixed with small quantities of other gases, including volatile organic compounds (VOCs). The amount of CH_4 generated by landfills per country is determined by a number of factors that include population size, the quantity of waste disposed of per capita, composition of the waste disposed of, and the waste management practices applied at the landfill. Changes in these key factors drive projected trends in CH_4 emissions. For a number of countries, LFG is one of the largest anthropogenic sources of CH_4 emissions. Despite efforts to control large landfill emissions, the landfill sector remains a significant source of CH_4 emissions because of increasing waste streams in developed countries. In developing countries, the shift toward sanitary landfills and increased use of abatement measures is a key driver toward CH_4 mitigation.

In 2010, global CH_4 emissions from landfills accounted for approximately 850 $MtCO_2e$. Emissions from landfills are moderately concentrated in several countries. Over 50% of emissions in 2010 come from just ten countries. Figure 1-1 displays the business-as-usual (BAU) emissions for the landfill sector and identifies the top five emitting countries. Landfill emissions are projected to grow 13% between 2010 and 2030. In 2030, emissions from landfills represent 10% of the global total CH_4 from all sources.

Figure 1-1: Emissions Projections for the Landfill Sector: 2000–2030

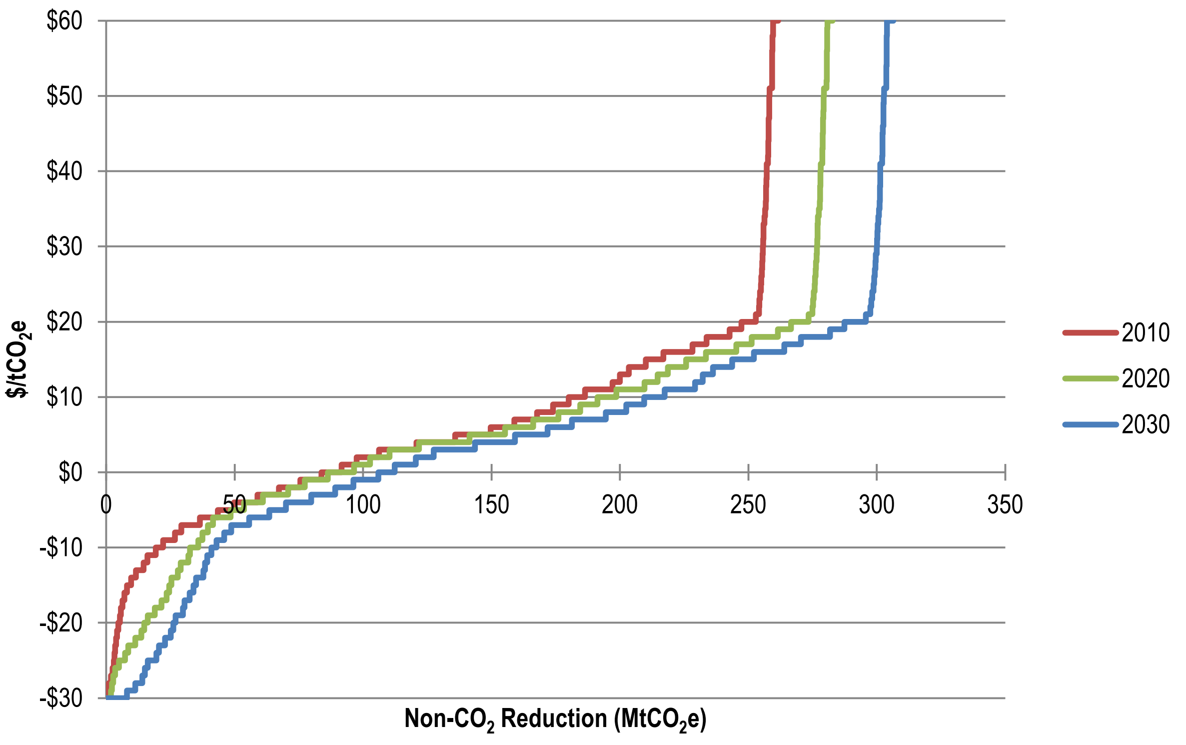


Source: U.S. Environmental Protection Agency (USEPA), 2012

Several abatement measures are available to control landfill CH_4 emissions and they are commonly grouped into three major categories: (1) collection and flaring, (2) LFG utilization systems (LFG capture for energy use), and (3) enhanced waste diversion practices (e.g., recycling and reuse programs). Although flaring is currently the most common abatement measure, energy recovery options may be more cost-effective. Similarly, under favorable market conditions, recycling and reuse or composting alternatives may provide additional means for reducing emissions from landfills. Note that options may not be mutually exclusive in that recycling can reduce the quantity of methane generated, which, in turn, will affect the economics of utilization systems.

Global abatement potential in the solid waste landfill sector is estimated to be approximately 589 $MtCO_2e$ of total annual emissions in 2030, or 61% of the baseline emissions. The marginal abatement cost (MAC) curve results are presented below in Figure 1-2. These curves suggest that there are significant opportunities for CH_4 reductions in the landfill sector at carbon prices below $20. Furthermore there are approximately 70 to 80 $MtCO_2e$ of reductions that are cost-effective (no regret options) at current energy prices.

Figure 1-2: Global Abatement Potential in Landfill Sector: 2010, 2020, and 2030



The following section briefly explains CH_4 emissions from landfills. This is followed by the international baseline CH_4 emissions projections from landfills. Subsequent sections characterize the abatement technologies and present the costs and potential benefits. The chapter concludes with a discussion of the MAC analysis and the regional results.

III.1.2 Methane Emissions from Landfills

This section discusses the characteristics of landfills and how these characteristics affect CH_4 emissions. In this section, we also describe historical and projected trends that influence baseline emissions from municipal solid waste (MSW) landfills. By volume, LFG is about half CH_4 and half CO_2. Typically, LFG also contains small amounts of nitrogen, oxygen, and hydrogen; less than 1% non-CH_4 volatile organic compounds (NMVOCs); and trace amounts of inorganic compounds. The amount and rate of CH_4 generation depend on the quantity and composition of the landfilled material, as well as the site design and resulting physical conditions inside the fill.

Organic waste is initially decomposed by aerobic bacteria after being landfilled. When the oxygen in the landfill cell (section of a landfill) is depleted, the remaining waste is broken down by anaerobic bacteria through decomposition. Fermentation creates gases and short-chain organic compounds that form the substrates, which provide for the growth of methanogenic bacteria, which in turn generates a biogas consisting of approximately 50% CO_2 and 49% CH_4, by volume. Measurable gas volumes are generally available between 1 or 2 years after the waste is landfilled and continue to be generated for 10 to 60 years.

The amount and rate of CH_4 production over time at a landfill depends on five key characteristics of the landfill material and surrounding environment:

- **Quantity of Organic Material:** The quantity of organic material, such as paper, food, and yard waste, is crucial to sustaining CH_4-producing microorganisms. The CH_4 production capacity of a landfill is directly proportional to its quantity of organic waste. CH_4 generation increases as the waste disposal site continues to receive waste and then gradually declines after the site stops receiving waste.
- **Nutrients:** CH_4-generating bacteria need nitrogen, phosphorus, sulfur, potassium, sodium, and calcium for cell growth. These nutrients are derived primarily from the waste placed in the landfill.
- **Moisture Content:** The bacteria need water for cell growth and metabolic reactions to convert cellulose to CH_4. Landfills receive water from incoming waste, water produced by decomposition, surface water infiltration (precipitation), groundwater infiltration (in unlined landfills). In general, CH_4 generation occurs at slower rates in arid climates than in nonarid climates.
- **Temperature:** Warm temperatures in a landfill speed the growth of CH_4-producing bacteria. The temperature of waste in the landfill depends on landfill depth, the number of layers covering the landfill, and the regional climate.
- **pH:** CH_4 is produced in a neutral acidic environment (close to pH 7.0). The pH of most landfills is between 6.8 and 7.2. Above pH 8.0, CH_4 production is negligible.

The methodology for estimating CH_4 emissions from municipal solid waste landfills in this analysis is based on the first order decay model (Intergovernmental Panel on Climate Change [IPCC], 2006).

The key characteristics described above can vary considerably across the different types and features of the waste disposal site, and this, in turn, influences landfill CH_4 generation. This analysis considers abatement measures' impacts on three model facilities representing the solid waste management alternatives with different levels of methane generating capacity. The following are the model facilities considered:

Open dump sites: defined as solid waste disposal facilities where the waste is left uncompacted and without cover. The waste in open dump sites is relatively shallow, therefore promoting aerobic biodegradation. This model facility is particularly relevant to developing countries where solid waste management practices are not well established. These facilities generate relatively small amounts of methane and for this, and safety reasons, have more limited applicability of mitigation technologies, which are less effectiveness where applicable.

Basic landfills (also referred to as managed dump sites): defined as solid waste disposal facilities where the waste is compacted and covered but do not have additional engineered systems. These facilities generate methane and in some cases can be modified to support an oxidation system and/or a gas collection and flaring or energy recovery system. However, the collection efficiency[1] may not be as efficient with a capture efficiency of approximately 75%. These facilities represent the baseline in most developing countries.

Engineered sanitary landfills: defined as facilities that include not only waste compaction and cover but they also are designed and constructed with gas and leachate collection systems. The higher degree of engineering at these facilities generally allows for more efficient gas collection and control than basic sanitary landfills. Engineered landfills typically have a collection efficiency of around 85%. These facilities represent the majority of baseline emissions in major industrialized countries.

III.1.2.1 Activity Data or Important Sectoral or Regional Trends and Related Assumptions

This section discusses the historical and projected activity factor data that determine CH_4 generation at solid waste disposal sites and policies set to improve waste management practices. Historical and projected changes in population and household income are used as indicators of changes in the quantity and type of consumption, which are directly linked to the quantity and type of waste generated by countries.

For developing and emerging economies, the projected baseline emissions reflect assumptions about population growth, economic growth, and changes in waste management practices over time in (USEPA, 2012). Continued growth in population along with increased household income and improvements in waste management practices will result in the growth of both waste generated and waste disposed of in managed and engineered landfills.

For developed countries with stable or declining growth in population and income, consumption is assumed to result in only small increases in emissions over time. Developed countries are also assumed to increasingly engage in waste diversion practices (e.g., recycling and composting) that divert biodegradable waste from landfills, ultimately changing the composition of landfilled waste and lowering the annual methane generated over time.

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[1] Collection efficiency refers to the amount of methane generated in the landfill that is captured by the collection system. In contrast, the reduction efficiency refers to the share of collected methane that is destroyed. For example flare have a reduction efficiency of approximately 98%.

III.1.2.2 Emissions Estimates and Related Assumptions

This section briefly discusses the historical and projected emission trends globally and presents the baseline emissions used in the MAC analysis.[2]

Historical Emissions Estimates

Emissions from landfills were estimated to have grown by 13% between 1990 and 2010. Key factors that contribute to the growth in landfill emissions include population growth, growth in personal income, increased industrialization, and improvements in waste management practices (USEPA, 2012).

Projected Emissions Estimates

Worldwide CH_4 emissions from landfills are expected to increase at an average long run annual rate of 0.6% (USEPA, 2012). Although some of the largest economies in the world continue to emit significant quantities of CH_4, developing and emerging economies are projected to account for majority of growth in CH_4 emissions. Table 1-1 presents the projected baseline CH_4 emissions for the top five emitting countries and remaining country groups by world region.

Table 1-1: Projected Baseline Emissions for MSW Landfills by Country: 2010–2030 ($MtCO_2e$)

Country	2010	2015	2020	2025	2030	CAGR (2010–2030)
Top 5 Emitting Countries						
China	47.1	48.2	49.0	49.4	49.3	0.2%
Malaysia	29.9	32.5	35.1	37.8	40.3	1.5%
Mexico	56.4	59.5	62.5	65.2	67.7	0.9%
Russia	47.2	46.1	44.8	43.4	42.1	−0.6%
United States	129.7	128.4	127.7	128.0	128.0	−0.1%
Rest of Regions						
Africa	101.2	106.5	111.9	117.3	122.4	1.0%
Central & South America	71.4	74.2	76.8	79.1	81.1	0.6%
Middle East	67.3	72.3	77.1	81.7	86.1	1.2%
Europe	87.2	92.4	96.8	100.9	104.6	0.9%
Eurasia	55.8	58.6	61.5	64.3	66.8	0.9%
Asia	133.2	135.1	138.4	141.5	144.4	0.4%
North America	20.3	21.9	23.3	24.8	26.5	1.3%
World Total	**846.7**	**875.6**	**905.0**	**933.3**	**959.4**	**0.6%**

[a]CAGR = Compound Annual Growth Rate

Source: USEPA. 2012.

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[2] For more detail on baseline development and estimation methodology, we refer the reader to the USEPA's Global Emissions Projection Report available at: http://www.epa.gov/climatechange/economics/international.html.

The United States is the largest emitter of landfill CH_4, accounting for over twice the emissions of the second largest emitter, Mexico. Although emissions from the top 4 emitters observed in 2010 are projected to remain relatively constant, emissions from developing regions including Africa, non-Organisation for Economic Co-Operation and Development (OECD) Asia, and the Middle East are all projected to have annual grow rates of greater than 1%. This trend reflects higher population growth rates, changing consumption patterns, and improved waste management systems among developing nations.

III.1.3 Abatement Measures and Engineering Cost Analysis

This analysis considers two types of abatement measures: mitigation technologies and diversion alternatives (see Table 1-2). It is important to note the distinction between these two approaches to emission reductions. Mitigation technologies represent add-on technologies that can be applied to one or more landfill types (i.e., open dump, basic landfill, engineered landfill) intended to capture and destroy the CH_4 generated at the facility. Diverting organic waste from the landfill for alternative uses is the second approach to reduce the quantity of LFG generated at existing landfills. As noted previously, these measures are not mutually exclusive. By changing the composition of waste that is landfilled, diversion options lower the methane-generating potential of remaining waste that is landfilled. Diversion alternatives are covered in this analysis but are distinguished from landfill-based mitigation technologies.

This section discusses the abatement measures considered for this analysis. Each technology is briefly characterized followed by a discussion of abatement measures' implementation costs, potential benefits, and system design assumptions used in the MAC analysis.

Table 1-2: Summary of the Engineering and Cost Assumptions for Abatement Measures at Landfills

Abatement Option	Total Installed Capital Cost (millions 2010 USD)	Annual O&M Cost (millions 2010 USD)	Time Horizon (Years)	Reduction Efficiency (%)[a]
LFG Mitigation Options				
LFG collect and flaring system	1.7	0.3	15	85%
LFG for electricity generation				85%
Internal combustion engine	6.3	0.8	15	85%
Gas turbine (> 3 MW)	5.6	0.6	15	85%
Micro-turbine (< 1 MW)	4.1	0.1	15	85%
Combined heat and power production	7.9	0.8	15	85%
Direct gas use	2.6	0.5	15	85%
Enhanced oxidation systems	5.4	0.0	50	44%
Waste Diversion Options				
Composting	1.8	0.7	15	95%
Anaerobic digestion	16.9	1.7	20	95%
Mechanical biological treatment	15.4	1.8	20	95%
Paper recycling	34.9	8.9	20	95%
Waste to energy	165.7	8.0	20	100%

[a] Reduction efficiency reflects the abatement measures ability to mitigation/avoid methane generation. However this does not reflect the total mitigation potential.

III.1.3.1 Landfill CH_4 Mitigation Technologies

This section characterizes the mitigation technologies that can be applied to landfills to reduce CH_4 emissions. Mitigation options considered for this analysis include collection of LFG for flaring, collection for electricity production, collection for direct use, and enhanced oxidation systems.

LFG Collection and Flaring

Most basic landfills and engineered landfills have (or are applicable for) LFG collection systems for both public health and facility safety concerns to prevent high concentrations of LFG in the fill. These systems prevent the migration of CH_4 to on-site structures and adjacent property and prevent the release of non-CH_4 organic compounds (NMOCs) to the atmosphere. Wells and gathering lines may be constructed in advance or installed after waste has been landfilled. LFG collection usually begins after a portion of a landfill is closed. Collection systems are configured either as vertical wells (which are most common), horizontal trenches (which are primarily used for deeper landfills and landfill cells that are actively being filled), or a combination of the two. Trenches or wellheads are connected to lateral piping that transports the LFG to a collection header. Typically there is a collection system monitor installed to allow operators to adjust the gas flow (USEPA, 2010).

Flares ignite and burn LFG. Large landfills have historically collected CH_4 and flared the gas.[3] Flare designs include open and enclosed flares. Enclosed flares are more expensive but provide greater control of combustion conditions, allow for stack testing, reduce light and noise nuisances, and might have higher combustion efficiencies (USEPA, 2010).

- **Capital Cost:** Capital cost includes the construction of wells, wellheads, and laying of gathering lines that make up the collection system, as well as the flare system with monitoring and control systems. Costs were derived from the USEPA Landfill Methane Outreach Program (LMOP) Project Cost Estimation Model. The capital costs assume one well per acre installed at an average installation cost of $150/ft. Installation of the wellheads and gathering lines is approximately $17,000 per acre. Installed cost of the knockout blower and flare system is based on open flares with the maximum expected flow of LFG per minute ($963/maximum cubic feet per meter [cfm]).
- **Annual Operation and Maintenance (O&M) Cost:** Typical annual O&M costs for collection systems are $2,250 per well and $4,500 per flare. Electricity costs to operate the blower for a 600 cfm active gas collection system average $44,500 per year[4] (USEPA, 2010), assuming an electricity price of 7 cents/kWh and consumption rate of 0.002 kWh per ft^3.
- **Annual Benefits:** No economic benefits (energy production) are associated with this option.
- **Applicability:** This option applies to all basic landfills and engineered landfills.
- **Technical Efficiency:** This analysis assumes a collection efficiency of 75% for basic landfills and of 85% for engineered landfills and a flaring efficiency of 98%.
- **Technical Lifetime:** 15 years

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[3] Flares are typically a required component of energy recovery projects. In energy recovery projects, the flare system is used to control LFG emissions during energy generation startups and downtime and may also be used to control excess gas production.

[4] For this analysis we assume an electricity price of 7.5 cents/kWh and an energy consumption rate of 0.002 kWh/ft^3.

LFG Collection for Electricity Generation

Converting LFG to electricity offers a potentially cost-effective way to use the gas being generated by the landfill. Often, revenue from the sale of energy produced can provide a cash flow that more than offsets the implementation costs of this option. This option requires a LFG collection and flare system as described earlier in this section, as well as the electricity generation system. Components of the electricity generation system include the equipment for generating energy (e.g., internal combustion engine, gas turbine, or microturbine) and the interconnections for transmitting electricity produced to the energy grid.

LFG is extracted from landfills using a series of vertical or horizontal wells and a blower (or vacuum) system. This system directs the collected gas to a central point, where it can be processed and treated depending on the ultimate use of the gas. LFG treatment removes moisture and other contaminants (e.g., siloxanes) that may disrupt the energy generation equipment (USEPA, 2010). Treatment requirements depend on the end-use application.

This analysis considers four alternative technologies under this abatement measure that include internal combustion engine, gas turbine, micro-turbine, and combined heat and power (CHP) approach. Table 1-3 summarizes the typical costs for the alternative electricity-generating technologies.

- **Capital Cost:** Capital cost includes the costs of the collection and flare system discussed and the treatment system, energy generation equipment, and interconnection equipment for selling electricity to the power grid. Costs were derived from the USEPA LMOP Project Cost Estimation Model, which is available at USEPA's LMOP web page. Costs ranged from $1,400 to $5,500 per Kwh (see Table 1-3).
- **Annual O&M Cost:** Typical annual O&M costs for energy generation systems are between $130 and $380 per kilowatt of capacity.
- **Annual Benefits:** Annual revenues are derived from the sale of electricity.
- **Applicability:** This option applies to all basic landfills and engineered landfills.
- **Technical Efficiency:** This analysis assumes a collection efficiency of 75% for basic landfills and 85% for engineered landfills and combustion efficiency of 98%.
- **Technical Lifetime:** 15 years

Table 1-3: Electricity Generation Technology Costs

Technology	Capital Cost (2010 $/kW)	Annual O&M Costs (2010 $/kW)
Internal combustion engine (> 0.8 MW)	$1,700	$180
Small IC engine (< 1 MW)	$2,300	$210
Gas turbine (> 3 MW)	$1,400	$130
Microturbine (< 1 MW)	$5,500	$380
CHP with IC engine (< 1 MW)	$2,300	$210

Source: USEPA 2010. U.S. Environmental Protection Agency (USEPA). September 2010. *Project Development Handbook*. Chapter 3. Project Technology Options. Landfill Methane Outreach Program. Obtained from: http://www.epa.gov/lmop/publications-tools/#one.

Note: Costs include the cost of the basic treatment system typically required with each type of technology.

LFG Collection for Direct Use

Direct use provides an alternative use of LFG with minimal treatment. Under this option, LFG collected at the landfill is pumped to a nearby (< 5 miles) end user. The gas delivered can serve as a medium-BTU fuel for boiler or drying operations, kiln operations, and cement and asphalt production.[5] Although little condensate removal and filtration is needed, combustion equipment might need slight modifications to run with LFG (USEPA, 2010). However these modification costs are not considered part of the technology costs.

There is no cost-effective way to store LFG, so ideally the LFG consumer has a steady annual gas demand compatible with the landfill's gas flow. If a landfill does not have adequate flow, the LFG can be used to power only a portion of the machinery or mixed with other fuels. The cost for a gas compression and treatment system includes compression, moisture removal, and filtration equipment necessary for transporting and using the gas.

- **Capital Cost:**[6] The capital costs for direct use include the equipment and installation cost of a skid-mounted filter, compressor, and dehydrator, and the cost to construct a gas pipeline to carry the gas to a nearby (< 5 miles) end user(s). Filter, compressor, and dehydrator costs are scaled to the project's expected minimum LFG flow and equal to approximately $300 per cfm. Pipeline construction costs are assumed to be $320,000 per mile.
- **Annual Cost:** Annual O&M costs include the cost of electricity and maintenance of the filters, compressors, and dehydrators. The electricity costs are calculated by multiplying electricity price times the energy required to power the equipment and transmit gas to end users, assuming a system power demand of 0.002 kWh/ft^3. Non energy-related O&M costs are scaled to LFG project volumes assuming a cost of $0.0014/ft^3.
- **Benefits:** Annual revenue accrues to the project through the sale of LFG to an end user at an assumed price that is 80% of the current natural gas price; the discounted price reflects the lower BTU content of the gas. There may also be local or national policies such as tax incentives, loans, and grants available to landfill operators to incentivize LFG utilization.
- **Applicability:** This option is available to all basic landfills and engineered landfills.
- **Technical Efficiency:** This analysis assumes a collection efficiency of 75% for basic landfills and 85% for engineered landfills and an end-use combustion efficiency of 98%.
- **Technical Lifetime:** 15 years

Enhanced Oxidation Systems

Enhanced oxidation systems are considered mitigation technologies that exploit the propensity of some naturally occurring bacteria to oxidize CH_4.[7] By providing optimum conditions for microbial

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[5] Other direct use applications include use in infrared heaters, greenhouses, artisan studios, leachate evaporation, and biofuel production.

[6] It is important to note that direct use of LFG may require equipment modifications at the end-user site to handle the lower BTU content of LFG or additional treatment systems to improve the energy content; these costs are not considered part of this abatement measure's project costs. Including these costs would increase project costs by more than $200,000 (USEPA, 2010).

[7] Oxidation of methane entails mixing the gas (CH_4) with oxygen (O_2) and converting the CH_4 to CO_2 and water (H_2O).

habitation and efficiently routing landfill gases to where they are cultivated, a number of bio-based systems, such as temporary or long-term biocovers, passively or actively vented biofilters, and biowindows, have been developed that can alone, or with gas collection, mitigate landfill CH_4 emissions. The previous non-CO_2 mitigation report (USEPA, 2006) evaluated the use of a biocover consisting of a clay cap topped by a soil cover.

- **Capital Cost:** Capital costs are the incremental costs of enhanced oxidation systems above the traditional clay/soil cover. These costs assume an incremental cost of $6 million for 100 acres of cover. The cost of designing and constructing the biocover assumes $3/yd^3 for earth moving, a compost price of $5/tonne,[8] and an average cover depth of 3 feet.
- **Annual O&M Cost:** The O&M cost is assumed to be less than 0.1% of installed capital costs.
- **Annual Benefits:** No revenues are associated with this option.
- **Applicability:** This option applies to basic landfills and engineered landfills.
- **Technical Efficiency:** This option analysis assumes a reduction efficiency of 44% of the remaining 15% of methane not collected by LFG collection system (Weitz, 2011).
- **Technical Lifetime:** 50 years

III.1.3.2 Diversion Alternatives

Diversion alternatives redirect biodegradable components of the waste stream from the landfill for reuse through recycling or conversion to a value-add product (e.g. energy or compost). Diverting organic waste components such as yard waste, paper, and food waste lowers the amount of methane generated at the landfill. These measures derive benefits through the sale of recyclables (both organic and non-organic), electricity, and cost savings in avoided tipping fees. Although these options were considered in the previous mitigation report (USEPA, 2006), all diversion options were not included in the final mitigation estimates reported. The following diversion alternatives were considered for this analysis:

- composting
- anaerobic digestion (AD) for electricity production from gas
- mechanical biological treatment (MBT)
- paper recycling
- waste to energy

Composting

Composting consists of the aerobic digestion of the fermentable organic fraction of MSW to produce a reusable product. In the presence of oxygen, microorganisms decompose the biodegradable organic matter to form compost, which contains nutrients and trace elements, and is used in agriculture as soil conditioner. The composting process emits a gas basically formed by CO_2 and H_2O, while traces of (VOCs are also present. This analysis considers three types of composting processes—windrow composting, aerated static pile (ASP) composting, and in-vessel composting—but cost and emissions data were only obtained for windrow composting because it is the most common type.

Windrow composting processes occur in the open, usually in long rows of triangular cross-sections, these being turned periodically to introduce air into the process. The material received by the composters is processed, formed into a windrow, turned (using portable diesel-powered equipment), and screened

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[8] The compost price assumes a weight by volume of 0.32 tonnes/yd^3 (DST Model Documentation).

prior to sale. A typical facility will accept both green material and wood waste from residential curbside programs and an increasing number of composting facilities are beginning to accept food scraps from residential curbside programs, as well as from dedicated commercial routes or large generators. Windrow composting processes may have CH_4 emissions from anaerobic decomposition and nitrous oxides (N_2O) emissions from NO_x denitrification during the latest composting stages. The IPCC (2006) provides representative CH_4 emissions of 4 to 10 g/Kg of waste (dry weight) and N_2O emissions of 0.3 to 0.6 g/kg waste (dry weight).

- **Capital Costs**: Capital cost includes the purchase of land and equipment, site preparation and facility construction equal to $1.8 million (2010 USD). Capital costs were obtained from the composting process model documentation of the Municipal Solid Waste Decision Support Tool (MSW DST) (MSW DST Documentation), which presents this cost for 100 tons/day facilities producing marketable high-quality compost products as opposed to nonmarketable, low-quality compost product (e.g., used as landfill cover).
- **Annual Cost:** The O&M cost of the windrow composting facility includes the labor, overhead, fuel, electricity, and equipment maintenance costs.[9] This analysis assumes an O&M cost of $19/tonne-yr (obtained from the composting process model documentation of the MSW DST (MSW DST Documentation).
- **Annual Benefits:** Revenue from compost is from sales and cost savings from avoided landfilling. The composting process is not perfectly efficient, and this analysis assumes that 80% of the incoming organic waste is converted to marketable compost product. A compost price of $5/tonne[10] was used to estimate the revenue from compost sales. A tipping fee of $29/tonne is used to estimate the costs savings of avoided landfilling.
- **Applicability:** This option applies to yard and food components of the waste stream.
- **Technical Efficiency:** This analysis assumes reduction efficiency of 95%, which represents the avoided methane potential.
- **Technical Lifetime:** 15 years

Anaerobic Digestion (AD)

AD is a complex biological process that uses anaerobic microorganisms to hydrolyze complex organics to simple monomers and hence to volatile fatty acids; the volatile fatty acids are converted to CH_4 and CO_2 in the biogasification step. The biogas can be recovered and used to generate energy. Existing AD facilities are most commonly located at wastewater treatment plants, but the process is equally applicable for solid waste. A few of these facilities supplement their operations with other types of organic waste.

Solid waste AD facilities come in different shapes and sizes. Most digesters have vertical tanks, but some are horizontal. AD mechanisms vary considerably, and a number of patented processes exist. Processes may operate at high or low solids content, operate at mesophilic or thermophilic temperatures, be one- or two-stage systems, and be continuous or batch processes. The process could also differ

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[9] This analysis assumes that no precomposting screening will take place. Therefore, there will not be organics rejects from the process needing disposal at a landfill facility, which is consistent with the data provided for high quality compost production in the composting process model documentation of the MSW DST (MSW DST Documentation).

[10] Represents the lower end price $15 to 34/yard^3 assuming a 0.35 tonne/yard^3. Prices reported in Recycle.cc's December 2011 newsletter. Obtained at: http://www.recycle.cc/compostprices.pdf

according to the type of product produced, so some processes only produce electricity, others produce combined electricity and heat, and some produce gas upgraded for use as vehicle fuel. This analysis considers AD that produces electricity using a gas engine, which is the most common product. A small amount of CH_4 may be released as fugitive emissions during the digestion process. This analysis assumes CH_4 emissions of 1 to 2 g/kg of waste (dry weight) as reported in IPCC (2006).

- **Capital Costs**: The plant's capital cost includes the cost of land, the digestors, the gas engine, and air pollution control and monitoring devices. The capital cost for this analysis is $472/design tonne was considered in this analysis and obtained from Eunomia (2008), which describes this cost for facilities of 20,000 to 30,000 tonnes/yr in the United Kingdom (UK).
- **Annual Cost:** The O&M cost of the AD facility includes the labor, overhead, fuel, electricity, and maintenance cost. An O&M cost of \$55/tonne yr^{-1} (reported as £35 GBP/tonne) was considered in this analysis and obtained from Eunomia (2008), which presents costs typical of UK facilities. This analysis assumes that no predigestion screening will take place and that the digested solids are not commercialized. Therefore, there will be no organics rejects from the process needing disposal at a landfill facility.
- **Annual Benefits:** Revenue from the sale of electricity generated with the biogas is sold to an end user. The biogas recovery from the digestion process is not perfectly efficient and assumed to be 75% of total value, and the biogas composition is assumed 60/40% CH_4/CO_2 according to Eunomia (2008). Similarly, the efficiency of the biogas conversion to electricity in the gas engine is assumed to be 37% as reported by Eunomia (2008). The electricity produced per tonne of waste can be then estimated according to the CH_4 yield (2,781 ft^3 CH_4/wet ton) of the incoming waste. The market price of electricity is used to estimate the revenues.
- **Applicability:** This option assumes removal of wood, paper, and food waste.
- **Technical Efficiency:** This analysis assumes a capture efficiency of 75% and a reduction efficiency of 95%.
- **Technical Lifetime:** 20 years

Mechanical Biological Treatment (MBT)

MBT can be defined as the processing or conversion of solid waste with biologically degradable components via a combination of mechanical and other physical processes (for example, cutting or crushing, sorting) with biological processes (aerobic composting, anaerobic digestion). The primary objective is to reduce the mass and the volume of the waste. A secondary objective is a lower environmental impact of the waste after its deposition (i.e., low emissions of landfill gas, small amounts of leachate, and a reduced settlement of the landfill body). Furthermore, MBT includes the separation of useful waste components for industrial reuse, such as metals, plastics, and refuse-derived fuel (RDF).

There are three main types of biological treatment processes: (1) an aerobic stabilization system in which the stabilized output is assumed to be sent to a landfill or used for land remediation/recovery projects, (2) an aerobic biodrying system producing an RDF with the reject stream sent to a landfill (after undergoing an aerobic stabilization process), and (3) systems combining aerobic and anaerobic treatments in which the anaerobic process is used to produce biogas, followed by an aerobic process that produces a stabilized output that can be sent to a landfill. Because of the similarities that can be found between Option (1) and composting, and Option (3) and AD, this analysis focuses on Option (2) in which the RDF is destined for energy generation.

To produce RDF, both windrow and box systems are applied. In box systems, the waste is treated aerobically for only 1 week but with high aeration rates. The result is a dried material with a slightly reduced organic content. Only the most easily degradable compounds are metabolized so that the loss of caloric value is low. The dry material can be fractionated very easily, because adhesive substances were eliminated in the bio-process. Iron and nonferrous metals, as well as glass and minerals, are separated for material recovery. The remaining material has a calorific value of 15 to 18 MJ/kg, mainly due to the high content of plastics, wood, and paper. It can be used as a substitute for fossil fuels in power stations and cement kilns and in the production of process gases. Similar to the composting process, there is a small level of fugitive CH_4 emissions that accompany the aerobic degradation process as well as some N_2O emissions from NO_x denitrification during the curing stages of the stabilization process. Representative CH_4 emissions of 0.01 kg/tonne of waste and N_2O emissions of 0.02 kg/tonne of waste were obtained from Eunomia (2008).

- **Capital Costs**: The plant's capital cost includes the cost of land, facility, equipment, and air pollution control and monitoring devices. The analysis assumes a capital cost of $15 million based on reported facility costs of $244/design tonne (reported as £150 British pounds/tonne) was used for this analysis and obtained from Eunomia (2008). Costs are reported for a 60,000 tonne/yr facility in the UK.
- **Annual O&M Costs:** The O&M cost of the MBT facility is $2 million in 2010. This cost includes the labor, overhead, taxes, administration, insurance, indirect costs, energy, and maintenance costs. It does not include residues disposal. A 2007 annual O&M cost of $22/tonne (reported as £13 British pounds/tonne) was considered in this analysis and obtained from Eunomia (2008), which presents costs typical of UK facilities.
- **Annual Benefits:** Annual revenues from the sale of RDF and recyclables that are produced from the MBT process are sold to an end user (i.e., cement kilns or coal-fired utility). According to Eunomia (2008), RDF is produced at a typical rate of 0.48 tonne/tonne of waste. Eunomia (2008) also reports that 1 tonne of RDF can be assumed to replace 0.90 tonne of coal used to fuel a cement kiln and 0.38 tonne of coal for power generation. The market coal price of $40/tonne is used to estimate the revenues. Similarly, Eunomia (2008) reports an 80% recovery rate for ferrous metals, 70% recovery rate for nonferrous metals, and 70% recovery rate for glass. Sale prices of $352/tonne for ferrous metals (USGS, 2012), $1,881/tonne[11] for nonferrous metals, and $25/tonne for glass were used to estimate the revenues from recyclables sale.
- **Applicability:** This option applies to all landfill types
- **Technical Efficiency:** This analysis assumes a reduction efficiency of 95%.
- **Technical Lifetime:** 20 years

Paper Recycling

Recycling typically consists of two major processes: the separation process at a material recovery facility (MRF) and the remanufacturing process where recyclables are used to produce new products. For consistency with other mitigation option included in this report, the costing component of this analysis only considers the separation process. The different types of MRFs vary according to the type of waste they receive and the destination of the recyclables (e.g., mixed waste MRF, commingled recyclables MRF, presorted recyclables MRF, co-collection MRFs, and front-end MRFs to other waste diversion alternatives such as composting). Because it is the most common, this analysis considers a mixed waste MRF.

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[11] Price obtained from MetalPrices.com at http://www.metalprices.com/FreeSite/metals/al_scrap/al_scrap.asp#Tables.

Under the mixed waste MRF design, mixed waste is typically collected at curbside and dumped on a tipping floor at the MRF. It is then loaded onto a conveyer by using a front-end loader or Bobcat. This conveyer feeds a bag opening station because most waste is collected in bags. Undesirable items in the waste (e.g., white goods, bulky items) are removed from the mixed waste before and after the bag opening point in the MRF. Bags can be opened either manually or mechanically, and this analysis considers mechanical bag opening. Loose waste from the bag opening operation is then conveyed into an elevated and enclosed sorting room where the recyclables are recovered. Newsprint, old corrugated cardboard, and other paper can be picked from the mixed waste as individual components. Because other paper components are present in small quantities and are likely to be wet and contaminated, they can only be recovered as mixed paper. Metal cans remain in the refuse on the conveyer at the end of the sort room. Separation of aluminum cans can be manual or automated, and this analysis assumes manual separation. Ferrous metal is assumed to be recovered by a magnet.

Apart from power consumption, no residual greenhouse gas (GHG) emissions are assumed, and the MRF facility costs are divided into three components: capital cost, O&M cost, and revenue from recyclables sale.

- **Capital Costs**. The capital cost for this option is $35 million in (2010 USD). The capital cost consists of construction, engineering, and equipment costs. It assumes a handling capacity of 100,000 tonnes of waste per year. This analysis relies on a $297/tonne of annual capacity (2006 prices), which is an average of reported capital costs from CalRecycle (2009) for similar sized facilities.
- **O&M Cost**. The O&M cost of the MRF facility includes wages, overhead, equipment and building maintenance, and utilities. An O&M cost of $66/tonne of annual waste capacity before residue disposal, based on reported operating costs used in CalRecycle (2009) report. The cost of disposal of the MRF rejects can be estimated assuming an MRF separation efficiency of 55% of the incoming organic waste and that the rejects are sent to a regular landfill with a tipping fee of $29/tonne, which represents a U.S. national average tipping fee obtained from *Municipal Solid Waste Facility Directory* (Chartwell, 2004).
- **Annual Benefits:** Annual benefits come from the sale of recyclables and decreased waste. The recyclables that are separated at the MRF are sold to an end user (e.g., a remanufacturing facility) sometimes through brokers. The 55% separation efficiency and recyclables sale prices were used to estimate the revenues from recyclables sale. The following prices were used in the analysis: mixed paper[12]—$140/tonne; scrap metals[13]—$1,307/tonne; and scrap glass—$25/tonne. Tonnage sold for reuse avoids landfilling costs. Annual cost savings are equal to tonnage sold for reuse times the tipping fee of $29/tonne.
- **Applicability:** This option applies to the entire waste stream.
- **Technical Efficiency:** This analysis assumes a reduction efficiency of 95% of potential methane.
- **Technical Lifetime:** 20 years

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[12] Prices were obtained from: http://www.recycle.cc/freepapr.htm.

[13] Assumes a weighted average price of aluminum can scrap and ferrous metal scrap prices. The aluminum can scrap price was obtained from http://www.metalprices.com/. The ferrous metal price was obtained from 2012 USGS *Mineral Commodities Summary: Iron & Steel Scrap* at: http://minerals.usgs.gov/minerals/pubs/commodity/iron_&_steel_scrap/.

Waste-to-Energy (WTE)

WTE is a combustion process; thus, its main emissions include CO_2, CO, NO_x, and non-CH_4 volatile organic compounds (NMVOCs). Municipal waste is incinerated to reduce its volume to save landfill costs and recover energy from its combustion either for heating and/or electricity generation. The two most widely used and technically proven incineration technologies are mass-burn incineration and modular incineration. Fluidized-bed incineration has been employed to a lesser extent, although its use has been expanding and experience with this relatively new technology has increased. RDF production and incineration have also been used, primarily in Europe, but the number of successful cases is limited. This analysis considers WTE using mass-burn incineration and electricity recovery, which is the most common WTE design. Representative CH_4 emissions of 0.2 to 60 kg/Gg of waste (wet weight) and N_2O emissions of 41 to 56 g/ton of waste (wet weight) were obtained from IPCC (2006). WTE facility costs are divided into three components: capital cost, O&M cost, and revenue from electricity generation.

- **Capital Costs**. The plant's capital cost of $165 million includes the facility design engineering and construction. Capital equipment includes the cost of land, incinerators, ash handling system, turbine, and air pollution control and monitoring devices. Costs assume $829/tonne of design capacity. This cost was derived from Eunomia (2008), which describes this cost for a 200,000 tonne/yr facility in the UK.
- **O&M Cost**. The annual O&M cost of the WTE facility is $8 million, approximately 4% of installed capital costs. Annual costs include labor, overhead, taxes, administration, insurance, indirect costs, auxiliary fuel cost, electricity cost, and maintenance cost. It does not include the cost for disposing of the combustion residue and spray dryer residue. Cost is based on annual O&M cost of $41/tonne/yr. Annual avoided landfilling is also included as a cost savings. The cost of disposal of the fly and bottom ash from the incineration process assumes an estimated 15% of the incoming organic waste will be converted to ash (MSW DST Documentation). No reuse of the bottom ash (e.g., in construction projects) is assumed and the bottom and fly ash will be mixed and sent to a landfill. Both the avoided landfilling costs and residual waste landfilling costs assume a tipping fee of $29/tonne.
- **Annual Benefits:** Annual revenue from electricity sales. Electricity that is generated by recovering heat from combusting waste is sold to an end user. The recovery of the heat is not perfectly efficient. This inefficiency is represented by the heat rate of the plant, reported as 18,000 (BTU/kWh) in the WTE process model documentation of the MSW DST (MSW DST Documentation). The electricity produced per tonne of waste can then be estimated according to the heat value of the waste incinerated (4,750 BTU/tonne of waste). The market price of electricity is used to estimate the revenues.
- **Applicability:** This option applies to entire waste stream.
- **Technical Efficiency:** This analysis assumes reduction efficiency of 100%.
- **Technical Lifetime:** 20 years

III.1.4 Marginal Abatement Costs Analysis

The MAC analysis assimilates the abatement measures' technology costs, expected benefits, and emission reductions presented in above to compute the net cost/benefit of abatement for each project. Similar to the approach used in other non-CO_2 sectors of this report, we compute a break-even price for each abatement project (abatement measure by facility type). Project break-even prices are then weighted by emission abatement potential to construct MAC curves illustrate the technical, net GHG mitigation potential at specific break-even prices for 2010 to 2030. MAC curves are produced for 195 countries using country specific parameters, such as wage rates and energy prices.

This section describes the general modeling approach applied in the landfill sector as well as the approach used to define the international facility populations and the assessment of sectoral trends. These factors serve as additional inputs to the MAC analysis that adjust the abatement project costs, benefits, and the technical abatement potential in each country.

III.1.4.1 Methodological Approach

The overarching modeling framework applied in the landfill sector is captured in two basic steps. The first is to calculate the break-even price for each mitigation measure for each facility type by country. The second is to determine the country-level abatement potential.

The break-even price, as defined in the technical summary to this report, estimates the costs and expected benefits of each technology based on the characteristics of the model facility and relative international prices (equipment, labor, and energy).

Country abatement potential reflects the number of abatement measures available and technical effectiveness of each option. Figure 1-3 illustrates the conceptual modeling for estimating the abatement potential in the landfill sector.

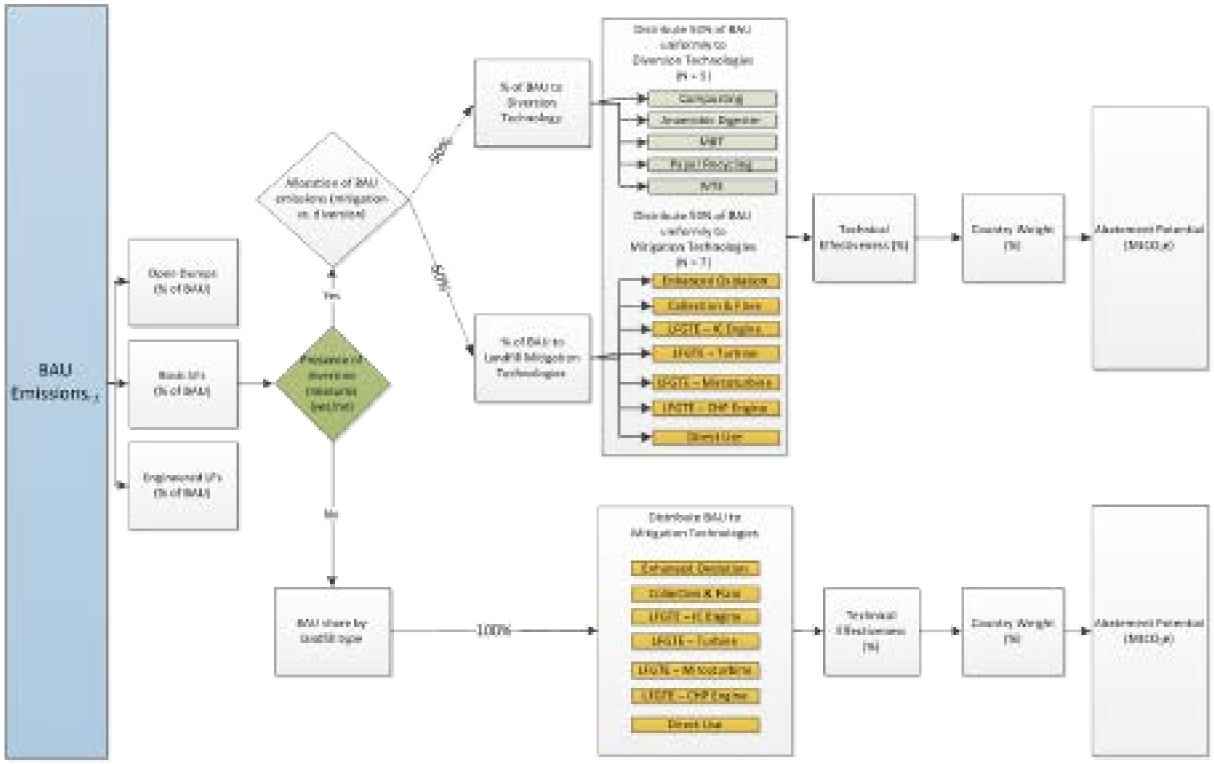
The MAC model uses a three-step approach to allocating a fraction of the BAU emissions to each facility and technology considered. The model starts by splitting the BAU emissions out to our three landfill types (open dump, basic landfill, engineered landfill). Next the model uniformly distributes BAU emissions by the number of abatement measures considered. Finally, the model estimates abatement potential by multiplying the BAU emissions (indexed by facility type and technology) by each technology's technical effectiveness. Summing over all abatement measures and facility type indicates this product yields a country's abatement potential.

It is important to note that depending on the scenario considered in the model, diversion options may or may not be included. As shown in Figure 1-3, if diversion options are considered, BAU emissions (indexed by facility type) are uniformly distributed by the total number of technologies (N = 12). If diversion options are omitted, BAU emissions are distributed by the number of landfill-based mitigation technologies (N = 7).

Assessment of Sectoral Trends

Underlying the general modeling approach, the MAC analysis also incorporated additional international considerations to capture shifts in the share of BAU emissions allocated to the three model landfill types defined earlier in Section III.1.2 (i.e., open dump, basic landfill, and engineered landfill). Table 1-4 presents the facility share of BAU emissions over time. In the United States and the EU, we assumed advanced waste management practices were already in place. Reflecting this assumption, we assumed zero emissions coming from open dumps in these countries and assumed all emissions come from basic and engineered landfills. Given the existing level of infrastructure in place there is very little change in the assumed distribution over the 20-year modeling horizon.

Figure 1-3: Conceptual Model for Estimating Mitigation Potential in the MSW Landfill Sector



For emerging economies and developing countries the analysis assumes a greater share of emissions is represented by open dumps in 2010. Over the next 20 years, this distribution is projected to shift away from open dumps as countries begin to adopt advanced waste management practices with greater shares of total waste going to basic sanitary and engineered landfills. These shares were developed using expert judgment after reviewing existing literature on waste disposal trends and abatement opportunities provided through various studies by the World Bank, USEPA's LMOP program, and the Global Methane Imitative (GMI).

Define Model Facilities for the Analysis

Seeking to improve the specificity of the break-even prices calculated for each country, this analysis developed an international population of model facilities. This step of the analysis consisted of defining the characteristics of the model facilities specific to countries and regions. The characteristics of interest included the

- average annual waste acceptance rates by facility type,
- average waste depth by facility,
- decay constant (k) based on climate and moisture content in waste landfilled, and
- potential CH_4 generation capacity (L_0) of the typical waste managed in a given model facility.

Table 1-4: Model Facilities Share of BAU Emissions: 2010–2030

Country/Region	2010 Dump Sites	2010 Basic LF	2010 Engineered LF	2020 Dump Sites	2020 Basic LF	2020 Engineered LF	2030 Dump Sites	2030 Basic LF	2030 Engineered LF
China	20%	60%	20%	10%	60%	30%	10%	50%	40%
Brazil	10%	60%	30%	10%	50%	40%	0%	50%	50%
Mexico	10%	60%	30%	10%	50%	40%	0%	50%	50%
Russia	20%	40%	40%	20%	40%	40%	10%	40%	50%
Ukraine	20%	40%	40%	20%	40%	40%	10%	40%	50%
Australia	10%	30%	60%	10%	30%	60%	0%	30%	70%
Canada	10%	30%	60%	10%	30%	60%	0%	30%	70%
Japan	10%	30%	60%	0%	30%	70%	0%	20%	80%
Turkey	20%	40%	40%	20%	40%	40%	10%	40%	50%
United States	0%	20%	80%	0%	20%	80%	0%	10%	90%
India	20%	60%	20%	10%	60%	30%	10%	50%	40%
South Korea	10%	30%	60%	0%	30%	70%	0%	20%	80%
EU-27	0%	20%	80%	0%	20%	80%	0%	10%	90%
Africa	40%	40%	20%	30%	40%	30%	20%	40%	40%
Central & South America	10%	60%	30%	10%	50%	40%	0%	70%	30%
Middle East	20%	60%	20%	10%	60%	30%	10%	60%	30%
Eurasia	20%	60%	20%	10%	60%	30%	10%	60%	30%
Asia	20%	60%	20%	10%	60%	30%	10%	60%	30%

Source: Based on expert judgment in consultation with World Bank (2010) and USEPA (2009, 2011).

Various data sources were consulted to define the characteristics of the model facilities in the different countries and regions, and a proxy country approach was used when data were not found for a given country. Under this approach, countries for which no data were available were paired with a representative proxy country based on similarities in socioeconomic and technology development trends that are closely correlated with a country's waste composition. Furthermore, waste composition is the only parameter that affects both L_0 (CH_4 generation rate) and k constant (decay rate), two key factors used to estimate gas generation from the model facilities.

To ensure project costs and benefits were comparable, we assumed annual waste acceptance rates (WAR) were fixed at 100,000 tonnes/yr, and the average depth of waste was assumed to be between 25 and 50 feet. Open dumps have shallower waste depths sprawling over large areas. In contrast, basic and engineered landfills concentrate the disposed waste over a smaller area and at increased depths of between 40 and 50 feet. Facility methane recovery (also referred to as capture efficiency), also varies by landfill type and range from 10% for open dumps to 85% for engineered landfills. Table 1-5 summarizes the standardized model facility assumptions.

Table 1-5: Model Facility Assumptions for International LFG Mitigation Options

Facility Type	No. Years Open	Annual WAR (tonnes/yr)	Project Design Acreage	Waste Depth (ft)	Facility CH_4 Recovery
Engineered landfill	15	100,000	40	50	85%
Basic landfill	15	100,000	50	40	75%
Open dump	15	100,000	80	25	10%

To improve the heterogeneity in the break-even options across countries, we developed a dataset of country-specific data of L_0 (methane generation potential) and k constant (decay rate) values, the two key parameters in the first order decay model, which is used to estimate landfill gas generation. Both parameters were calculated based on the composition of the waste being landfilled, which is determined by the country-specific socioeconomic conditions, consumption patterns, and waste management practices. Therefore, the methane generation results and, consequently, the amount of methane potentially mitigated by each landfill gas control measure are driven by the waste composition, which is related to consumption patterns and socioeconomic conditions. We grouped the countries according to the following logic:

First, we identified the decay constant (k) and CH_4 generation potential of waste (L_0) for 16 countries that included at least 1 country within the each major region (Africa, Asia, Caribbean/Central & South America, Eurasia, Europe, Middle East, and North America). This information was obtained from a number of sources, including international studies conducted by the World Bank, USEPA's voluntary program, the MSW Decision Support Tool (DST), and other peer-reviewed literature.

Second, we then used expert judgment, taking into consideration trends of socioeconomic and technological development to associate countries with other countries for which we have methane generation data (e.g., we have methane generation data for Jordan and considered that Algeria, Egypt, and South Africa have similar socioeconomic and technological conditions). Alternatively, we have methane generation data for Guinea, but we think that the socioeconomic and technological conditions in Egypt, Algeria, and South Africa are closer to those in Jordan than to those in Guinea.

Table 1-6 presents the data used to characterize the model facilities for specific countries identified for this analysis.

The international assessment of other OECD countries assumes waste management practices and landfill designs similar to those in the United States. For this reason, we leverage the existing United States-based landfill population, scaling the landfill size and emissions to meet projected baselines. For all non-OECD countries for which we had no data, we developed three model facilities to represent the allocation of waste to each type of waste management facility (i.e., engineered landfill, sanitary landfill, and open dump). Each facility type was assumed to have similar characteristics in terms of capacity, average depth of waste in place, and annual waste acceptance rates.

Table 1-6: CH_4 Generation Factors by Country

Country	Region[1]	k Constant (1/yr)	L_0 (ft^3/short ton)	Data Source
Guinea	Africa	0.18	4,690	WB
China	Asia	0.11	1,532	LMOP
India	Asia	0.11	3,988	Zhu et al. (2007)
Japan	Asia	0.11	4,620	WB
Nepal	Asia	0.04	6,890	WB
Pakistan	Asia	0.11	3,193	WB
Philippines	Asia	0.18	1,922	MSW DST
Argentina	CCSA	0.11	4,122	WB
Belize	CCSA	0.12	2,499	MSW DST
Colombia	CCSA	0.11	2,948	LMOP
Nicaragua	CCSA	0.11	2,627	MSW DST
Panama	CCSA	0.11	3,236	MSW DST
Bosnia and Herzegovina	Eurasia	0.06	4,295	WB
Ukraine	Eurasia	0.06	4,886	LMOP
Jordan	Middle East	0.02	5,984	WB
United States	North America	0.04	3,055	LMOP

[1] CCSA = Central & South America

Sources: WB—World Bank Studies by Country; LMOP—USEPA's LMOP country-specific landfill gas models; MSW DST—decision support model; and Zhu et al. (2007) "Improving municipal solid waste management in India."

Estimate Abatement Project Costs and Benefits

This analysis leveraged the USEPA *LFG to energy project costs model* to estimate abatement project costs and benefits for the landfill-based mitigation technologies (with the exception of enhanced oxidation). Key model facility characteristics discussed above were used as inputs to estimate the project costs across countries. For waste diversion alternatives, we assumed that waste was diverted from landfills and sent to alternative facilities for separation and reuse. Any residual waste from these facilities is then sent to a landfill for final disposal. Model facilities reflect the recycling or reuse facility's annual waste processing capacity as described in Section III.1.3.2.

Table 1-7 and Table 1-8 provide example break-even prices for model landfills and diversion facilities using U.S. parameters and costs.

Table 1-7: Example Break-Even Prices for MSW Landfill Technology Options

Option by Landfill Type	Reduced Emissions (tCO_2e)	Annualized Capital Costs ($/$tCO_2e$)	Annual Cost ($/$tCO_2e$)	Annual Revenue ($/$tCO_2e$)	Annual Tax Benefit of Depreciation ($/$tCO_2e$)	Break Even Price ($/$tCO_2e$)
Open Dump						
Direct use	7,475	$50	$28	$11	$10	$57
Combined heat and power	7,475	$86	$31	$10	$17	$89
Engine	7,475	$55	$30	$10	$11	$64
Microturbine	7,475	$54	$31	$7	$11	$67
Turbine	7,475	$57	$29	$8	$12	$66
Flare	7,475	$38	$27	$0	$8	$58
Basic Landfill						
Direct use	56,061	$6	$4	$11	$1	−$2
Combined heat and power	56,061	$17	$6	$10	$4	$10
Engine	56,061	$12	$6	$10	$2	$6
Microturbine	56,061	$11	$4	$7	$2	$6
Turbine	56,061	$13	$5	$8	$3	$7
Flare	56,061	$4	$3	$0	$1	$6
Engineered Landfill						
Direct use	63,536	$5	$4	$11	$1	−$4
Combined heat and power	63,536	$16	$6	$10	$3	$8
Engine	63,536	$11	$5	$10	$2	$4
Microturbine	63,536	$10	$3	$7	$2	$4
Turbine	63,536	$12	$4	$8	$3	$6
Flare	63,536	$3	$2	$0	$1	$5

Note: Based on USA CH_4 generation parameters: L_0 = 3,204 and k = 0.04. Assuming model landfill standardized size assumptions from Table 1-5. Break-even price is calculated using a discount rate of 10% and a tax rate of 40% and assumes energy prices of $3.2/Mcf and $0.07/kWh for gas and electricity.

Table 1-8: Break-Even Prices of Waste Diversion Options

Waste Diversion Options	Reduced Emissions (tCO_2e)	Annualized Capital Costs ($/$tCO_2e$)	Annual Cost ($/$tCO_2e$)	Annual Revenue ($/$tCO_2e$)	Annual Tax Benefit of Depreciation ($/$tCO_2e$)	Break Even Price ($/$tCO_2e$)
Composting	5,222	$119	$121	$185	$24	$31
Anaerobic digestion	4,658	$1,626	$360	$330	$277	$1,380
Mechanical biological treatment	18,605	$414	$68	$263	$70	$148
Paper recycling	6,164	$1,613	$1,249	$1,028	$275	$1,559
Waste to energy	55,816	$2,247	$142	$284	$383	$1,722
Enhanced oxidation systems	10,483	$143	$1	$0	$11	$132

Note: Assuming model sizes as described in Section III.1.3. Present values calculated using a discount rate of 10% and a tax rate of 40%.

III.1.4.2 MAC Analysis Results

The MAC curve results are presented in Table 1-9 and Figure 1-4 by major emitting country and rest of regional country groups. The MAC curves illustrate the increase in abatement achievable at higher carbon prices. In 2030, the MAC curves show that approximately 589 MtCO_2e, or 61% of global baseline CH_4 emissions from landfills, can be abated by adopting mitigation and avoidance options presented in Section III.1.3.

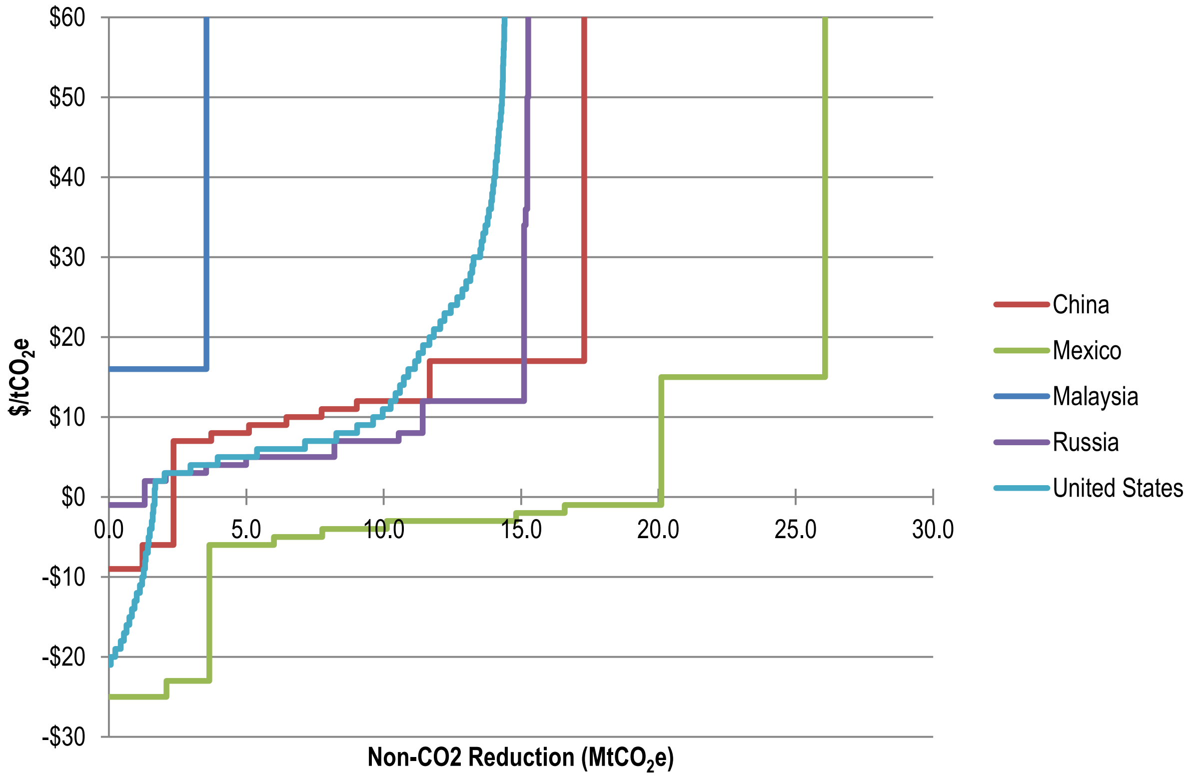
Approximately 112 MtCO_2e, or 19% of global abatement potential has a break-even price of zero or less. These mitigation options are sometimes referred to as “no regret” options because the benefit cost analysis implies that they would have a positive return. However, as discussed previously, there may be transaction costs not captured in this analysis that are currently limiting their adoption.

At break-even prices between \$20/tCO_2e to \$50/tCO_2e most countries MAC curves become non responsive (vertical). This is because there are few options within this break-even range. Between \$50/tCO_2e to \$100/tCO_2e an additional 20% of abatement potential becomes economically viable. And, at break-even prices (> \$100/t CO_2e) the remaining set of emission reduction options are economically viable, but at extremely higher prices. The point at which the MAC becomes unresponsive to any price change can also be considered the full technical potential associated with the suite of abatement measures considered. Thus, it can be inferred that additional reductions beyond approximately 60% of the projected baseline in 2030 would be unlikely without additional policy incentives or technology improvements.

Table 1-9: Abatement Potential by Region at Selected Break-Even Prices in 2030 (MtCO_2e)

	Break Even Price (\$/tCO_2e)										
Country/Region	**10**	**5**	**0**	**5**	**10**	**15**	**20**	**30**	**50**	**100**	**100+**
Top 5 Emitting Countries											
China		2.4	2.4	2.4	9.0	11.7	17.3	17.3	17.3	23.8	37.0
Malaysia						3.5	3.5	3.5	3.5	8.7	19.6
Mexico	3.7	7.8	20.1	20.1	20.1	26.1	26.1	26.1	26.1	34.8	53.0
Russia			1.3	8.2	11.4	15.1	15.1	15.1	15.3	20.7	32.0
United States	1.3	1.5	1.7	7.1	10.3	11.1	12.1	13.6	14.3	14.5	14.6
Rest of Region											
Africa	5.6	5.6	5.6	9.7	26.1	31.3	42.7	42.7	43.2	60.3	95.4
Central and South America	1.6	4.4	8.7	8.8	8.8	9.1	16.3	16.4	16.4	27.6	50.9
Middle East	3.5	4.0	7.5	20.1	20.8	23.2	25.0	26.3	27.0	36.2	55.7
Europe	22.8	36.0	49.0	70.9	82.6	86.7	91.8	92.7	93.1	98.8	110.4
Eurasia						1.6	2.3	2.3	2.3	5.8	12.9
Asia	2.9	6.7	11.8	15.8	17.5	19.1	29.7	30.1	30.1	48.7	86.3
North America	1.5	1.6	4.2	8.7	10.8	13.6	13.8	14.0	14.1	15.0	21.5
World Total	**43.0**	**70.0**	**112.4**	**171.9**	**217.4**	**252.2**	**295.7**	**300.1**	**302.8**	**394.9**	**589.4**

Figure 1-4: Marginal Abatement Cost Curve for Top 5 Emitters in 2030



III.1.4.3 Uncertainties and Limitations

Uncertainty and limitations persist despite attempts to incorporate all publicly available information. Additional country-specific detailed information would improve the accuracy of the MAC projections.

- Energy prices are negotiated on a case-by-case basis and may not be as high as the wholesale price used in the analysis.
- National/regional or local policies for permitting projects may differ; also incentives such as tax credits, grants, loans and other financial incentives for LFG projects differ across states.
- Additional data characterizing specific landfills are necessary for a more accurate financial analysis of each technology or specific project at a specific site. Costs can vary depending on the depth area, waste composition, and annual waste in place.

Efforts to reduce landfilling (e.g., recycling, composting) can also reduce CH_4 emissions and will have an effect on the most appropriate type of project and its cost-effectiveness at a given landfill. In general, additional country specific information would be useful in determining which abatement measures would be most likely to be adopted over time.

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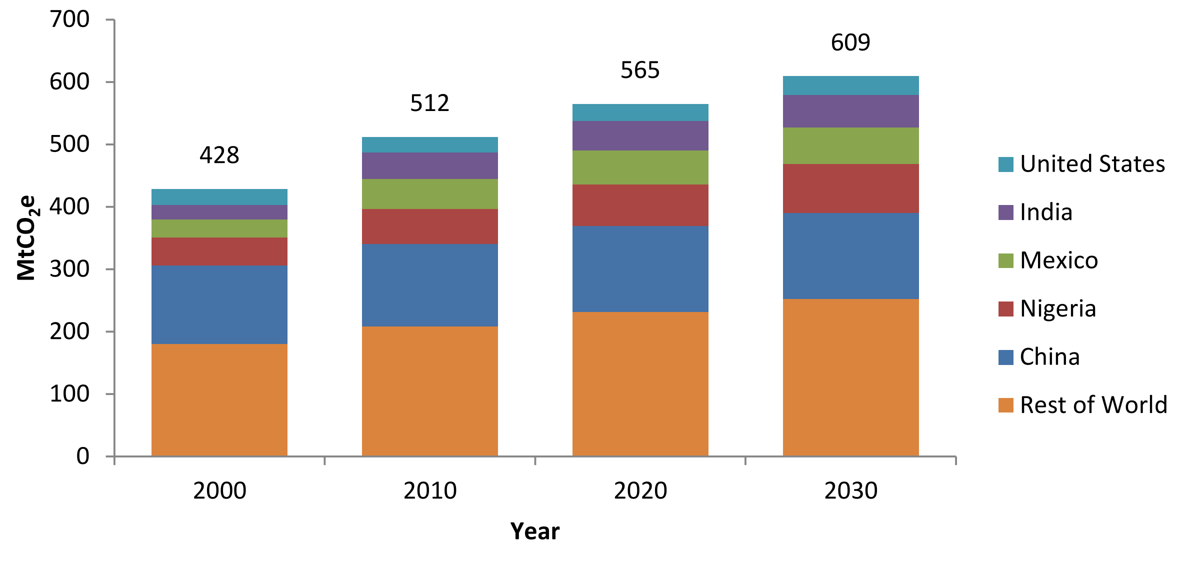
III.2. Wastewater

III.2.1 Sector Summary

Domestic and industrial wastewater treatment activities can result in deliberate venting and fugitive emissions of methane (CH_4). In addition, domestic wastewater is also a source of nitrous oxide (N_2O) emissions. CH_4 is produced when the organic material present in the wastewater flows decomposes under anaerobic conditions. Although most developed countries rely on centralized aerobic wastewater treatment systems, which limit the level of CH_4 generated, less developed countries often rely on a broader suite of wastewater treatment technologies with a significant proportion of wastewater flows handled by anaerobic systems such as septic tanks, latrines, open sewers, and lagoons (USEPA, 2012a).

Worldwide CH_4 from wastewater accounted for more than 500 $MtCO_2e$ in 2010. Wastewater is the fifth largest source of anthropogenic CH_4 emissions, contributing approximately 4% of total global CH_4 emissions in 2010. China, Nigeria, Mexico, India, and the United States, combined account for 60% of the world's CH_4 emissions from wastewater (see Figure 2-1). Global CH_4 emissions from wastewater are expected to grow by approximately 19% between 2010 and 2030.

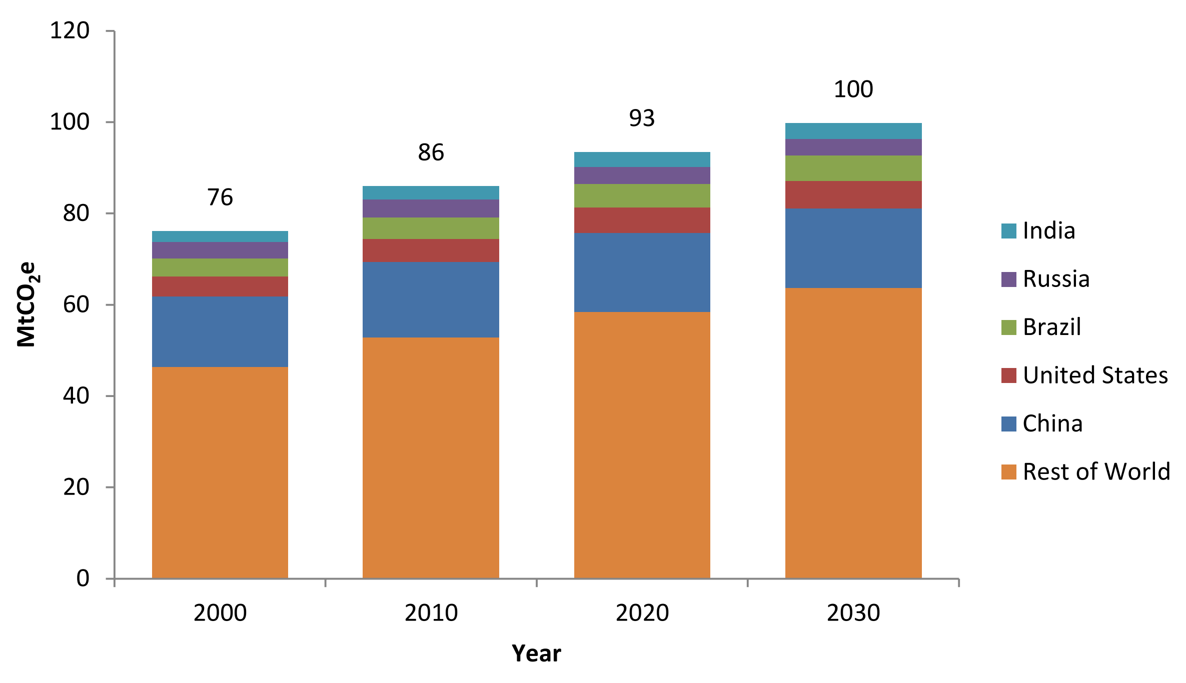
Figure 2-1: CH_4 Emissions from Wastewater: 2000–2030



Source: U.S. Environmental Protection Agency (USEPA). 2012a.

N_2O emissions from human sewage are a second significant source of GHG emissions within the wastewater sector, contributing an additional 2% of global N_2O emissions in 2010. Figure 2-2 illustrates the growth in N_2O emissions out to 2030 for the wastewater sector. China, the United States, Brazil, Russia, and India are projected to be the five largest emitters of N_2O in 2030, representing 36% of total N_2O emissions in the wastewater sector. Growth in N_2O emissions between 2010 and 2030 is expected to be 16%, slightly lower than the projected growth in CH_4 emissions over the same time period.

Figure 2-2: N_2O Emissions from Domestic Wastewater: 2000–2030



Source: U.S. Environmental Protection Agency (USEPA). 2012a.

Global abatement potential[1] of CH_4 in wastewater treatment is 138 and 218 $MtCO_2e$ in 2020 and 2030, respectively.[2] These corresponding sectoral MAC curves are shown in Figure 2-3. As the marginal abatement cost (MAC) curves show, high-cost mitigation measures in the wastewater treatment sector constrain the level of abatement achievable at lower carbon prices (less than \$30 tCO_2e^{-1}) to less than 5% of CH_4 emissions in 2030. Maximum abatement potential (218 $MtCO_2e$) is 36% of total CH_4 emissions in the wastewater sector in 2030.

The following section provides a brief explanation of sector activity, how CH_4 and N_2O emissions are generated, and projected emissions from wastewater from 2010 to 2030. Subsequent sections characterize the abatement measures available to the wastewater sector and present the costs of their implementation and operation. The chapter concludes with a discussion of the MAC analysis approach unique to this sector and presents the regional MAC results.

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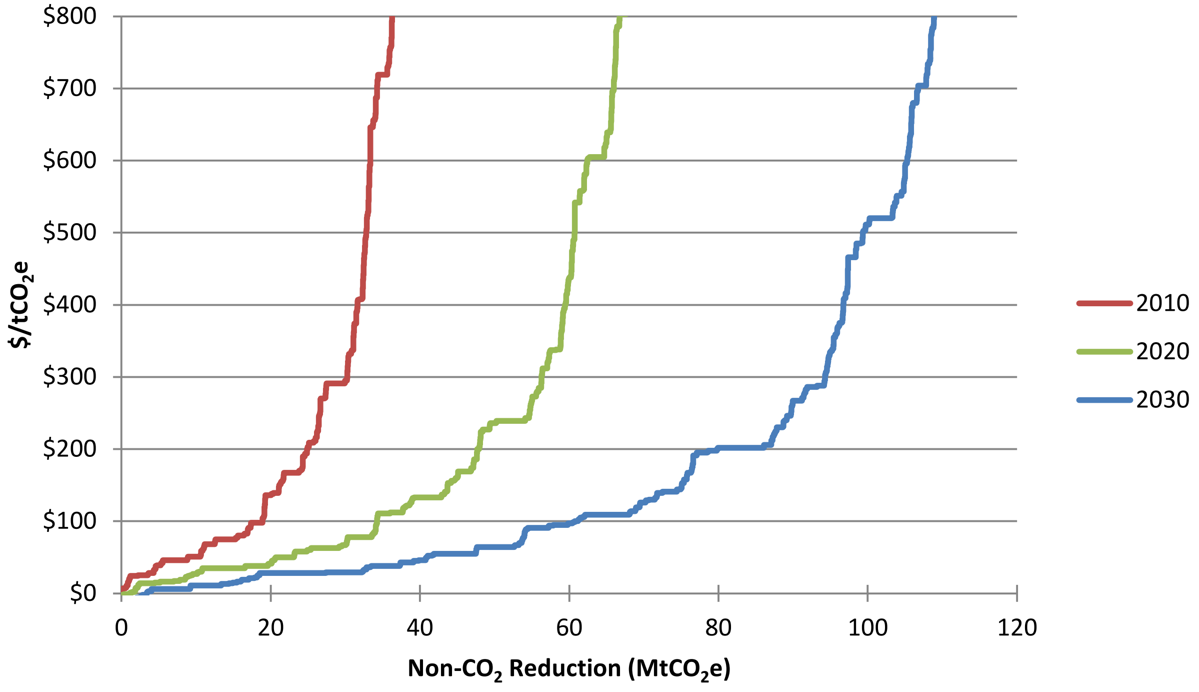
[1] This analysis only assesses abatement measures to reduce CH_4 emissions. Mitigation potentials reported in this chapter do not consider potential reductions in N_2O emissions, because of limited information on abatement measure costs.

[2] Vertical axis is scaled to limited range of prices between \$0 and \$800/tCO_2e. This scale was chosen because it shows sufficient detail in the MAC curves at lower break-even prices. Only 45% of the total abatement is visible in the figure simply due to the price limits chosen for the vertical axis when reporting the data.

Figure 2-3: Global MAC for Wastewater: 2010, 2020, and 2030



III.2.2 GHG Emissions from Wastewater

This section discusses how CH_4 and N_2O emissions are produced in wastewater treatment and disposal activities and the current projections of baseline emissions between 2010 and 2030.

III.2.2.1 CH_4 Emissions from Domestic and Industrial Wastewater

CH_4 is emitted during the handling and treatment of domestic and industrial wastewater. Wastewater CH_4 emissions are produced through the anaerobic decomposition of organic material present in the wastewater. Three key factors that determine the CH_4 generation potential are the quantity of degradable organic material present in the wastewater, the temperature, and the type of treatment system used (Intergovernmental Panel on Climate Change [IPCC], 2006). The organic content of wastewater is typically expressed in terms of either biochemical oxygen demand (BOD) or chemical oxygen demand (COD) (IPCC, 2006; USEPA, 2012a). CH_4 generation is positively related to temperature so that higher temperatures result in a great amount of CH_4 produced. The third key factor that determines CH_4 generation is the type of treatment system used and more specifically the amount of decomposition occurring under anaerobic conditions which is positively related the quantity of CH_4 generated.

Types of centralized systems that can result in CH_4 emissions include 1) aerobic systems that are either improperly operated or designed to have periods of anaerobic activity and 2) anaerobic lagoons (USEPA, 2012b). Most developed countries currently use centralized aerobic wastewater treatment facilities with closed anaerobic sludge digester systems to process municipal and industrial wastewater, minimizing CH_4 emissions.

The IPCC guidelines for national greenhouse gas reporting identifies five major industrial wastewater sources for CH_4 emissions, which include pulp and paper manufacturing, meat and poultry processing (slaughterhouses), alcohol/beer and starch production, organic chemicals production, and other drink and food processing (e.g., dairy products, vegetable oil, fruits and vegetables, canneries, juice making) (IPCC, 2006). The significance of CH_4 emissions from the various industrial sources will depend on the concentration of degradable organics present in the wastewater flow, volume of wastewater generated, the quantity of wastewater treated in anaerobic treatment systems (e.g., anaerobic lagoons).

III.2.2.2 N_2O Emissions from Domestic Wastewater—Human Sewage

N_2O is produced during both the nitrification and denitrification of urea, ammonia, and proteins. These waste materials are converted to nitrate (NO_3) via nitrification, an aerobic process converting ammonia-nitrogen to nitrate. Denitrification occurs under anoxic conditions (without free oxygen) and involves the biological conversion of nitrate into dinitrogen gas (N_2). N_2O can be an intermediate product of both processes but is more often associated with denitrification (Sheehle and Doorn, 2002).

III.2.2.3 Emissions Estimates and Related Assumptions

This section discusses the historical and projected baseline emissions for the wastewater sector.[3] Historical emissions are characterized as those emissions released between 1990 and 2010. Projected emissions estimates cover the 20-year period starting in 2010 and ending in 2030.

Historical Emissions Estimates

Between 1990 and 2005, CH_4 and N_2O emissions from wastewater increased by 20% from a combined total of 421 $MtCO_2e$ in 1990 to 505 $MtCO_2e$ in 2005. The primary driver of both CH_4 and N_2O emissions associated with wastewater is population growth. Country-level CH_4 emissions are particularly sensitive to population growth in countries that rely heavily on anaerobic treatment systems such as septic tanks, latrines, open sewers, and lagoons for wastewater treatment (USEPA, 2012a).

The share each countries total emissions that is attributed to domestic versus industrial wastewater sources is determined by the level of industrial activity and types of domestic wastewater treatment systems employed. In developing countries, domestic wastewater sources account for the majority if not all of CH_4 emissions from wastewater. In countries with industrial wastewater sources, the contribution of industrial wastewater emissions will depend on the level of production and the commodity produced (e.g. paper, sugar, alcoholic beverages, and processed meat/poultry/fish). Based on the UNFCCC's national reporting inventory database of GHG emissions, only a small number of developed countries have historically reported CH_4 emission from Industrial sources. For these 24 countries reporting industrial and domestic CH_4 emissions the share of emissions reported for industrial wastewater ranged from less than 2% to nearly 70% of total CH_4 emissions from all wastewater sources. Section III.2.4 discusses these distributions of emissions to domestic and industrial sources in more detail.

Projected Emissions Estimates

Worldwide CH_4 emissions are projected to increase by approximately 19% (97 $MtCO_2e$) between 2010 and 2030. N_2O emissions are projected to increase by a similar proportion, up 16% (14 $MtCO_2e$) over the same time period. Tables 2-1 and 2-2 present the CH_4 and N_2O emissions projections for the wastewater sector.

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[3] For more detail on baseline development and estimation methodology, we refer the reader to the USEPA's *Global Emissions Projection Report* available at: http://www.epa.gov\climatechange\economics\international.html.

Table 2-1: Projected CH_4 Baseline Emissions from Wastewater: 2010–2030 ($MtCO_2e$)

Country	2010	2015	2020	2025	2030	CAGR[a] (2010–2030)
Top 5 Emitting Countries						
China	132	135	137	138	138	0.2%
Nigeria	56	62	67	73	78	1.7%
Mexico	48	51	54	56	58	0.9%
India	42	45	47	50	52	1.1%
United States	25	26	27	29	30	0.9%
Rest of Regions						
Africa	27	29	32	35	38	1.9%
Central & South America	47	50	53	56	59	1.1%
Middle East	22	23	25	26	28	1.2%
Europe	19	19	20	20	20	0.2%
Eurasia	26	25	25	24	23	−0.5%
Asia	68	72	76	81	84	1.1%
North America	0	0	0	0	0	0.7%
World Total	**512**	**539**	**565**	**588**	**609**	**0.9%**

[a] CAGR = Compound Annual Growth Rate

Source: U.S. Environmental Protection Agency (USEPA). 2012a.

Table 2-2: Projected N_2O Baseline Emissions from Human: 2010–2030 ($MtCO_2e$)

Country	2010	2015	2020	2025	2030	CAGR (2010–2030)
Top 5 Emitting Countries						
China	17	17	17	17	17	0.2%
United States	5	5	6	6	6	0.9%
Brazil	5	5	5	5	6	0.9%
Russia	4	4	4	4	4	1.1%
India	3	3	3	3	4	−0.6%
Rest of Region						
Africa	11	13	14	15	17	1.8%
Asia	5	5	6	6	6	1.0%
Central & South America	4	5	5	5	6	1.0%
Eurasia	14	14	14	14	14	0.1%
Europe	3	3	3	3	3	0.0%
Middle East	12	13	14	14	15	1.3%
North America	3	3	3	3	3	0.9%
World Total	**86**	**90**	**93**	**97**	**100**	**0.7%**

Source: U.S. Environmental Protection Agency (USEPA). 2012a.

As shown in Table 2-1, Africa and the Middle East are two regions projected to experience significant growth in CH_4 emissions over the next 20 years, increasing by 50% and 33%, respectively. CH_4 emissions growth in Asia and the Central and South American regions is also expected to be significant, growing by 25% over the same time period.

N_2O emissions are expected to grow by similar proportions across all regions with the exception of Eurasia, where emissions are expected to remain relatively unchanged over the next 20 years. The primary driver of this trend is Russia's 11% drop in N_2O emissions between 2010 and 2030. Despite this decline, Russia still ranks as one of the top five emitters in 2030.

III.2.3 Abatement Measures and Engineering Cost Analysis

This section characterizes the abatement measures considered for the wastewater sector. This analysis focused on domestic wastewater treatment and implementation of abatement measures aimed at reducing CH_4 emissions, which can be mitigated through investment in infrastructure and/or equipment. Conversely, there are no proven and reliable technologies for mitigation of N_2O emissions. Mitigation steps to limit N_2O emissions from wastewater treatment are operational, and include careful control of dissolved oxygen levels during treatment, controlling the biological waste load-to-nitrogen ratio, and limiting operating system upsets. These measures require technical expertise and experience rather than an engineered solution, thus they fall outside the scope of an engineered cost analysis.

It is important to couch the discussion of greenhouse abatement measures for municipal wastewater in the appropriate context. In practice, changes to wastewater management strategies in developing countries are unlikely to be driven by the mitigation of greenhouse gases. Factors such as economic resources, population density, government, and technical capabilities are all important in determining both the current state and the potential for improvement to a country's wastewater sanitation services. Figure 2-4 is an illustration of the sanitation ladder, which relates the level of available wastewater sanitation to the population and cost for treatment. The transition from a latrine to a sewer/wastewater treatment plant (WWTP)/anaerobic digester can increase the operation and maintenance wastewater treatment cost per person by a factor 20 (Guchte and Vandeweerd, 2004). This does not account for the capital cost that would be required in such large scale projects.

The reader should bear in mind throughout the analysis that the wastewater sanitation technology is likely to be fixed by these external factors, and improvements in technology will be driven by the population's desire/capacity for improved sanitation and hygiene, with any improvements to greenhouse gas emissions a secondary result of the change. Thus, although abatement measures are presented in this chapter, they should not be considered to be a viable control measure that could be implemented for the sole purpose of reducing a country's GHG emissions, but rather a byproduct of a country's position on the sanitation ladder.

This analysis considers abatement measures that may be applied to one of five existing wastewater treatment systems currently being utilized in a given country. Scenarios 1 and 2 correspond to the upper half of the sanitation ladder, while scenarios 3 through 5 correspond to the lower half the sanitation ladder. The five baseline scenarios for the existing status quo are presented in Figure 2-5. In actuality, there are many more than five baseline technology scenarios that may be utilized throughout the world, within a country, or even within a municipality. For example, a population may utilize aerobic or anaerobic ditches for centralized treatment of wastewater, which could be viewed as an intermediate option between scenarios 1 and 2 in Figure 2-5. These baseline scenarios are not meant to be an exhaustive list of the actual existing treatment technologies employed worldwide, but rather an attempt

Figure 2-4: Sanitation Ladder for Improvements to Wastewater Treatment

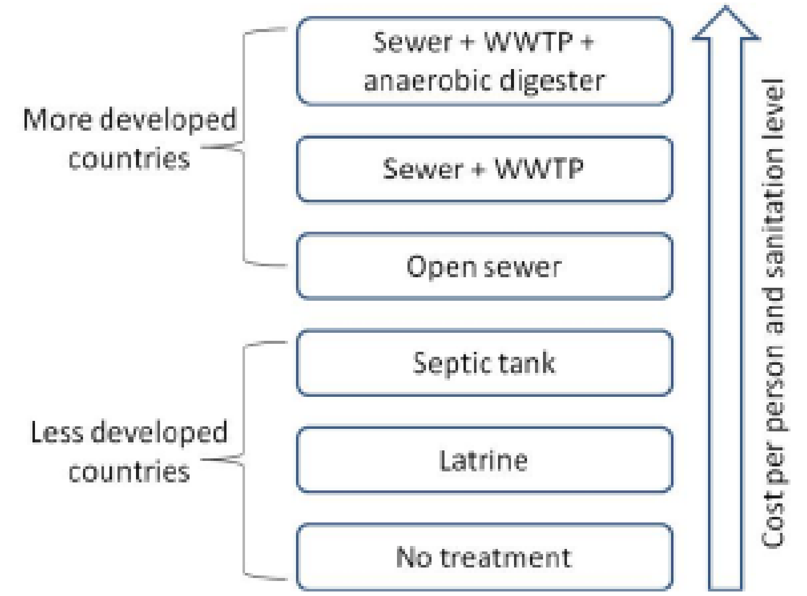
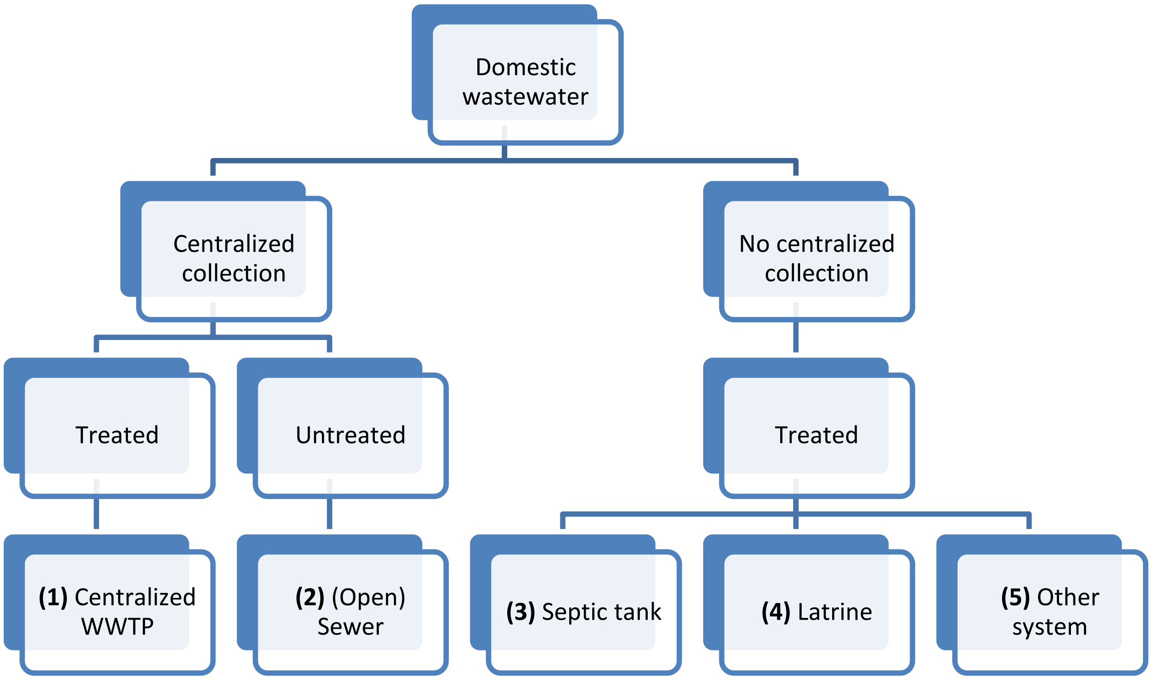


Figure 2-5: Five Existing Scenarios Evaluated for Given Wastewater Discharge Pathways Based on Technology Level, Treatment Alternative, and Collection Method



to broadly categorize and quantify technologies that represent the major classes of treatment technologies employed throughout the world.

Discharge pathways 1 and 2 (in Figure 2-5) assume the existence of a collection system for all wastewater generated and are grouped according to the final disposal/treatment approach. Pathways 3, 4, and 5 are the scenarios for which no existing centralized treatment exists and the waste is treated on site with latrines or septic tanks. For each of the five pathways and corresponding treatment systems, a mitigation approach is evaluated for CH_4 reduction. The analysis considers three abatement measures that include both mitigation technologies as well as complete shifts in wastewater management, that is, a jump up the sanitation ladder.

It is important to note the distinction between the two types of abatement measures. Mitigation technologies represent add-on technologies that can be applied to existing wastewater treatment systems (such as an anaerobic digester with cogeneration) intended to capture and destroy the CH_4 generated at the facility. The second type of abatement measure represents a shift away from an existing anaerobic wastewater treatment approach to an aerobic system which in turn will reduce the volume of CH_4 generated during the treatment process. This shift in wastewater treatment approaches will require the construction of a new facility that fundamentally changes the existing wastewater management approach. This approach usually requires construction of new infrastructure and, therefore, will require significant capital investment. As demonstrated in the cost analysis, the construction and operation and maintenance cost per person is dependent on the population density of the region. For a collection system, more rural areas require the more material (per person) to be used to build a system to collect and transport the waste.

III.2.3.1 Overview of Abatement Measures

This section discusses the abatement measures considered for this analysis. Each technology is briefly characterized and followed by a discussion of abatement measures' implementation costs, potential benefits, and system design assumptions used in the MAC analysis. Table 2-3 compares the three abatement alternatives for an example population of 400,000 people, population density of 3,000/km², and wastewater generation rate of 340 L/person/day.

Table 2-3: Abatement Measures for the Wastewater Sector

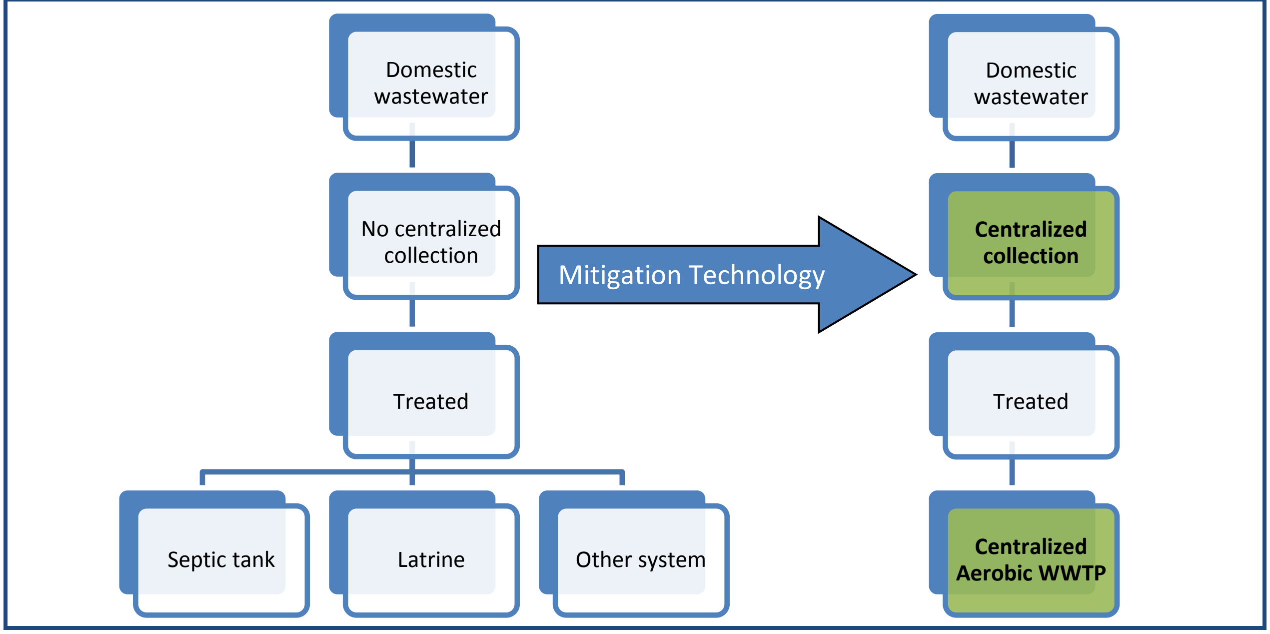
Abatement Option	Total Installed Capital Cost (2010 106 USD)	Annual O&M Cost (2010 106 USD)	Time Horizon (Years)	Technical Efficiency
Anaerobic biomass digester with CH_4 collection and cogen.	21.1	5.0	20	60–80%
Aerobic wastewater treatment plant (WWTP)	97.2	4.7	20	60–80%
Centralized wastewater collection (+ aerobic WWTP)	55.9 (153.1)	1.6 (6.3)	50	60–80%

For this analysis, abatement measures are assigned based by on the existing wastewater treatment system pathway in place. For example, a population considering the addition of an anaerobic biomass digester will already have an existing collection system and aerobic WWTP in place. There is no technology selection in the current analysis because we have identified one abatement measure for each type of treatment system. The following subsections characterize each of the three abatement measures and the assumptions regarding applicability and costs. In reality, feasible mitigation measures will vary due to the wide range of wastewater disposal options currently employed in each country and the external factors that govern a country's ability to transition from one technology to another. In addition, as discuss above regarding the baseline scenarios, there are dozens of wastewater technology options available to a population; this discussion highlights three major categories that represent shifts in water management or add-on technology.

III.2.3.2 CH_4 Mitigation Technology for Existing Decentralized Treatment

This section characterizes the reduction in CH_4 emissions by adding a collection system and centralized treatment facility in developing countries where the current practice is decentralized wastewater treatment. As shown in Figure 2-6, this approach necessitates two large-scale capital investments: the construction of a sewerage system for centralized collection and the construction of an anaerobic WWTP.

Figure 2-6: Mitigation Technology Approach for Developing Countries with Decentralized Treatment



Wastewater Collection System—New Construction

For areas of the developing world without centralized wastewater treatment, latrines and/or septic tanks are typically used to dispose of domestic wastewater. In both of these cases, the organic matter in the wastewater will undergo anaerobic degradation to produce CH_4. The construction and implementation of a collection system and subsequent treatment at a centralized facility would significantly reduce CH_4 formation because transporting wastewater through sewers promotes aerobic conditions and reduces the fraction of organic content that undergoes anaerobic digestion.

The design and size of a wastewater collection system depend on the population served, the service area size, and water use characteristics of the population. Wastewater collection systems link all household and commercial discharges through underground piping, conveying the water to either a centralized treatment facility or directly to an outfall point where it is released into the environment. Pipelines can vary from 6 inches in diameter to concrete-lined tunnels up to 30 feet in diameter. Collection systems are built with a gradient so gravity can facilitate the water flow; where there are large distances that must be covered, periodic pump stations (also called lift stations) are sometimes used to pump the sewage to a higher elevation and again allow gravity to transport the sewage. Sewage pumps are typically centrifugal pumps with open impellers, designed to have a wide opening to prevent the raw sewage from clogging the pump. This scenario evaluates the impact of installing a sewer collection system without a centralized treatment facility.

- **Capital Cost:** The cost estimation model Water and Wastewater Treatment Technologies Appropriate for Reuse (WAWTTAR) (Finney and Gearheart, 2004) was used to determine the capital cost of the sewer construction. The model is used by engineers, planners, decision makers, and financiers to estimate the costs of making improvements to wastewater treatment systems while minimizing impacts to water resources. The capital cost curve for wastewater collection systems is based on the population density: Capital Cost ($MM/km^2) = $360.54 \times D_p^{-0.844}$, where D_p is population density in (persons/km^2).
- **Annual Operation and Maintenance (O&M) Cost:** Annual O&M costs for collection systems were scaled from the capital cost and assumed to be a factor of 0.028 × initial capital cost, which for this case gives the following cost curve, based on population density: O&M Cost ($MM/km^2) = $10.095 \times D_p^{-0.844}$.
- **Annual Benefits:** No benefits are associated with this option.
- **Applicability:** This option applies to all scenarios having no existing centralized collection system.
- **Technical Efficiency:** This analysis assumes an initial collection efficiency of 60%, which increases by 10% each year, due to an assumed improvement in technical efficiency.
- **Technical Lifetime:** 50 years

Aerobic WWTP—New Construction

Contaminants in wastewater are removed using a variety of physical, chemical, and biological methods. A WWTP typically comprises many unit operations from each of these broad categories. Wastewater treatment technologies are also divided into stages of treatment, each of which comprises one or more individual treatment processes. A brief summary of each of these classifications is as follows:

- **Pretreatment:** This stage involves the removal of wastewater constituents. These constituents can include rags, sticks, floatables, grit, and grease that may cause maintenance or operational problems with the treatment operations, processes, and ancillary systems. Screening methods are employed here, suing bars, rods, grates, or wire meshes.
- **Primary treatment:** This stage focuses on the removal of a portion of the total suspended solids (TSS) and organic matter from the wastewater. Primary treatment is a physical unit process in which the sewage flows into large tanks, known as primary clarifiers or primary settling tanks. A settling tank is constructed of concrete and designed so that the residence time of the wastewater is such that the flow slows down enough so that readily settleable particles are collected at the bottom of the tank.
- **Secondary treatment:** This stage focuses on the removal of biodegradable organic matter (in solution or suspension) and TSS by aerobic or anaerobic biological treatment. Disinfection is also typically included in the definition of conventional secondary treatment. Secondary treatment is a biological process that cultivates and uses a consortium of microorganisms to degrade the organic wastes and reduce nutrient levels in wastewater. Secondary treatment can either be aerobic (with oxygen) or anaerobic (without oxygen). By far, the most common approach used in WWTPs is the activated sludge process. This process is an aerobic suspended-growth system

containing a biomass that is maintained with oxygen and is capable of stabilizing organic matter found in wastewater. During the activated sludge process, the effluent flows into a concrete tank where air or oxygen is bubbled through the wastewater to encourage microbial degradation of the organic material. The treated effluent flows to a secondary settling tank, where it is separated from the biomass. Most of the biomass collected at the bottom of the settling tank is removed for further dewatering and stabilization before final disposal. A small fraction of the biomass is recycled back into the bioreactor to maintain the population. It is important to monitor proper control of oxygen levels, pH, and the amount of sludge recycled back into the reactor to ensure that proper treatment levels of the wastewater are maintained.

- **Tertiary treatment:** This stage involves the removal of residual suspended solids (after secondary treatment), usually by granular medium filtration or microscreens. Disinfection is also typically a part of tertiary treatment. Nutrient removal is often included in this stage.

The cost breakdown for this mitigation approach is as follows:

- **Capital Cost:** Capital costs were estimated using EPA cost curves detailing the construction costs of publicly owned wastewater treatment facilities (USEPA 1980). The costs curves in this report are based on actual winning bids for treatment plans, which include detailed equipment and materials requirements, including labor, amortization, land, concrete, pumps, pipes, power, haulage, chemicals, and design fees. All cost curves were updated to year 2010 dollars. The cost curve is based on the flow rate of the WWTP: Capital Cost ($MM) = $0.0174 \times Q^{0.73}$, where Q is the flow rate in m^3/day.
- **Annual Operation and Maintenance (O&M) Cost:** Typical annual O&M costs of an aerobic WWTP are due to electricity used to provide aeration and operation equipment, labor to operate the plant, chemicals, and equipment replacement. EPA cost curves (updated to 2010 dollars) provides the following cost curve for an aerobic WWTP, based on the flow rate: $0.0002 \times Q^{0.8517}$.
- **Annual Benefits:** None.
- **Applicability:** This option applies to all conditions when new WWTPs are constructed.
- **Technical Efficiency:** This analysis assumes an initial collection efficiency of 60%, which increases by 10% each year.
- **Technical Lifetime:** 20 years.

III.2.3.3 CH_4 Mitigation Technology for Existing Collection System without Treatment

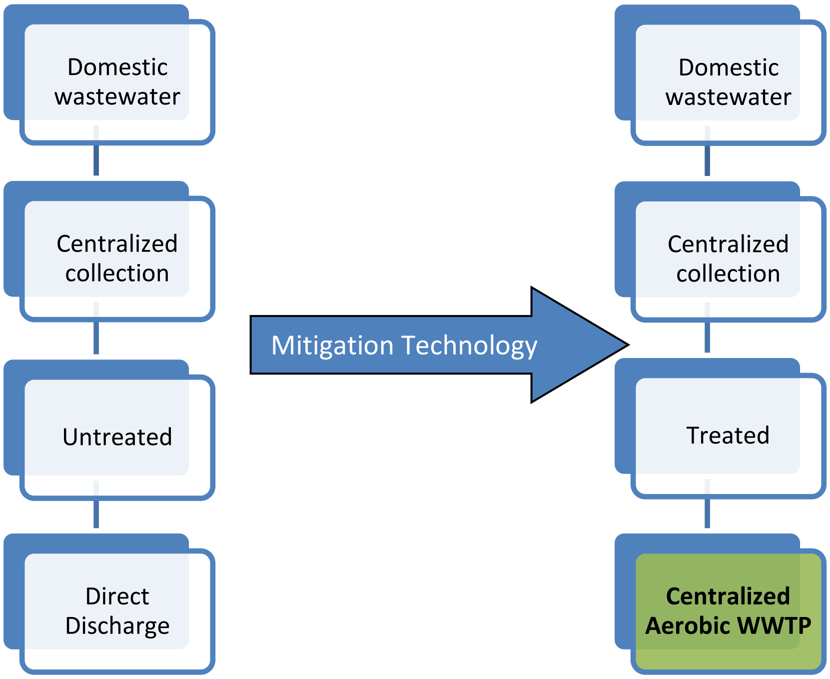
This section characterizes the reduction in CH_4 emissions for the existing condition of a centralized collection system without a treatment facility**.** Figure 2-7 illustrates the step change in technical capability, which in this case necessitates the construction of a new anaerobic WWTP.

As noted above, contaminants in wastewater are removed via a variety of physical, chemical, and biological methods. An anaerobic WWTP typically comprises many unit operations divided into stages of treatment: pretreatment, primary treatment, secondary treatment, and tertiary treatment.

The cost breakdown for this mitigation approach is identical to that above and is as follows:

- **Capital Cost:** Capital costs were estimated using EPA cost curves detailing the construction costs of publicly owned wastewater treatment facilities. The cost curve is based on the flow rate of the WWTP: Capital Cost ($MM) = $0.0174 \times Q^{0.73}$, where Q is the flow rate in m^3/day.

Figure 2-7: Mitigation Technology Approach for Developing Countries with Decentralized Treatment



Domestic wastewater

Centralized collection

Untreated

Direct Discharge

Mitigation Technology

Domestic wastewater

Centralized collection

Treated

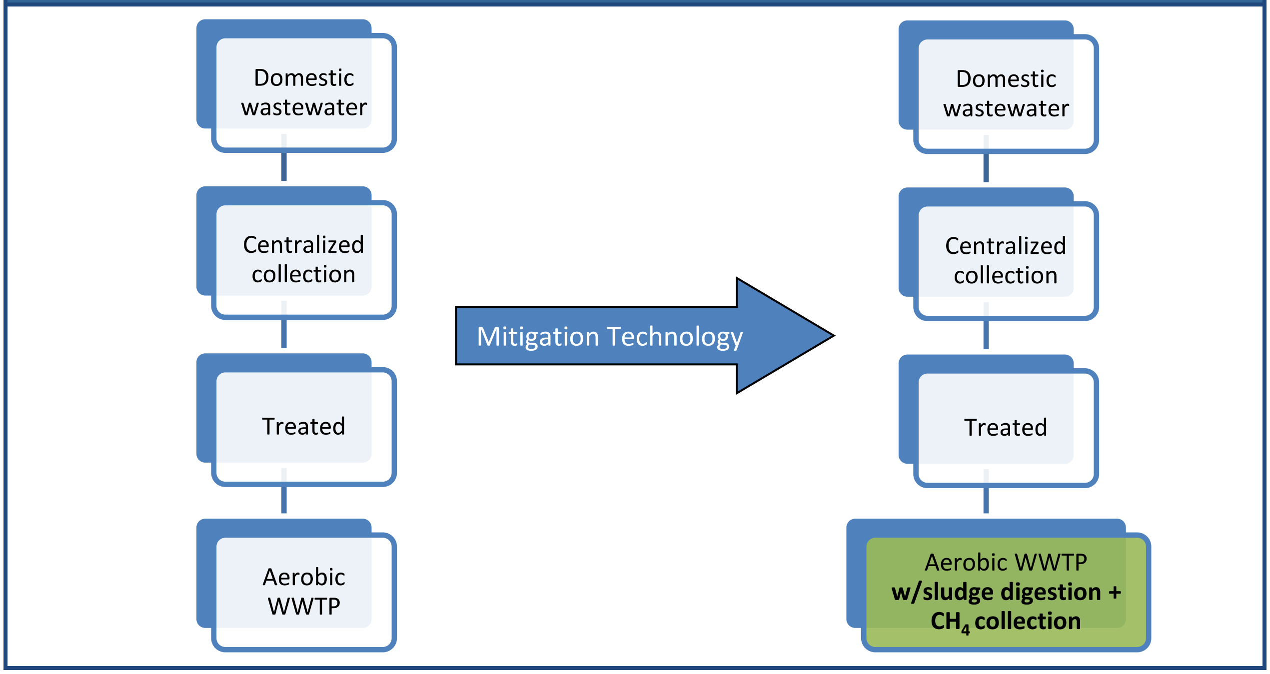
Centralized Aerobic WWTP

- **Annual Operation and Maintenance (O&M) Cost:** Typical annual O&M costs of an aerobic WWTP are due to electricity used to provide aeration and operation equipment, labor to operate the plant, chemicals, and equipment replacement. Capdetworks v2.5 was used to estimate O&M costs. Capdetworks is a planning level tool that enables the user to evaluate the costs associated with individual treatment units or entire systems. The costs are based on detailed equipment and materials database that utilizes published cost indices, including labor, amortization, and energy requirements. Capdetworks provides the following cost curve for an aerobic WWTP, based on the flow rate: O&M cost ($MM) = $0.0002 \times Q^{0.8517}$.
- **Annual Benefits:** None.
- **Applicability:** This option applies to all conditions when new WWTPs are constructed.
- **Technical Efficiency:** This analysis assumes an initial collection efficiency of 60%, which increases by 10% each year.
- **Technical Lifetime:** 20 years.

III.2.3.4 CH_4 Mitigation Technology for Existing Centralized Aerobic WWTPs

This section characterizes the reduction in CH_4 emissions from adding an activated sludge digester for CH_4 collection and energy generation. This option is only applicable to existing centralized aerobic WWTPs primarily found in developed countries (Figure 2-8).

Figure 2-8: Mitigation Technology Approach for Countries with Existing Centralized WWTPs



Anaerobic Biomass Digester with CH_4 Collection

The top of the technology ladder evaluated assumes an existing centralized WWTP is used to treat all wastewater generated in the region. The significant quantity of biomass generated during the decomposition of the sewage is a major operational component of WWTP operation. Typical approaches to sludge handling include dewatering to reduce the overall volume and further water reduction in open-air drying beds. The sludge is rich in organic matter and has the potential to produce high amounts of CH_4 during degradation. Anaerobic digestion is an additional sludge-handling step that can be employed to further reduce the sludge volume; it is a process that involves the decomposition of this organic material in an oxygen-free environment to produce and collect CH_4. Anaerobic digesters are large covered tanks that are heated to optimize the methane-generating process. The tanks typically employ a mixing mechanism to ensure uniform conditions throughout the tank and are designed with headspace to collect the gas generated, which is typically a mix of 60 to 70% CH_4 and the 30 to 40% CO_2, along with trace gases. The remaining solid material is nutrient rich and is a suitable fertilizer for land application. The heat from the flared gas can be used to heat the digester, lowering the overall energy requirements of the system. Alternatively, the gas can be used to produce electricity with a turbine.

- **Capital Cost:** Costs were derived from EPA process cost curves for new construction of an anaerobic digester. The capital cost covers the construction of the tank with heater and cover and includes concrete, all equipment, process piping and steel required for digester construction. Costs were derived from CapdetWorks. The cost curve is based on the flow rate of the WWTP: Capital Cost (\$MM) = $0.0004 \times Q^{0.92}$, where Q is the flow rate in m^3/day.
- **Annual Operation and Maintenance (O&M) Cost:** Typical annual O&M costs for collection systems are based on CapdetWorks. CapdetWorks provides the following cost curve for aerobic WWTP, based on the flow rate: O&M cost (\$MM) = $0.00042 \times Q^{0.7939}$.

- **Annual Benefits:** Stabilized sludge can be land applied as fertilizer. The cogeneration option provides electricity. Flared gas can be used elsewhere at the plant to reduce overall energy requirements.
- **Applicability:** This option applies to all existing WWTP types.
- **Technical Efficiency:** This analysis assumes an initial collection efficiency of 60%, which increases by 10% each year.
- **Technical Lifetime:** 20 years

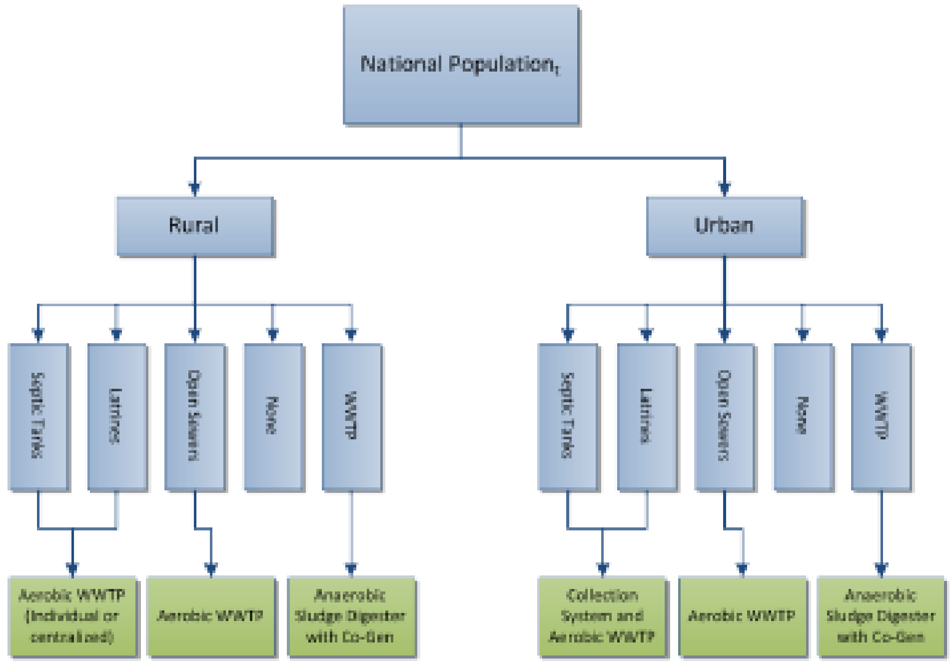
III.2.4 Marginal Abatement Costs Analysis

This section describes the methodological approach to the international assessment of CH_4 abatement measures for wastewater treatment systems.

III.2.4.1 Methodological Approach

The MAC analysis is based on project costs developed for a set of model facilities based on the technical and economic parameters discussed in Section III.2.3. Similar to the steps taken in other sectors, we developed an inventory of facilities that are representative of existing facilities. Next, we applied the abatement costs reported above to calculate the break-even prices for each option and wastewater treatment scenario. Finally, the model estimates the mitigation potential based on the country-specific share of emissions attributed to each wastewater treatment scenario. Figure 2-9 shows the organization of the domestic wastewater MAC model. The country-specific distributions are based on analysis conducted by USEPA (2012a).

Figure 2-9: Domestic Wastewater MAC Analysis Flow Chart

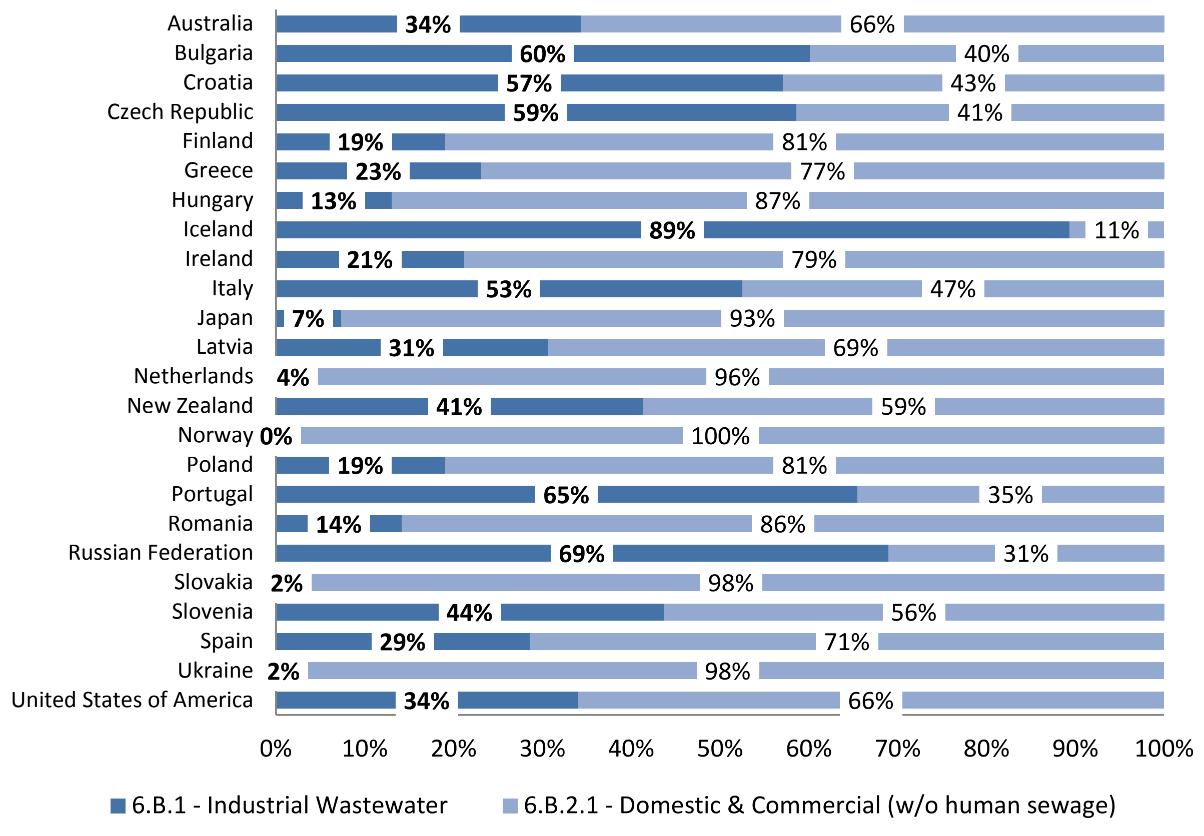


Assessment of Sectoral Trends

The first step in the analysis is to assess the level of baseline emissions attributable to domestic versus industrial wastewater sources. The analysis allocates, when information is available, a percentage of annual emissions to domestic wastewater treatment. For each country, the remaining share of emissions is allocated to industrial wastewater treatment.

Shares allocated to each source (domestic/industrial) were based on historical emissions data obtained from the United Nations Framework Convention on Climate Change's (UNFCCC's) GHG emissions reporting database. Data were limited to 24 Annex I countries accounting for 15% of emissions in 2010. For these 24 countries, we calculated a 5-year average share of CH_4 emissions attributable to domestic sources based on emissions reported between 2002 and 2007. For all other countries, because of a lack of data, we assumed emissions projections are wholly attributable to domestic wastewater treatment systems to be consistent with USEPA (2012a) projections methodology. Figure 2-10 presents the average share of emissions attributed to domestic and industrial sources by country.

Figure 2-10: Share of Wastewater CH_4 Emissions to Domestic and Industrial Sources (Avg. 2002–2007)



Source: United Nations Framework Convention on Climate Change (UNFCCC). Flexible Data Queries. Online Database. Available at: http://unfccc.int/di/FlexibleQueries/Event.do?event=hideProjection.

The analysis also leverages estimated changes in wastewater disposal activity along each wastewater treatment pathway discussed earlier in this chapter. This data was obtained from previous USEPA analysis used to developed international wastewater projections. Trends in wastewater disposal activity are determined by population projections, distribution of population between rural and urban settings, population density, and wastewater flow rates per person. These parameters are used to estimate country- and technology-specific abatement project costs.

Other trends applied for this analysis include increasing the technical applicability factor and technical effectiveness factor. The technical applicability factor is assumed to increase at 1% per year between 2010 and 2030. The technical effectiveness factor increases at a similar rate, growing from 60% to 80% over the 20-year time period. These assumptions are based on expert judgment and intended to reflect increases in both the adoption of improved sanitation systems and improvements through learning best management practices for the alternative treatment systems that reduced CH_4 emissions.

Estimate Abatement Project Costs and Benefits

Project costs were estimated based on the cost functions defined in Section III.2.3. Country-specific demographic information on wastewater flow rates and population density was used to estimate the initial capital costs for each population segment. Table 2-4 provides example abatement measure cost estimates for the United States and the corresponding break-even prices associated with each option.

Table 2-4: Example Break-Even Prices for Wastewater Abatement Measures in 2030 for the United States

Abatement Option	Reduced Emissions (tCO_2e)	Installed Capital Costs ($\$/tCO_2e$)	Present Value of Annual Cost ($\$/tCO_2e$)	Present Value of After Tax Benefits ($\$/tCO_2e$)	Present Value of Tax Benefit of Depreciation ($\$/tCO_2e$)	Break Even Price ($\$/tCO_2e$)
Rural						
Septic to aerobic WWTP	6,493,070	$51,771	$3,080	$179	$4,106	$5,100
Latrine to aerobic WWTP	288,581	$25,886	$1,540	$179	$2,053	$2,541
Open sewer to aerobic WWTP	—	—	—	—	—	—
Anaerobic sludge digester with co-gen	57,716	$6,929	$533	$154	$1,180	$720
Urban						
Septic to aerobic WWTP	1,082,178	$10,936	$2,251	$179	$867	$1,224
Latrine to aerobic WWTP	—	—	—	—	—	—
Open sewer to aerobic WWTP	—	—	—	—	—	—
WWTP—add-on anaerobic sludge digester with co-gen	2,056,139	$5,206	$255	$154	$886	$519

Note: Break-even price was calculated using a 10% discount rate and 40% tax rate.

III.2.4.2 MAC Analysis Results

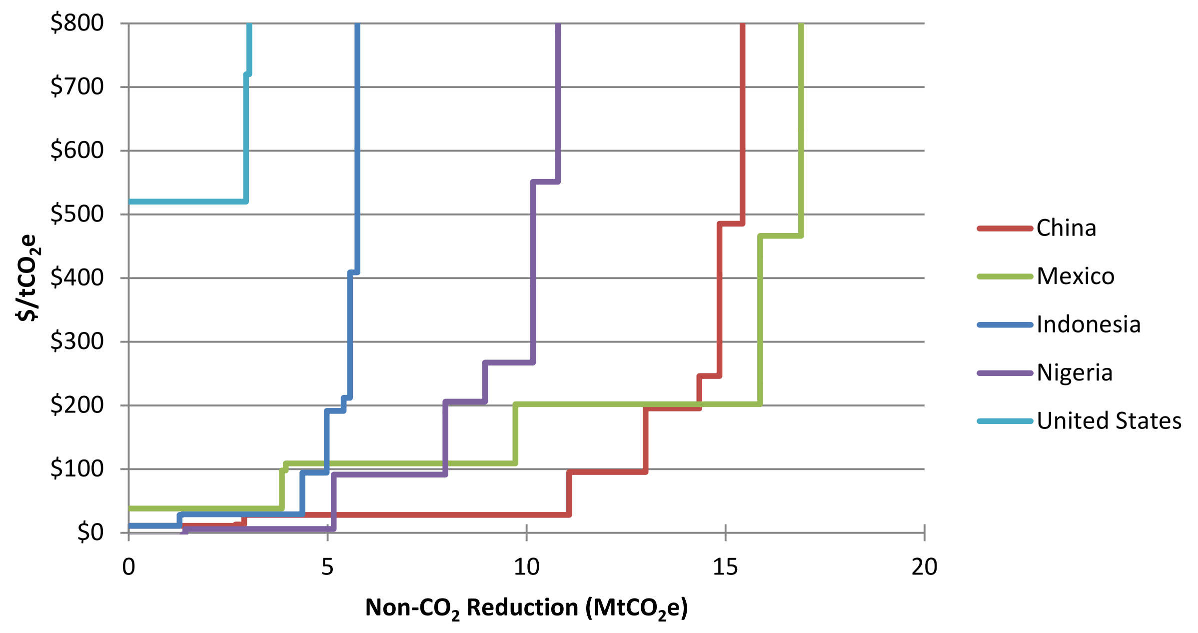
The global abatement potential of CH_4 emissions in wastewater treatment is 36% of total annual emissions by 2030. Table 2-5 and Figure 2-11 present the MAC curve results for 2030 showing a cumulative reduction potential of 218 $MtCO_2e$. The top five emitters contribute approximately 58% of total abatement potential.

Significant initial capital costs combined with no direct monetary benefits limits the abatement potential achieved at lower break-even prices. As shown in Table 2-5, less than 20% of the total abatement potential is realized at prices below $\$50/tCO_2e$ in 2030. These results do not reflect human health benefits or other positive externalities that accompany improvements in wastewater sanitation. If these additional social benefits were included, it would result in higher levels of abatement achievable at lower break-even prices.

Table 2-5: Abatement Potential by Region at Selected Break-Even Prices in 2030

Country/Region	Break-Even Price ($/tCO$_2$e)										
	–10	–5	0	5	10	15	20	30	50	100	100+
Top 5 Emitting Countries											
China	—	—	—	—	—	2.9	2.9	11.1	11.1	13.0	49.7
Indonesia	—	—	—	—	—	1.3	1.3	4.4	4.4	5.0	18.8
Mexico	—	—	—	—	—	—	—	—	3.8	3.9	20.9
Nigeria	—	1.4	1.4	1.4	5.2	5.2	5.2	5.2	5.2	8.0	21.9
United States	—	—	—	—	—	—	—	—	—	—	14.3
Rest of Region											
Africa	0.2	0.5	0.7	0.9	0.9	1.4	1.5	1.6	1.8	3.2	10.8
Asia	—	0.7	0.8	0.9	2.0	2.6	2.6	3.3	5.7	6.8	21.1
Central and South America	—	—	0.0	0.0	0.0	0.0	0.0	0.2	1.3	1.8	9.9
Eurasia	—	—	—	—	—	0.1	0.1	0.3	0.7	1.0	8.9
Europe	—	—	—	—	—	—	—	—	0.0	5.5	10.9
Middle East	—	0.0	0.5	0.8	1.2	2.0	3.5	6.3	7.0	12.9	30.9
North America	—	—	—	—	—	—	—	—	—	—	0.2
World Total	**0.2**	**2.6**	**3.4**	**4.0**	**9.3**	**15.5**	**17.1**	**32.4**	**41.0**	**61.2**	**218.3**

Figure 2-11: Marginal Abatement Cost Curve for Top 5 Emitters in 2020



III.2.4.3 Uncertainties and Limitations

The 2006 version of this report did not explicitly model any abatement measures. This analysis makes an initial attempt at estimating the abatement potential that could be achieved in the wastewater sector. The previous report identified two major factors preventing the modeling of abatement in this sector. The first was data limitations on the type of treatment systems currently employed in each country. The second was the overriding economic and social factors influencing wastewater treatment practices and investment throughout the world.

The analysis presented in this chapter attempts to address the data limitations issue by estimating the quantities of wastewater treated in a number of alternative treatment systems. For simplification purposes, we have exogenously assigned abatement measures to specific existing wastewater treatment systems. Ideally, one would have significantly more data on existing treatment pathway types to support the incorporation of substitutable abatement measures when the investment decision is driven by cost minimization under country- and system-specific conditions.

The investment in large-scale public infrastructure required to improve wastewater treatment systems would not be determined solely by the carbon price associated with CH_4 emissions reductions. The public health benefits of such large-scale sanitation infrastructure projects greatly outweigh the potential benefits provided through any carbon market mechanism. However, the analysis presented here estimates the level of abatement that is technically achievable and the marginal costs of supplying reductions through these technologies, ignoring other potential positive externalities derived from putting these systems in place.

Finally, this chapter does not consider the potential impact of abatement measures applied to industrial wastewater treatment systems. The authors acknowledge that CH_4 emissions from industrial sources can be significant, and in some countries industrial wastewater emissions may represent more than half of total emissions associate with wastewater. However, data limitations, specifically information on the types of treatment systems employed in specific industries and correspondingly the abatement measures available to those systems is needed to estimate the abatement potential from industrial sources. International partnerships like the Global Methane Initiative (GMI) have begun to assess the level of CH_4 emissions available for recovery and use. Any future attempt to model abatement potential from the industrial wastewater sector would also require additional detail on the relative contribution of CH_4 emissions coming from domestic versus industrial wastewater sources.

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