# BEFORE THE ARIZONA CORPORATION COMMISSION



**COMMISSIONERS**
KRISTIN K. MAYES, CHAIRMAN
GARY PIERCE
PAUL NEWMAN
SANDRA D. KENNEDY
BOB STUMP

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| IN THE MATTER OF THE APPLICATION OF RECLAMATION POWER GROUP, LLC FOR APPROVAL OF A PILOT PROGRAM UNDER THE RENEWABLE ENERGY RULES OR, IN THE ALTERNATIVE, A LIMITED WAIVER | DOCKET NO. RE-00000C-05-0030<br><br>Application for Pilot Program Or, in the Alternative, for a Limited Waiver |

Reclamation Power Group, LLC, by and through its undersigned attorneys, respectfully requests the Commission for an order (1) recognizing energy produced at a single municipal waste-to energy ("WTE") facility owned, operated or developed by Reclamation Power Group, LLC as a pilot program pursuant to A.A.C. R14-2-1802(D) or (2) granting a waiver to the Renewable Energy Standard and Tariff Rules, pursuant to A.A.C. R14-2-1816(A), to the limited extent necessary to recognize energy produced at such WTE facility as an "Eligible Renewable Energy Resource" as defined by A.A.C. R14-2-1802 and as otherwise qualifying as "Renewable Energy Credits" under A.A.C. R14-2-1803 and eligible to satisfy the annual renewable energy requirements established by A.A.C. R14-2-1804. This Application is supported by the following:

1. Reclamation Power Group, LLC ("RPG") is an Arizona limited liability company formed in 2008. It has been actively working with entities that haul and dispose of municipal solid waste ("MSW") to develop an economically viable and environmentally safe WTE facility that will use steam produced from the direct combustion of municipal waste to run a turbine and electric generator.

2. After more than a year of discussions and evaluating partnering with various waste haulers and local utilities, RPG has concluded that the state-of-the-art WTE facility it desires to develop in Arizona is not economically viable unless the energy output of the WTE facility qualifies as an "Eligible Renewable Energy Resource" as defined by A.A.C. R14-2-1802 or such energy is otherwise treated as "Renewable Energy Credits" under A.A.C. R14-2-1803 and eligible to satisfy the annual renewable energy requirements established by A.A.C. R14-2-1804.

3. WTE technology is common in Europe (where in 1999 the European Union established a legally binding requirement to reduce landfilling of biodegradable waste) and in several states, [1] but has not yet been actively developed in Arizona where relatively inexpensive land close to municipalities once seemed almost inexhaustible.

4. A WTE facility serves multiple purposes, including disposing of municipal waste, minimizing the need for landfills and producing clean renewable energy. WTE avoids greenhouse gas emissions, generates clean renewable energy, promotes energy independence, and provides safe reliable disposal services. As part of the production cycle recyclable materials, where economical, can first be removed. As a result, communities with WTE facilities generally have a higher average recycling rate than the national EPA average. The remaining waste is screened for hazardous materials (even though most sanitation providers prohibit disposition of hazardous materials with general municipal waste). The sorted municipal waste is then heated to extreme temperatures to incinerate trash while generating clean energy.

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[1] The factual statements contained in this Application are generally derived from the following articles: P. Oze Kaplan, DeCarolis and Thorneloe, *Is It Better to Burn or Bury Waste for Clean Electricity Generation*? (2008) (Kaplin); Waste Not, Want Not: the Facts Behind Waste-to-Energy, Reported by Ted Michaels, President Integrated Waste Services Association (IWSA), September 2008. (IWSA was formed in 1991 to promote integrated solutions to municipal solid waste management challenges). The articles are attached as Appendix A.

5. The production of clean energy from MSW is attained by a heavy investment by the WTE industry and its municipal partners.

6. In 2005, a total of 245 million tons of MSW was generated in the United States, with 166 million tons discarded to landfills. As there is a constant need for MSW disposal, there is no foreseeable end to the amount of MSW available as renewable fuel. At the same time there is an equally constant need for reliable energy generation.

7. Implementing a WTE controlled burning process reduces the volume of waste that is placed in landfills by approximately 90%. Solid waste combustion processes using refuse derived fuel, can also be equipped, where economical, to recover recyclables before shredding the combustible fraction to uniform size for incineration.

8. MSW is a viable energy source for electricity generation. The use of MSW to generate electricity has been estimated to represent roughly 14% of U.S. nonhydro renewable electricity generation. The 87 WTE plants operating in 25 states dispose of more than 90,000 tons of trash each day while generating enough clean energy to supply electricity to about 2.3 million homes nationwide.

9. The energy derived from WTE results from the combustion of both biogenic and fossil materials. WTE facilities can operate 365-days-a-year, 24-hours a day and can operate under severe conditions and thus are generally considered baseload electricity.

10. The WTE facilities generally operate in or near an urban area. As a result they can ease congestion on electric transmission and minimize line loss.

11. The Clean Air Act regulations require WTE facilities to have the latest in air pollution control equipment. A variety of pollution control technologies (such as scrubbers and filters) significantly reduce the regulated gases emitted in the air and there have been major improvements in stack gas emissions controls for both criteria and metal emissions. Performance data indicates that actual emissions from WTE's are less than regulatory requirements.

12. WTE is capable of producing a significantly greater amount of electricity with the same amount of MSW than can be produced through the landfill-gas-to-energy (LFGTE) process. Approximately 65 kWh/ton of MSW can be generated through LFGTE, while 600 kWh/ton of MSW of electricity can be generated from a WTE facility.

13. Burning waste at extremely high temperatures also destroys chemical compounds such as dioxins and furans and disease-causing bacteria.

14. WTE advances the reduction of greenhouse gas emission in three ways: first, it displaces carbon dioxide emissions from fossil fuel based electrical generation; second, it avoids creation and potential release of methane resulting from the disposal of waste in landfills; and third, it recovers ferrous and nonferrous metals from MSW displacing less energy efficient production from raw materials. These result in one (1) ton carbon dioxide equivalent reduction per ton of MSW burned.

15. Life-cycle analysis of the environmental and energy impacts for different combinations of recycling, landfilling and WTE show that WTE yielded the maximum energy with the least environmental impact. WTE has been found to be the best waste management option for both energy and environmental parameters and specifically for greenhouse gas emissions.

16. Section 203 of the Energy Policy Act of 2005 defines municipal solid waste as "renewable energy." Public Law 109-58; 42 USC §15852(b)(2).

17. WTE is already included in many state renewable portfolio standards, including: Alaska, Arkansas, California, Connecticut, District of Columbia, Florida, Hawaii, Iowa, Indiana, Maine, Maryland, Massachusetts, Michigan, Minnesota, Montana, Nevada, New Hampshire, New Jersey, New York, Oregon, Pennsylvania, South Dakota, Virginia, Washington and Wisconsin.

18. When Arizona developed its Renewable Energy Standard it defined a "Renewable Energy Resource" as "an energy resource that is replaced rapidly by a natural,

ongoing process and that is not nuclear or fossil fuel." However, in defining "Eligible Renewable Energy Resources" it failed to list WTE, while listing the less energy efficient and less environmentally safe "Biogas Electricity Generator,"[2] "Biomass Electricity Generator"[3] and "Landfill Gas Generator"[4] as an acceptable Renewable Energy Resource.

19. Under A.A.C. R14-2-1802(D) the Commission may adopt pilot programs in which additional technologies are established as Eligible Renewable Energy Resources.

20. A.A.C. R14-2-1816 (A) permits the Commission "to waive compliance with any provision of this Article for good cause."

21. RPG will submit further explanation of the WTE technology and its proposed WTE facility to the Commission upon request and provided any proprietary or trade secrets related thereto are filed in a manner that protects their confidentiality.

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[2] A.A.C. R14-2-1802(A)(1) defines "Biogas Electricity Generator" as "a generator that produces electricity from gases that are derived from plant-derived organic matter, agricultural food and feed matter, wood wastes, aquatic plants, animal wastes, vegetative wastes, or wastewater treatment facilities using anaerobic digestion or from municipal solid waste through a digester process, an oxidation process, or other gasification process."

[3] A.A.C. R14-2-1802(A)(2) defines "Biomass Electricity Generator" as an electricity generator that uses any raw or processed plant-derived organic matter available on a renewable basis, including: dedicated energy crops and trees; agricultural food and feed crops; agricultural crop wastes and residues; wood wastes and residues, including landscape waste, right-of-way tree trimmings, or small diameter forest thinnings that are 12" in diameter or less; dead and downed forest products; aquatic plants; animal wastes; other vegetative waste materials; non-hazardous plant matter waste material that is segregated from other waste; forest-related resources, such as harvesting and mill residue, pre-commercial thinnings, slash, and brush; miscellaneous waste, such waste pellets, crates, and dunnage; and recycled paper fibers that are no longer suitable for recycled paper production, but not including pained, treated, or pressurized wood, wood contaminated with plastics or metals, tires or recyclable post-consumer waste paper."

[4] A.A.C. R14-2-1802(A)(8) defines "Landfill Gas Generator" as "an electricity generator that uses methane gas obtained from landfills to produce electricity."

WHEREFORE, RPG prays the Commission enter its Order:

1. Designating the first Waste-To-Energy facility owned, operated or developed by Reclamation Power Group, LLC within Arizona as a pilot program pursuant to A.A.C. R14-2-1802(D) and declaring that all energy produced by the WTE facility is an "Eligible Renewable Energy Resource" that produces "Renewable Energy Credits" that can be used to satisfy an "Annual Renewable Energy Requirement" of any "Affected Utility" as those terms are defined by the Commission's Renewable Energy Standard and Tariff Rules. A.A.C. R14-2-1801 *et seq.*; or

2. Alternatively, pursuant to its authority under A.A.C. R14-2-1816 (A), waive the definitional requirements of an "Eligible Renewable Energy Resource" for the first Waste-To-Energy facility owned, operated or developed by Reclamation Power Group, LLC within Arizona and declare that such facility qualifies as an "Eligible Renewable Energy Resource" that produces "Renewable Energy Credits" that can be used to satisfy an "Annual Renewable Energy Requirement" of any "Affected Utility" as those terms are defined by the Commission's Renewable Energy Standard and Tariff Rules.

DATED this 29th day of January, 2010.

CURTIS, GOODWIN, SULLIVAN,
UDALL & SCHWAB, P.L.C.

By: [signature]
William P. Sullivan
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Attorneys for Reclamation Power Group, LLC

## PROOF OF AND CERTIFICATE OF MAILING

I hereby certify that on this 29th day of January, 2010, I caused the foregoing document to be served on the Arizona Corporation Commission by delivering the original and thirteen (13) copies of the above to:

Docket Control
Arizona Corporation Commission
1200 West Washington
Phoenix, Arizona 85007

Mary Walker

1902\pleadings\Application for Pilot Program or Waiver 01-28-10

# APPENDIX A

# WASTE NOT, WANT NOT: THE FACTS BEHIND WASTE-TO-ENERGY

Data and facts show that waste-to-energy avoids greenhouse gas emissions, generates clean renewable energy, promotes energy independence, and provides safe reliable disposal services.

ENERGY
RECOVERY COUNCIL

# Waste Not, Want Not: The Facts Behind Waste-to-Energy

Report by:
Ted Michaels
President
Energy Recovery Council

April 2009

The Energy Recovery Council (ERC) was formed to provide a forum for companies and local governments to promote waste-to-energy.

In addition to providing essential trash disposal services cities and towns across the country, today's waste-to-energy plants generate clean, renewable energy. Through the combustion of everyday household trash in facilities with state-of-the-art environmental controls, ERC's members provide viable alternatives to communities that would otherwise have no alternative but to buy power from conventional power plants and dispose of their trash in landfills.

The 87 waste-to-energy plants nationwide dispose of more than 90,000 tons of trash each day while generating enough clean energy to supply electricity to approximately two million homes nationwide.

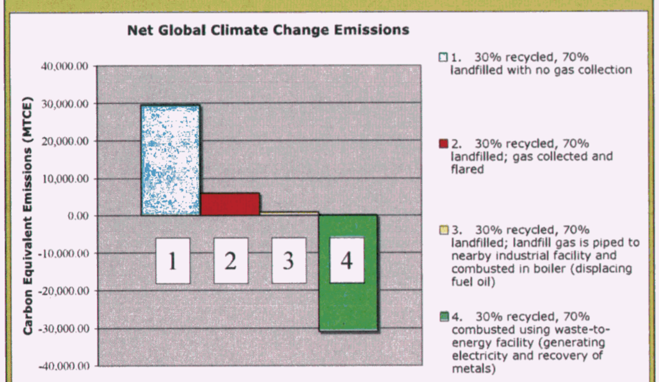
ENERGY
RECOVERY COUNCIL

There is a national need for energy sources that promote energy independence, avoid fossil fuel use, and reduce greenhouse gas emissions. Waste-to-energy is well-positioned to deliver these qualities while also providing for safe and reliable disposal of household trash. Application of EPA's lifecycle analysis demonstrates that for every ton of waste processed at a waste-to-energy facility, a nominal one ton of carbon dioxide equivalents is prevented from entering the atmosphere. As progressive environmental policymakers in Europe have learned, waste-to-energy not only reduces a nation's carbon footprint, it is compatible with high recycling rates and helps to minimize the landfilling of trash.

## The Role of Waste-to-Energy in Mitigating Climate Change

*Waste-to-Energy reduces greenhouse gas emissions*

Waste-to-energy achieves the reduction of greenhouse gas emission through three separate mechanisms: 1) by generating electrical power or steam, waste-to-energy avoids carbon dioxide ($CO_2$) emissions from fossil fuel based electrical generation, 2) the waste-to-energy combustion process effectively avoids all potential methane emissions from landfills thereby avoiding any potential release of methane in the future and 3) the recovery of ferrous and nonferrous metals from MSW by waste-to-energy is more energy efficient than production from raw materials.




Data Source: Thorneloe SA, Weitz K, Jambeck J. Application of the U.S. Decision Support Tool for Materials and Waste Management. WM Journal 2006 August.

These three mechanisms provide a true accounting of the greenhouse gas emission reduction potential of waste-to-energy. A lifecycle analysis, such as the Municipal Solid Waste Decision Support Tool, is the most accurate method for understanding and quantifying the complete accounting of any MSW management option. A life cycle approach should be used to allow decision makers to weigh all greenhouse gas impacts associated with various activities rather than targeting, limiting or reducing greenhouse gas emissions on a source-by-source basis. *(IPCC, EPA)*

The Municipal Solid Waste Decision Support Tool is a peer-reviewed tool, available through the U.S. Environmental Protection Agency and its contractor RTI International, which enables the user to directly compare the energy and environmental consequences of various management options for a specific or general situation. Independent papers authored by EPA (such as *"Moving From Solid Waste Disposal to Management in the United States," Thorneloe (EPA) and Weitz (RTI) October, 2005; and "Application of the U.S. Decision Support Tool for Materials and Waste Management," Thorneloe (EPA), Weitz (RTI), Jambeck (UNH), 2006*) report on the use of the Municipal Solid Waste Decision Support Tool to study municipal solid waste management options.

These studies used a life-cycle analysis to determine the environmental and energy impacts for various combinations of recycling, landfilling, and waste-to-energy. The comprehensive analysis examines collection and transportation, material recovery facilities, transfer stations, composting, remanufacturing, landfills, and combustion. The results of the studies show that waste-to-energy yielded the best results—maximum energy with the least environmental impact (emissions of greenhouse gas, nitrogen oxide, fine particulate precursors, and others). In brief, waste-to-energy was demonstrated to be the best waste management option for both energy and environmental parameters and specifically for greenhouse gas emissions.

When the Municipal Solid Waste Decision Support Tool is applied to the nationwide scope of waste-to-energy facilities that are processing 30 million tons of trash—the waste-to-energy industry prevents the release of approximately 30 million tons of carbon dioxide equivalents that would have been released into the atmosphere if waste-to-energy was not employed.

**Recognition of Waste-to-Energy as a Contributor to Climate Change Solutions**

*International Acceptance*

The ability of waste-to-energy to prevent greenhouse gas emissions on a lifecycle basis and mitigate climate change has been recognized in the actions taken by foreign nations trying to comply with Kyoto targets. The European Union (Council Directive 1999/31/EC dated April 26, 1999) established a legally binding requirement to reduce landfilling of biodegradable waste. Recognizing the methane release from landfills, the European Union established this directive to prevent or reduce negative effects on the environment "including the greenhouse effect" from landfilling of waste, during the whole life-cycle of the landfill.

The Intergovernmental Panel on Climate Change (IPCC) has also recognized the greenhouse gas mitigation aspect of waste-to-energy. The IPCC acknowledges that "incineration reduces the mass of waste and can offset fossil-fuel use; in addition greenhouse gas emissions are avoided, except for the small contribution from fossil carbon." This acknowledgement by the IPCC is particularly relevant due to the IPCC being an independent panel of scientific and technical experts that shared the Nobel Peace Prize with Al Gore.

The German Ministry of the Environment published a report in 2005 entitled "Waste Sector's Contribution to Climate Protection," which states that "the disposal paths of waste incineration plants and co-incineration display the greatest potential for reducing emissions of greenhouse gases." The German report concluded that the use of waste combustion with energy recovery coupled with the reduction in landfilling of biodegradable waste will assist the European Union-15 to meet its obligations under the Kyoto Protocol.

Under the Kyoto Protocol, the Clean Development Mechanism (CDM) is a method of emissions trading that allows the generation of tradable credits (Certified Emission Reductions [CERs]) for greenhouse gas emissions reductions achieved in developing countries, which are then purchased by developed countries and applied toward their reduction targets. CERs are also accepted as a compliance tool in the European Union Emissions Trading Scheme.

Waste-to-energy projects can be accorded offset status under the CDM protocol (AM0025 v7) by displacing fossil fuel-fired electricity generation and eliminating methane production from landfills. An associated CDM memorandum that set out methodology for including waste-to-energy, among others, in CDM projects. The memorandum, entitled "Avoided emissions from organic waste through alternative waste treatment processes," stated in part that CDM status could be accorded projects where "the project activity involves … incineration of fresh waste for energy generation, electricity and/or heat" where the waste "would have otherwise been disposed of in a landfill."

*Domestic Recognition*

The contribution of waste-to-energy to reduce greenhouse gas emissions has been embraced domestically as well. The U.S. Conference of Mayors adopted a resolution in 2004 recognizing the greenhouse gas reduction benefits of waste-to-energy. In addition, the U.S. Mayors Climate Protection Agreement supports a 7 percent reduction in greenhouse gases from 1990 levels by 2012. By signing the agreement, mayors have pledged to take actions in their own communities to meet this target, and have recognized waste-to-

> *"Generation of energy from municipal solid waste disposed in a waste-to-energy facility not only offers significant environmental and renewable benefits, but also provides greater energy diversity and increased energy security for our nation."*
>
> —The United States Conference of Mayors, Adopted Resolution on Comprehensive Solid Waste Disposal Management (2005)

## *How are greenhouse gases measured?*

There are two types of carbon dioxide emissions: biogenic and anthropogenic. The combustion of biomass generates biogenic carbon dioxide. Although waste-to-energy facilities do emit carbon dioxide from their stacks, the biomass-derived portion is considered to be part of the Earth's natural carbon cycle. The plants and trees that make up the paper, food, and other biogenic waste remove carbon dioxide from the air while they are growing, which is returned to the air when this material is burned. Because they are part of the Earth's natural carbon cycle, greenhouse gas regulatory policies do not seek to regulate biogenic greenhouse gas emissions. *(IPCC)*

Anthropogenic carbon dioxide is emitted when man-made substances in the trash are burned, such as plastic and synthetic rubber. Testing of stack gas from waste-to-energy plants using ASTM Standards D-6866 can determine precisely the percentage of carbon dioxide emissions attributable to anthropogenic and biomass sources. Long-term measurements of biogenic $CO_2$ from waste-to-energy plants measure consistently at approximately sixty-seven percent. The amount of anthropogenic $CO_2$ is approximately 1,294 lbs/MWhr when considered as a separate factor. However, when other unit operations are also factored in on a life cycle basis—such as avoided $CO_2$, avoided methane, and recovered materials—the result is a negative value of 3,636 lbs/MWhr. This approach is favored by the IPCC, which has endorsed the use of life cycle assessment.

One must remember that direct emissions are only part of the equation. Because we live in a three-dimensional world, we must look at all inputs if we are truly interested in reducing how much greenhouse gas is being released to the atmosphere and how to reduce that number by the greatest amount. The use of waste-to-energy: avoids landfilling and prevents subsequent methane generation; replaces and offsets electric power generated by fossil fuels and offsets their higher greenhouse gas emissions; and recovers and recycles metals that can be used in products rather than virgin materials, which results in a large greenhouse gas savings.

It is the large amount of greenhouse gases avoided by the use of waste-to-energy compared to the limited amount of direct carbon dioxide emissions emitted through the combustion of trash that has led to the conclusion that for every ton of trash processed by a waste-to-energy plant, approximately one ton of carbon dioxide equivalents are avoided.

**Air Emissions of Waste-To-Energy and Fossil Fuel Power Plants**
(Pounds per Megawatt Hour)

| Fuel Type | Direct $CO_2$[1] | Life Cycle $CO_2E$[2] |
|---|---|---|
| Coal | 2,138 | 2,196 |
| Residual Fuel Oil | 1,496 | 1,501 |
| Natural Gas | 1,176 | 1,276 |
| Waste-to-Energy[3] | 1,294 | **-3,636** |

[1]Based on 2007 EPA eGRID data except WTE which is a nationwide average using 34% anthropogenic $CO_2$.
[2]Life Cycle CO2E for fossil fuels limited to indirect methane emissions using EPA GHG inventory and EIA power generation data. Life Cycle value would be larger if indirect $CO_2$ was included.
[3]Life Cycle $CO_2E$ for WTE based on nominal nationwide avoidance ratio of 1 ton $CO_2E$ per ton of MSW using the Municipal Solid Waste Decision Support Tool, which includes avoided methane and avoided $CO_2$.

energy technology as a means to achieve that goal. As of July 2, 2008, 850 mayors have signed the agreement.

Columbia University's Earth Institute convened the Global Roundtable on Climate Change (GROCC), which unveiled a joint statement on February 20, 2007 identifying waste-to-energy as a means to reduce $CO_2$ emissions from the electric generating sector and methane emissions from landfills. This important recognition from the GROCC, which brought together high-level, critical stakeholders from all regions of the world, lends further support that waste-to-energy plays an important role in reducing greenhouse gas emissions. The breadth of support for the GROCC position is evidenced by those that have signed the joint statement, including Dr. James Hansen of the NASA Goddard Institute for Space Studies, as well as entities as diverse as American Electric Power and Environmental Defense.

### The History and Role of Waste-to-Energy as a Renewable Energy Resource

Municipal Solid Waste is a Renewable Fuel

The sustainable nature of MSW is a major component of its historic renewable status. For more than three and a half decades, despite all of the efforts of EPA and many others to reduce, reuse and recycle, the U.S. diversion rate of municipal solid waste has climbed to barely above 30%. During this same time period, the solid waste generation rate has more than *doubled* and the population has risen by more than 96 million people. Furthermore, for the past several years, the national average diversion rate has increased by less than one percentage point per year. Today, Americans dispose of 278 million tons of municipal solid waste per year of which less than 30 million tons is used as fuel in waste-to-energy facilities. It is clear to see that for the foreseeable future there will be no end to an amount of municipal solid waste available as a renewable fuel.

> *Waste-to-energy plants are a "clean, reliable, renewable source of energy" that 'produce 2,800 megawatts of electricity with less environmental impact than almost any other source of electricity." Communities "greatly benefit from the dependable, sustainable [solid waste disposal] capacity of municipal waste-to-energy plants."*
>
> —USEPA letter from Assistant Administrators Marianne Horinko, Office of Solid Waste and Emergency Response, and Jeffery Holmstead, Office of Air and Radiation to IWSA, 2/14/03

Waste-to-Energy has a Long Track Record as Renewable

Policymakers for three decades (since the inception of the commercial waste-to-energy industry) have recognized municipal solid waste as a renewable fuel. The most recent statutory recognition came in section 203 of the Energy Policy Act of 2005, which defined municipal solid waste as "renewable energy."

While the Energy Policy Act of 2005 is the most recent example, waste-to-energy is given full renewable status for the municipal solid waste it processes under a number of statutes, regulations, and Executive Orders, including:

- the Federal Power Act
- the Public Utility Regulatory Policy Act
- the Biomass Research and Development Act of 2000
- the Pacific Northwest Power Planning and Conservation Act
- Section 45 of the Internal Revenue Code
- Executive Order 13423
- Federal Energy Regulatory Commission regulations (18 CFR.Ch. I, 4/96 Edition, Sec. 292.204)
- statutes in more than two dozen states, including more than a dozen renewable portfolio standards.

The production of clean energy from garbage has been attained by a heavy investment by the waste-to-energy industry and its municipal partners. Waste-to-energy facilities achieved compliance in 2000 with Clean Air Act standards for municipal waste combustors. More than $1 billion was spent by companies and their municipal partners to upgrade facilities, leading EPA to write that the "upgrading of the emissions control systems of large combustors to exceed the requirements of the Clean Air Act Section 129 standards is an impressive accomplishment."

*Waste-to-Energy Generates Much Needed Baseload Renewable Power*

It is important to consider that waste-to-energy plants supply power 365-days-a-year, 24-hours a day and can operate under severe conditions. For example, Florida's waste-to-energy facilities have continued operation during hurricanes, and in the aftermath of the storm provide clean, safe and reliable waste disposal and energy generation. Waste-to-energy facilities average greater than 90% availability of installed capacity. The facilities generally operate in or near an urban area, easing electric transmission to the customer and minimizing waste transport. Waste-to-energy power is sold as "baseload" electricity to utilities that can rely upon its supply of electricity. There is a constant need for trash disposal, and an equally constant need for reliable energy generation.

*Waste-to-Energy Actively Participates in the REC Markets*

Municipalities and companies that own and operate waste-to-energy facilities are already actively participating in the renewable energy trading markets. Waste-to-energy is included in many state renewable portfolio standards and has traded frequently in those markets. Facilities have also sold RECs to entities interested in acquiring RECs on a voluntary basis. Furthermore, waste-to-energy facilities have successfully won bids to sell RECs to the federal government through competitive bidding processes.

**States Defining Waste-to-Energy as Renewable in State Law**
**(as of 6/30/08)**

| | | |
|---|---|---|
| Alaska | Maine | New York |
| Arkansas | Maryland | Oregon |
| California | Massachusetts | Pennsylvania |
| Connecticut | Michigan | South Dakota |
| District of Columbia | Minnesota | Virginia |
| Florida | Montana | Washington |
| Hawaii | Nevada | Wisconsin |
| Iowa | New Hampshire | |
| Indiana | New Jersey | |

*Waste-to-Energy is Compatible with Recycling*

Statistics compiled for more than a decade have proven that waste-to-energy and recycling are compatible despite many attempts by naysayers to conclude otherwise. Since research on the subject began in 1992, communities that rely upon waste-to-energy maintain, on average, a higher recycling rate than the national EPA average.

**WTE Community Average Recycling Rate vs. National Average**

| Year | WTE Recycling Rate | National Recycling (4) |
|---|---|---|
| 2004 | 34% (1) | 31% |
| 2002 | 33% (2) | 30% |
| 1992 | 21% (3) | 17% |

(1) Source: J. V. L. Kiser, based on feedback from 94 WTE communities.
(2) Source: J. V. L. Kiser, based on feedback from 98 WTE communities.
(3) Source: J. V. L. Kiser, based on feedback from 66 WTE communities.
(4) Source: U.S. EPA, based on most recent data available during the study year

Communities that employ integrated waste management systems usually have higher recycling rates and the use of waste-to-energy in that integrated system plays a key role. Specific examples of why waste-to-energy communities are successful recyclers include:

- communities with waste-to-energy plants tend to be more knowledgeable and forward thinking about recycling and MSW management in general;
- communities with waste-to-energy plants have more opportunities to recycle since they handle the MSW stream more;
- the municipal recycling program can be combined with on-site materials recovery at the waste-to-energy plant (e.g. metals recovered at a waste-to-energy plant post-combustion usually cannot be recycled curbside and would otherwise have been buried had that trash been landfilled); and
- waste-to-energy plant officials promote recycling during facility tours and conduct community outreach efforts that may not be occurring in other locations.

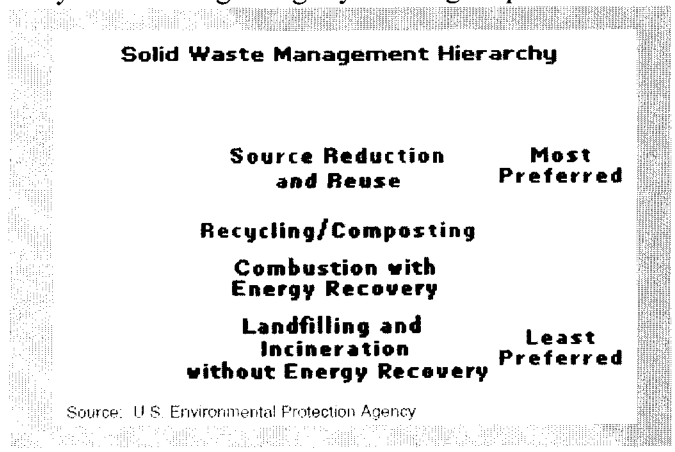
Many communities are connected to off-site recycling programs, such as curbside collection, drop off centers, MRFs, and/or yard waste management. In addition to the typical metals, glass, plastic, and paper from household and/or commercial sources, the communities reported having recycling programs for handling other materials. These ranged from batteries, used oil, and e-waste, to household hazardous waste, public and school outreach programs, and tires management, to scrap metals, food waste, and artificial reef construction projects.

### The U.S. Environmental Protection Agency and the European Union Prefers Waste-to-Energy to Landfilling

Waste-to-energy has earned distinction through the U.S. Environmental Protection Agency's solid waste management hierarchy, which recognizes combustion with energy recovery (as they refer to waste-to-energy) as preferable to landfilling. EPA recommends that after efforts are made to reduce, reuse, and recycle, trash should be managed at waste-to-energy plants where the volume of trash will be reduced by 90%, the energy content of the waste will be recovered, and clean renewable electricity will be generated.

Municipal solid waste should be managed using an integrated waste management system. IWSA encourages and supports community programs to reduce, reuse, recycle and compost waste. Unfortunately, one hundred percent recycling rates are not technically, economically, or practically feasible. After waste is reduced, reused, and recycled, waste will be leftover that must be managed. That is where waste-to-energy comes in.

As noted earlier, EPA's hierarchy is consistent with actions taken by the European Union, which went further by establishing a legally binding requirement to




reduce landfilling of biodegradable waste. The result has been increased recycling rates, higher waste-to-energy usage, reduced greenhouse gas emissions, and less dependence on fossil fuels.

EPA's Solid Waste Management Hierarchy underscores the importance of waste-to-energy as a critical component of any sustainable integrated waste management system.

**Waste-to-Energy Reduces Greenhouse Gas Emissions in Three Important Ways**

**Avoided methane emissions from landfills.** When a ton of solid waste is delivered to a waste-to-energy facility, the methane that would have been generated if it were sent to a landfill is avoided. While some of this methane could be collected and used to generate electricity, some would not be captured and would be emitted to the atmosphere. Waste-to-energy generates more electrical power per ton of municipal solid waste than any landfill gas-to-energy facility.

**Avoided $CO_2$ emissions from fossil fuel combustion.** When a megawatt of electricity is generated by a waste-to-energy facility, an increase in carbon dioxide emissions that would have been generated by a fossil-fuel fired power plant is avoided.

**Avoided $CO_2$ emissions from metals production.** Waste-to-energy plants recover more than 700,000 tons of ferrous metals for recycling annually. Recycling metals saves energy and avoids $CO_2$ emissions that would have been emitted if virgin materials were mined and new metals were manufactured, such as steel.

# Is It Better To Burn or Bury Waste for Clean Electricity Generation?

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The use of municipal solid waste (MSW) to generate electricity through landfill-gas-to-energy (LFGTE) and waste-to-energy (WTE) projects represents roughly 14% of U.S. nonhydro renewable electricity generation. Although various aspects of LFGTE and WTE have been analyzed in the literature, this paper is the first to present a comprehensive set of life-cycle emission factors per unit of electricity generated for these energy recovery options. In addition, sensitivity analysis is conducted on key inputs (e.g., efficiency of the WTE plant, landfill gas management schedules, oxidation rate, and waste composition) to quantify the variability in the resultant life-cycle emissions estimates. While methane from landfills results from the anaerobic breakdown of biogenic materials, the energy derived from WTE results from the combustion of both biogenic and fossil materials. The greenhouse gas emissions for WTE ranges from 0.4 to 1.5 $MTCO_2e/MWh$, whereas the most agressive LFGTE scenerio results in 2.3 $MTCO_2e/MWh$. WTE also produces lower $NO_x$ emissions than LFGTE, whereas $SO_x$ emissions depend on the specific configurations of WTE and LFGTE.

## Introduction

In response to increasing public concern over air pollution and climate change, the use of renewable energy for electricity generation has grown steadily over the past few decades. Between 2002 and 2006, U.S. renewable electricity generation—as a percent of total generation—grew an average of 5% annually (*1*), while total electricity supply grew by only 1% on average (*2*). Support mechanisms contributing to the growth of renewables in the United States include corporate partnership programs, investment tax credits, renewable portfolio standards, and green power markets. These mechanisms provide electric utilities, investment firms, corporations, governments, and private citizens with a variety of ways to support renewable energy development. With several competing renewable alternatives, investment and purchasing decisions should be informed, at least in part, by rigorous life-cycle assessment (LCA).

In 2005, a total of 245 million tons of MSW was generated in the United States, with 166 million tons discarded to landfills (*3*). Despite the increase in recycling and composting rates, the quantity of waste disposed to landfills is still significant and expected to increase. How to best manage the discarded portion of the waste remains an important consideration, particularly given the electricity generation options. Although less prominent than solar and wind, the use of municipal solid waste (MSW) to generate electricity represents roughly 14% of U.S. nonhydro renewable electricity generation (*1*). In this paper we compare two options for generating electricity from MSW. One method, referred to as landfill-gas-to-energy (LFGTE), involves the collection of landfill gas (LFG) (50% $CH_4$ and 50% $CO_2$), which is generated through the anaerobic decomposition of MSW in landfills. The collected LFG is then combusted in an engine or a turbine to generate electricity. A second method, referred to as waste-to-energy (WTE) involves the direct combustion of MSW, where the resultant steam is used to run a turbine and electric generator.

Clean Air Act (CAA) regulations require capture and control of LFG from large landfills by installing a gas collection system within 5 years of waste placement (*4*). The gas collection system is expanded to newer areas of the landfill as more waste is buried. Not all LFG is collected due to delays in gas collection from initial waste placement and leaks in the header pipes, extraction wells, and cover material. Collected gas can be either flared or utilized for energy recovery. As of 2005, there were 427 landfills out of 1654 municipal landfills in the United States with LFGTE projects for a total capacity of 1260 MW. It is difficult to quantify emissions with a high degree of certainty since emissions result from biological processes that can be difficult to predict, occur over multiple decades, and are distributed over a relatively large area covered by the landfill.

CAA regulations require that all WTE facilities have the latest in air pollution control equipment (*5*). Performance data including annual stack tests and continuous emission monitoring are available for all 87 WTE plants operating in 25 states. Since the early development of this technology, there have been major improvements in stack gas emissions controls for both criteria and metal emissions. The performance data indicate that actual emissions are less than regulatory requirements. Mass burn is the most common and established technology in use, though various MSW combustion technologies are described in ref 6. All WTE facilities in the United States recover heat from the combustion process to run a steam turbine and electricity generator.

Policy-makers appear hesitant to support new WTE through new incentives and regulation. Of the 30 states that have state-wide renewable portfolio standards, all include landfill gas as an eligible resource, but only 19 include waste-to-energy (*7*). While subjective judgments almost certainly play a role in the preference for LFGTE over WTE, there is a legitimate concern about the renewability of waste-to-energy. While the production of methane in landfills is the result of the anaerobic breakdown of biogenic materials, a significant fraction of the energy derived from WTE results from combusting fossil-fuel-derived materials, such as plastics. Countering this effect, however, is significant methane leakage—ranging from 60% to 85%—from landfills (*8*). Since methane has a global warming potential of 21 times that of $CO_2$, the $CO_2e$ emissions from LFGTE may be larger than those from WTE despite the difference in biogenic composition.

Although WTE and LFGTE are widely deployed and analyzed in the literature (*9–13*), side-by-side comparison of the life-cycle inventory (LCI) emission estimates on a mass

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per unit energy basis is unavailable. LCI-based methods have been used to evaluate and compare solid waste management (SWM) unit operations and systems holistically to quantify either the environmental impacts or energy use associated with SWM options in the broad context of MSW management (*14–16*).

The purpose of this paper is to present a comprehensive set of life-cycle emission factors—per unit of electricity generated—for LFGTE and WTE. In addition, these emission factors are referenced to baseline scenarios without energy recovery to enable comparison of the emissions of LFGTE and WTE to those of other energy sources. While the methodology presented here is applicable to any country, this analysis is based on U.S. waste composition, handling, and disposal, with which the authors are most familiar. In addition, parametric sensitivity analysis is applied to key input parameters to draw robust conclusions regarding the emissions from LFGTE and WTE. The resultant emission factors provide critical data that can inform the development of renewable energy policies as well as purchasing and investment decisions for renewable energy projects in the prevailing marketplace.

## Modeling Framework

The LFGTE and WTE emission factors are based on the composition and quantity of MSW discarded in the United States in 2005 (Table S1 of Supporting Information (SI)). We excluded the estimated quantity and composition of recycled and composted waste.

The emission factors are generated using the life-cycle-based process models for WTE (*17*) and LF/LFGTE (*18*) embedded in the municipal solid waste decision support tool (MSW-DST). The MSW-DST was developed through a competed cooperative agreement between EPA's Office of Research and Development and RTI International (*19–22*). The research team included North Carolina State University, which had a major role in the development of the LCI database, process, and cost models as well as the prototype MSW-DST. While a summary is provided here, Table S2 (SI) provides a comprehensive set of references for those interested in particular model details. The MSW-DST includes a number of process models that represent the operation of each SWM unit and all associated processes for collection, sorting, processing, transport, and disposal of waste. In addition, there are process models to account for the emissions associated with the production and consumption of gasoline and electricity. The objective of each process model is to relate the quantity and composition of waste entering a process to the cost and LCI of emissions for that process. The LCI emissions are calculated on the basis of a combination of default LCI data and user-input data to enable the user to model a site-specific system. For example, in the landfill process model, one key exogenous input is the efficiency of the LFG collection system. The functional unit in each process model is 1 ton of MSW set out for collection. The MSW includes the nonhazardous solid waste generated in residential, commercial, institutional, and industrial sectors (*3*).

Each process model can track 32 life-cycle parameters, including energy consumption, $CO_2$, CO, $NO_x$, $SO_x$, total greenhouse gases ($CO_2e$), particulate matter (PM), $CH_4$, water pollutants, and solid wastes. $CO_2$ emissions are represented in two forms: fossil and biogenic. $CO_2$ released from anthropogenic activities such as burning fossil fuels or fossil-fuel-derived products (e.g., plastics) for electricity generation and transportation are categorized as $CO_2$-fossil. Likewise, $CO_2$ released during natural processes such as the decay of paper in landfills is categorized as $CO_2$-biogenic.

The management of MSW will always result in additional emissions due to collection, transportation, and separation of waste. However, for this analysis, the configuration of the SWM system up through the delivery of the waste to either a landfill or WTE facility is assumed to be same.

**TABLE 1. Inputs to the Landfill Process Model**

| | LFG collection system efficiency [a] (%) | oxidation rate (%) |
|---|---|---|
| during venting | 0 | 15 |
| during first year of gas collection | 50 | 15 |
| during second year of gas collection | 70 | 15 |
| during third year and on of gas collection | 80 | 15 |

[a] We assumed efficiency of the collection system based on the year of the operation and the ranges stated in U.S. EPA's AP-42 (*8*).

**Electricity Grids.** While LFGTE and WTE provide emissions reductions relative to landfill scenarios without energy recovery, the generation of electricity from these sources also displaces conventional generating units on the electricity grid. The process models in MSW-DST can calculate total electricity generated and apply an offset analysis on the grid mix of fuels specific to each of the North American Electric Reliability Council (NERC) regions, an average national grid mix, or a user-defined grid mix. Because our focus is on the emissions differences between WTE and LFGTE technologies, the emissions factors reported here exclude the displaced grid emissions.

For reference purposes, emission factors for conventional electricity-generating technologies are reported along with the emission factors for WTE and LFGTE (*23*). These emission factors on a per megawatt hour basis include both the operating emissions from power plants with postcombustion air pollution control equipment and precombustion emissions due to extraction, processing, and transportation of fuel. The background LCI data are collected on a unit mass of fuel (*23*); when converted on a per unit of electricity generated basis, the magnitude of resultant emissions depends on the efficiency of the power plant. A sensitivity analysis was conducted on plant efficiencies to provide ranges for emission factors.

**Estimating Emission Factors for Landfill Gas-to-Energy.** The total LCI emissions from landfills are the summation of the emissions resulting from (1) the site preparation, operation, and postclosure operation of a landfill, (2) the decay of the waste under anaerobic conditions, (3) the equipment utilized during landfill operations and landfill gas management operations, (4) the production of diesel required to operate the vehicles at the site, and (5) the treatment of leachate (*18*). The production of LFG was calculated using a first-order decay equation for a given time horizon of 100 years and the empirical methane yield from each individual waste component (*18, 24*). Other model inputs include the quantity and the composition of waste disposed (Table S1, SI), LFG collection efficiency (Table 1), annual LFG management schedule (Figure 1), oxidation rate (Table 1), emission factors for combustion byproduct from LFG control devices (Table S3, SI), and emission factors for equipment used on site during the site preparation and operation of a landfill. While there are hundreds of inputs to the process models, we have modified and conducted sensitivity analysis on the input parameters that will affect the emission factors most significantly.

The emission factors are calculated under the following scenario assumptions: (1) A regional landfill subject to CAA is considered. (2) A single cell in the regional landfill is modeled. (3) Waste is initially placed in the new cell in year 0. (4) The landfill already has an LFG collection network in place. (5) An internal combustion engine (ICE) is utilized to generate electricity. (6) The offline time that is required for

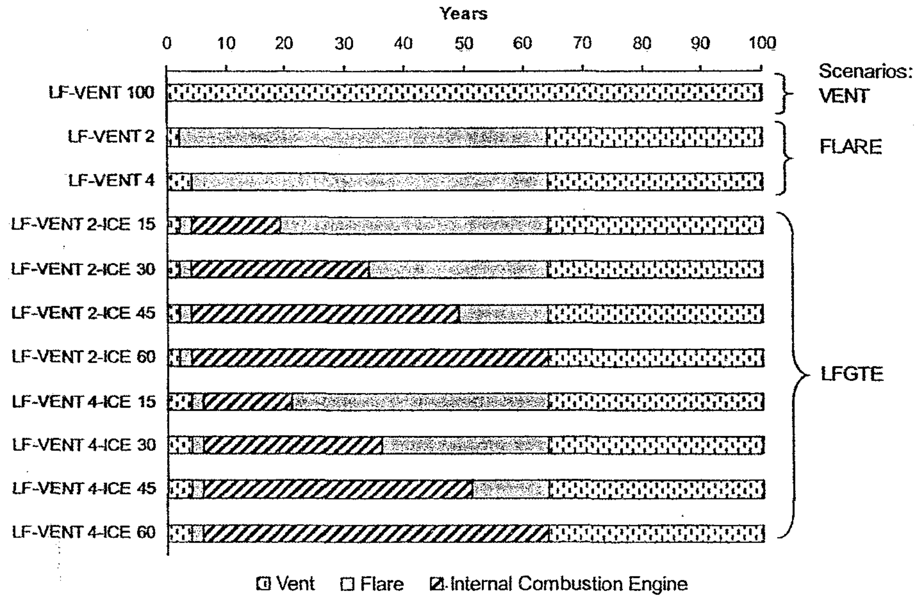


**FIGURE 1. Annual landfill gas management schedule assumed for alternative scenarios.**

the routine maintenance of the ICE is not considered. (7) The LFG control devices are assumed to have a lifetime of 15 years. (8) The LFG will be collected and controlled until year 65. This assumption is based on a typical landfill with an average operating lifetime of 20 years in which LFG production decreases significantly after about 60 years from initial waste placement. This is based on the use of a first-order decay equation utilizing empirical data from about 50 U.S. LFG collection systems.

The timing of LFG-related operations has significant variation and uncertainty that will influence the total emissions from landfills as well as the emission factors per unit of electricity generated. To capture these uncertainties and variation, several different management schemes were tested. Figure 1 presents the different cases considered for LFGTE projects. Each case differs according to the management timeline of the LFG. For instance, LF-VENT 2-ICE 15 corresponds to no controls on LFG for the first two years, after which the LFG is collected and flared in the third and fourth years. From year 5 until year 19, for a period of 15 years, the LFG is processed through an ICE to generate electricity, after which the collected gas is flared until year 65. Finally from year 65 on, the LFG is released to the atmosphere without controls.

To quantify the emissions benefit from LFGTE and WTE, landfill emissions occurring in the absence of an energy recovery unit can serve as a useful comparison. Thus, three baseline scenarios without electricity generation were defined for comparison to the energy recovery scenarios: LF-VENT 100 (LFG is uncontrolled for the entire lifetime of the LF), LF-VENT 2 (LFG is uncontrolled for the first two years, and then the LFG is collected and flared until year 65), LF-VENT 4 (LFG is uncontrolled for the first four years, and then the LFG is collected and flared until year 65). Since emissions are normalized by the amount of electricity generated (MW h) to obtain the emission rates, an estimate of hypothetical electricity generation for the baseline scenarios must be defined. The average electricity generation from a subset of the energy recovery scenarios is used to calculate the baseline emission rates. For example, emission factors [g/(MW h)] for LF-VENT 2 are based on the average of electricity generated in LF-VENT 2-ICE 15, LF-VENT 2-ICE 30, LF-VENT 2-ICE 45, and LF-VENT 2-ICE 60. Additional sensitivity analysis was conducted on oxidation rates where scenarios were tested for a range of 10−35%.

**Estimating Emission Factors for Waste-to-Energy.** The total LCI emissions are the summation of the emissions associated with (1) the combustion of waste (i.e., the stack gas (accounting for controls)), (2) the production and use of limestone in the control technologies (i.e., scrubbers), and (3) the disposal of ash in a landfill (*17*).

Emissions associated with the manufacture of equipment such as turbines and boilers for the WTE facility are found to be insignificant (<5% of the overall LCI burdens) and, as a result, were excluded from this analysis (*25*). In addition, WTE facilities have the capability to recover ferrous material from the incoming waste stream and also from bottom ash with up to a 90% recovery rate. The recovered metal displaces the virgin ferrous material used in the manufacturing of steel. The emission offsets from this activity could be significant depending on the amount of ferrous material recovered. Total LCI emissions for WTE were presented without the ferrous offsets; however, sensitivity analysis was conducted to investigate the significance.

In the United States, federal regulations set limits on the maximum allowable concentration of criteria pollutants and some metals from MSW combustors (*5*). The LCI model calculates the controlled stack emissions using either the average concentration values at current WTE facilities based on field data or mass emission limits based on regulatory requirements as upper bound constraints. Two sets of concentration values (Table S4, SI) are used in calculations to report two sets of emission factors for WTE (i.e., WTE-Reg and WTE-Avg). The emission factors for WTE-Reg were based on the regulatory concentration limits (*5*), whereas the emission factors for WTE-Avg were based on the average concentrations at current WTE facilities.

The $CO_2$ emissions were calculated using basic carbon stoichiometry given the quantity, moisture, and ultimate analysis of individual waste items in the waste stream. The LCI model outputs the total megawatt hour of electricity production and emissions that are generated per unit mass of each waste item. The amount of electricity output is a function of the quantity, energy, and moisture content of the individual waste items in the stream (Table S1, Supporting Information), and the system efficiency. A lifetime of 20 years and a system efficiency of 19% [18000 Btu/(kW h)] were assumed for the WTE scenarios. For each pollutant, the following equation was computed:

$$LCI\_WTE_i = \sum_j \{(LCI\_Stack_{ij} + LCI\_Limestone_{ij} + LCI\_Ash_{ij}) \times Mass_j\}/Elec \quad \text{for all } i \quad (1)$$

where $LCI\_WTE_i$ is the LCI emission factor for pollutant $i$ [g/(MW h)], $LCI\_Stack_{ij}$ is the controlled stack gas emissions for pollutant $i$ (g/ton of waste item $j$), $LCI\_Limestone_{ij}$ is the allocated emissions of pollutant $i$ from the production and use of limestone in the scrubbers (g/ton of waste item $j$), $LCI\_Ash_{ij}$ is the allocated emissions of pollutant $i$ from the disposal of ash (g/ton of waste item $j$), $Mass_j$ is the amount of each waste item $j$ processed in the facility (ton), and Elec is the total electricity generated from MSW processed in the facility (MW h). In addition, the sensitivity of emission factors to the system efficiency, the fossil and biogenic fractions of MSW, and the remanufacturing offsets from steel recovery was quantified.

## Results and Discussion

The LCI emissions resulting from the generation of 1 MW h of electricity through LFGTE and WTE as well as coal, natural gas, oil, and nuclear power (for comparative purposes) were calculated. The sensitivity of emission factors to various inputs was analyzed and is reported. Figures 2–4 summarize the emission factors for total $CO_2e$, $SO_x$, and $NO_x$, respectively.

Landfills are a major source of $CH_4$ emissions, whereas WTE, coal, natural gas, and oil are major sources of $CO_2$-fossil emissions (Table S5, SI). The magnitude of $CH_4$ emissions strongly depends on when the LFG collection system is installed and how long the ICE is used. For example, LF-VENT 2-ICE 60 has the least methane emissions among LFGTE alternatives because the ICE is operated the longest (Table S5, SI). $CO_2e$ emissions from landfills were significantly higher than the emissions for other alternatives because of the relatively high methane emissions (Figure 2, Table S5).

The use of LFG control during operation, closure, and postclosure of the landfill as well as the treatment of leachate contributes to the $SO_x$ emissions from landfills. $SO_x$ emissions from WTE facilities occur during the combustion process and are controlled via wet or dry scrubbers. Overall, the $SO_x$ emissions resulting from the LFGTE and WTE alternatives are approximately 10 times lower than the $SO_x$ emissions resulting from coal- and oil-fired power plants with flue gas controls (Figure 3). The $SO_x$ emissions for WTE ranged from 140 to 730 g/(MW h), and for LFGTE they ranged from 430 to 900 g/(MW h) (Table 2, Table S5). In a coal-fired power plant, average $SO_x$ emissions were 6900 g/(MW h) (Table S6 and S7, SI). Another important observation is that the majority of the $SO_x$ emissions from natural gas are attributed to processing of natural gas rather than the combustion of the natural gas for electricity-generating purposes.

The $NO_x$ emissions for WTE alternatives ranged from 810 to 1800 g/(MW h), and for LFGTE they ranged from 2100 to 3000 g/(MW h) (Figure 4, Table 2, Table S5). In a coal-fired power plant, average $NO_x$ emissions are 3700 g/(MW h) (Tables S6 and S7, Supporting Information). The emission factors for other criteria pollutants were also calculated. Besides CO and HCl emissions, the emission factors for all LFGTE and WTE cases are lower than those for the coal-fired generators (Tables S5–S8, SI).

While we have provided a detailed, side-by-side comparison of life-cycle emissions from LFGTE and WTE, there is an important remaining question about scale: How big an impact can energy recovery from MSW make if all of the discarded MSW (166 million tons/year) is utilized? Hypothetically, if 166 million tons of MSW is discarded in regional landfills, energy recovery on average of ~10 TW h or ~65 (kW h)/ton of MSW of electricity can be generated, whereas a WTE facility can generate on average ~100 TW h or ~600 (kW h)/ton of MSW of electricity with the same amount of MSW (Table 3). WTE can generate an order of magnitude more electricity than LFGTE given the same amount of waste. LFGTE projects would result in significantly lower electricity generation because only the biodegradable portion of the MSW contributes to LFG generation, and there are significant inefficiencies in the gas collection system that affect the quantity and quality of the LFG.

Moreover, if all MSW (excluding the recycled and composted portion) is utilized for electricity generation, the WTE alternative could have a generation capacity of 14000 MW, which could potentially replace ~4.5% of the 313000 MW of current coal-fired generation capacity (*26*).

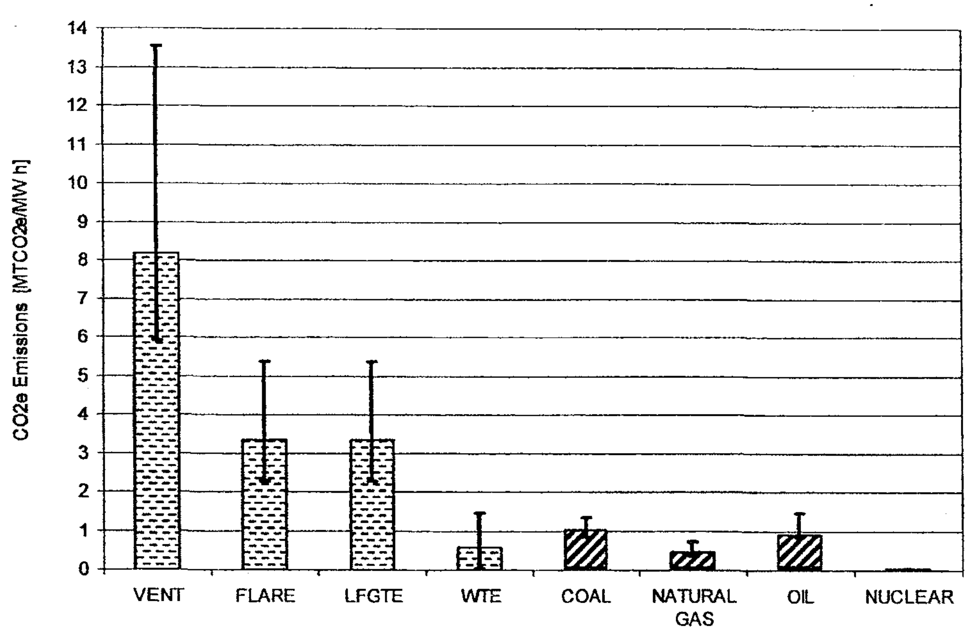


**FIGURE 2. Comparison of carbon dioxide equivalents for LFGTE, WTE, and conventional electricity-generating technologies (Tables S5–S8, Supporting Information, include the full data set).**

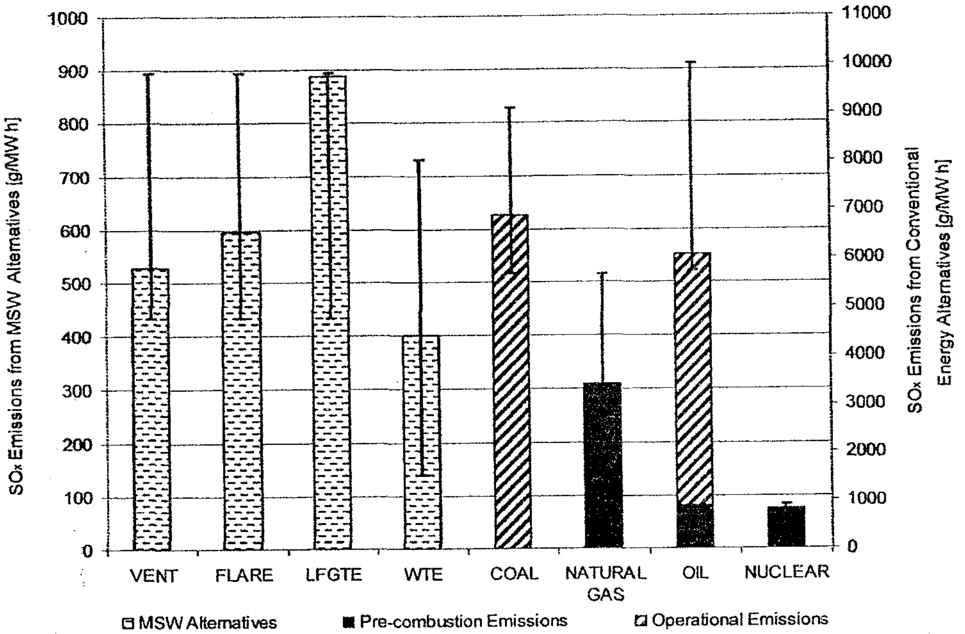


**FIGURE 3. Comparison of sulfur oxide emissions for LFGTE, WTE, and conventional electricity-generating technologies (Tables S5−S8, Supporting Information, include the full data set).**

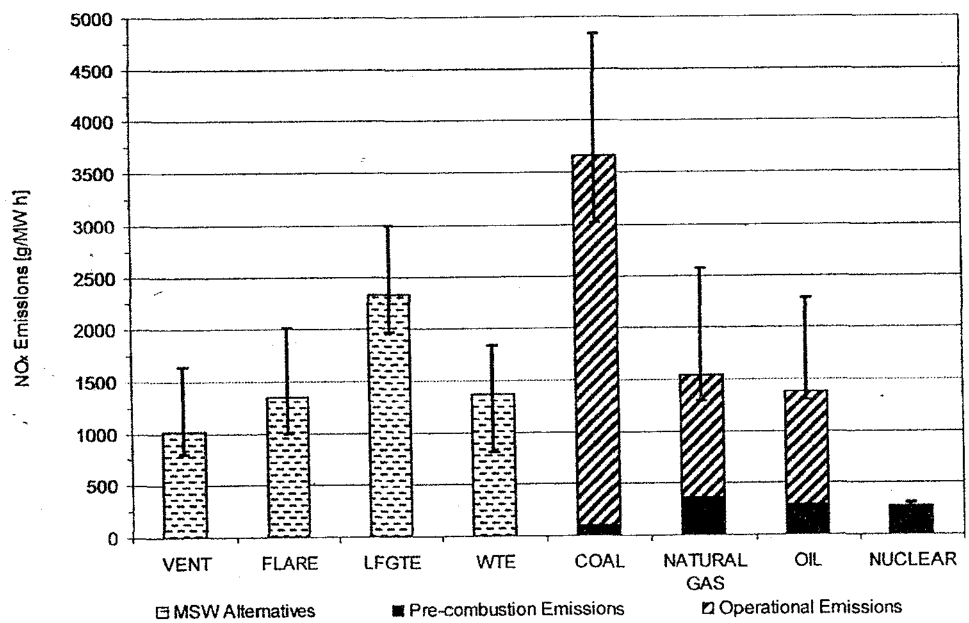


**FIGURE 4. Comparison of nitrogen oxide emissions for LFGTE, WTE, and conventional electricity-generating technologies (Tables S5−S8, Supporting Information, include the full data set).**

A significant portion of this capacity could be achieved through centralized facilities where waste is transported from greater distances. The transportation of waste could result in additional environmental burdens, and there are clearly limitations in accessing all discarded MSW in the nation. Wanichpongpan studied the LFGTE option for Thailand and found that large centralized landfills with energy recovery performed much better in terms of cost and GHG emissions than small, localized landfills despite the increased burdens associated with transportation (*13*). To quantify these burdens for the United States, emission factors were also calculated for long hauling of the waste via freight or rail. Table S9 (SI) summarizes the emission factors for transporting 1 ton of MSW to a facility by heavy-duty trucks and rail.

Sensitivity analysis was also conducted on key inputs. With incremental improvements, WTE facilities could achieve efficiencies that are closer to those of conventional power plants. Thus, the system efficiency was varied from 15% to 30%, and Table 2 summarizes the resulting LCI emissions. The variation in efficiencies results in a range of 470−930 kW h of electricity/ton of MSW, while with the default heat rate; only 600 (kW h)/ton of MSW can be generated. The efficiency also affects the emission factors; for example, $CO_2$-fossil emissions vary from 0.36 to 0.71 Mg/(MW h).

The emission savings associated with ferrous recovery decreased the $CO_2e$ emissions of the WTE-Reg case from 0.56 to 0.49 $MTCO_2e$/(MW h). Significant reductions were observed for CO and PM emissions (Table 2).

**TABLE 2. Sensitivity of Emission Factors for WTE to Plant Efficiency, Waste Composition, and Remanufacturing Benefits of Steel Recovery**

| | baseline factors | | Sensitivity on: system efficiency | waste composition | | steel recovery | |
|---|---|---|---|---|---|---|---|
| **Input Parameters Varied[a]** | | | | | | | |
| heat rate [Btu/(kW h)] | 18000 | 18000 | *[11000, 23000]* | 18000 | 18000 | 18000 | 18000 |
| efficiency (%) | 19 | 19 | *[15, 30]* | 19 | 19 | 19 | 19 |
| composition | default | default | default | *all biogenic* | *all fossil* | default | default |
| stack gas limits | reg | avg | *reg/avg* | reg | reg | *reg* | *avg* |
| steel recovery | excludes | excludes | excludes | excludes | excludes | *includes* | *includes* |
| **Results: Criteria Pollutants** | | | | | | | |
| CO [g/(MW h)] | 790 | 790 | [500,1000] | 740 | 880 | −110 | −110 |
| $NO_x$ [g/(MW h)] | 1300 | 1500 | [810, 1800] | 1200 | 1400 | 1200 | 1400 |
| $SO_x$ [g/(MW h)] | 578 | 221 | [140, 730] | 550 | 620 | 450 | 90 |
| PM [g/(MW h)] | 181 | 60 | [38, 230] | 180 | 190 | −190 | −310 |
| **Results: Greenhouse Gases** | | | | | | | |
| $CO_2$-biogenic [Mg/(MW h)] | 0.91 | 0.91 | [0.58, 1.2] | 1.5 | 0.03 | 0.91 | 0.91 |
| $CO_2$-fossil [Mg/(MW h)] | 0.56 | 0.56 | [0.36, 0.71] | 0.02 | 1.5 | 0.49 | 0.49 |
| $CH_4$ [Mg/(MW h)] | 1.3E−05 | 1.3E−05 | [8.1E−06, 1.6E−05] | 1.6E−05 | 7.9E−06 | −5.0E−05 | −5.0E−05 |
| $CO_2e$ [$MTCO_2e$/(MW h)] | 0.56 | 0.56 | [0.36, 0.71] | 0.02 | 1.45 | 0.49 | 0.49 |
| **Results: Electricity Generation** | | | | | | | |
| TW h [b] | 98 | 98 | [78, 160] | 61 | 37 | 98 | 98 |
| (kW h)/ton | 590 | 590 | [470, 930] | 470 | 970 | 590 | 590 |
| GW [c] | 12 | 12 | [9.7, 20] | 7.6 | 4.7 | 12 | 12 |

[a] For each sensitivity analysis scenario, the input parameters in italics were modified and resultant emission factors were calculated and are reported. [b] The values represent the TWh of electricity that could be generated from all MSW disposed into landfills. [c] 1 TWh/8000 h = TW; a capacity factor of approximately 0.91 was utilized.

**TABLE 3. Comparison of Total Power Generated**

| | total electricity generated from 166 million tons of MSW, TW h | total power [a], GW | electricity generated from 1 ton of MSW, (kW h)/ton |
|---|---|---|---|
| waste-to-energy | 78−160 | 9.7−19 | 470−930 |
| landfill-gas-to-energy | 7−14 | 0.85−1.8 | 41−84 |

[a] 1 TW h/8000 h = TW; a capacity factor of approximately 0.91 was utilized.

The composition of MSW also has an effect on the emission factors. One of the controversial aspects of WTE is the fossil-based content of MSW, which contributes to the combustion emissions. The average composition of MSW as discarded by weight was calculated to be 77% biogenic- and 23% fossil-based (Table S1, SI). The sensitivity of emission factors to the biogenic- vs fossil-based waste fraction was also determined. Two compositions (one with 100% biogenic-based waste and another with 100% fossil-based waste) were used to generate the emission factors (Table 2). The $CO_2e$ emissions from WTE increased from 0.56 $MTCO_2e$/(MW h) (WTE-Reg) to 1.5 $MTCO_2e$/(MW h) when the 100% fossil-based composition was used (Table 2, Figure 2). However, the $CO_2e$ emissions from WTE based on 100% fossil-based waste were still lower than the most aggressive LFGTE scenario (i.e., LF-VENT2-ICE60) whose $CO_2e$ emissions were 2.3 $MTCO_2e$/(MW h).

The landfill emission factors include the decay of MSW over 100 years, whereas emissions from WTE and conventional electricity-generating technologies are instantaneous. The operation and decomposition of waste in landfills continue even beyond the monitoring phases for an indefinite period of time. Reliably quantifying the landfill gas collection efficiency is difficult due to the ever-changing nature of landfills, number of decades that emissions are generated, and changes over time in landfill design and operation including waste quantity and composition. Landfills are an area source, which makes emissions more difficult to monitor. In a recent release of updated emission factors for landfill gas emissions, data were available for less than 5% of active municipal landfills (*27*). Across the United States, there are major differences in how landfills are designed and operated, which further complicates the development of reliable emission factors. This is why a range of alternative scenarios are evaluated with plausible yet optimistic assumptions for LFG control. For WTE facilities, there is less variability in the design and operation. In addition, the U.S. EPA has data for all the operating WTE facilities as a result of CAA requirements for annual stack testing of pollutants of concern, including dioxin/furan, Cd, Pb, Hg, PM, and HCl. In addition, data are available for $SO_2$, $NO_x$, and CO from continuous emissions monitoring. As a result, the quality and availability of data for WTE versus LFGTE results in a greater degree of certainty for estimating emission factors for WTE facilities.

The methane potential of biogenic waste components such as paper, food, and yard waste is measured under optimum anaerobic decay conditions in a laboratory study (*24*), whose other observations reveal that some portion of the carbon in the waste does not biodegrade and thus this quantity gets sequestered in landfills (*28*). However, there is still a debate on how to account for any biogenic "sequestered" carbon. Issues include the choice of appropriate time frame for sequestration and who should be entitled to potential sequestration credits. While important, this analysis does not assign any credits for carbon sequestered in landfills.

Despite increased recycling efforts, U.S. population growth will ensure that the portion of MSW discarded in landfills will remain significant and growing. Discarded MSW is a viable energy source for electricity generation in a carbon-constrained world. One notable difference between LFGTE and WTE is that the latter is capable of producing an order of magnitude more electricity from the same mass of waste. In addition, as demonstrated in this paper, there are significant differences in emissions on a mass per unit energy basis from LFGTE and WTE. On the basis of the assumptions in this paper, WTE appears to be a better option than LFGTE. If the goal is greenhouse gas reduction, then WTE should be considered as an option under U.S. renewable energy policies. In addition, all LFTGE scenarios tested had on the average higher $NO_x$, $SO_x$, and PM emissions than WTE. However, HCl emissions from WTE are significantly higher than the LFGTE scenarios.

## Supporting Information Available

MSW composition, physical and chemical characteristics of waste items, detailed LCI tables and sensitivity results, and emission factors for long haul of MSW. This material is available free of charge via the Internet at http://pubs.acs.org.

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