The potential of waste-to-energy in reducing GHG emissions

Carbon Management (2012) 3(2), 133–144



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Background: The combustion of municipal solid waste (MSW) to generate heat or electricity (waste-to-energy [WTE]) could reduce net GHG emissions in the USA compared with combusting methane from landfills. Moreover, negative CO_2 emissions could be achieved with CCS because 66% of the carbon in MSW is typically biogenic. **Results and conclusion:** For the five largest landfill sites in each state, we estimate that at least 58 and 11 sites have enough MSW to fuel WTE plants of >50 MWe and >100 MWe, respectively. Furthermore, half of these sites lie within 20 km of potential underground saline and other CO_2 storage reservoirs. We estimate that the levelized electricity cost for WTE without CO_2 capture is US$94/MWh and is $285/MWh with amine-based post-combustion capture technology. The cost of CO_2 capture is $58/Mg CO_2, resulting in a cost for carbon negative emissions of $93/Mg CO_2; substantially lower than for some geoengineering methods, including capturing CO_2 from air.

Background

Municipal solid waste (MSW) is a ubiquitous byproduct of industrialized societies. **Sanitary landfills** are the most commonly used means to dispose of MSW, but the limited availability of land in some places can make it difficult to find suitable locations for new landfills [1]. Additionally, in some cases, leachate produced from landfills can contaminate ground water. Current landfills are also the source of substantial GHG emissions. The US EPA estimates that 22.3% of US methane emissions in 2008 came from landfills [101]. Landfills also contain considerable unused energy in the form of MSW. Even when landfill-gas-to-energy (LFGTE) systems are used, they do not recover all of the methane produced by decomposition of the MSW.

One alternative to LFGTE is the combustion of MSW to generate electricity or heat in a process commonly known as **waste-to-energy** (WTE). This method reduces the land requirement for waste disposal and could be a more efficient energy recovery system than LFGTE. WTE systems fit well in the concept of 'zero waste', along with the recycling and reuse of the MSW. WTE can also provide additional economic benefit in recovering up to 90% of ferrous materials from both waste-stream inflow and bottom-ash outflow [2]; 77% of the WTE facilities in the USA already have this capacity [3]. If WTE facilities are properly equipped with pollution control devices for flue gases, these systems can be cleaner than sanitary landfills in terms of overall environmental pollution.

If CO_2 emissions from WTE plants were captured and stored underground, these plants could lead to **carbon negative** credits, as 66% of the carbon in MSW in the USA is typically biogenic [4–6]. WTE with **CCS** (WTE–CCS) is therefore one potential method to achieve carbon negative footprints [2,7]. In fact, Kaplan *et al.* estimate that in the USA the potential capacity for WTE is 9.7–19 GW [102]. In contrast, the total installed US capacity in 2008 was just 2.3 GW, combusting only 6.7% of the nation's MSW [8].

Based on the large potential for energy generation, and the opportunity that WTE provides to be carbon negative, we evaluate the electricity generation potential of WTE from MSW based on the waste streams of the

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10.4155/CMT.12.11 ISSN 1758-3004

five largest landfill sites in each US state. We then calculate the energy penalty and cost of CO_2 capture from these potential sites using amine-based post-combustion capture technology. Finally, we compare GHG emissions and costs of electricity generation from LFGTE and WTE with and without CO_2 capture.

In 2008, MSW generated in the USA was estimated to be 226–353 × 10^6 Mg [8,103]. Of this, only 24–29 × 10^6 Mg of MSW was used for WTE. Out of the 80 operating WTE plants in the USA, 65 are mass-burning plants [3]. Mass-burning plants are the most common worldwide and combust MSW directly, whether or not recyclable materials have first been removed. The other major type of WTE plants combust refuse-derived fuel, which is the MSW remaining after grit, glass and other non-combustibles have been removed and the MSW has been shredded, compressed, dried and formed into pellets [9].

Conceptually, all oxycombustion, precombustion and post-combustion CO_2 capture technologies suitable for coal or biomass plants can also be applied to WTE facilities. Klein *et al.* assessed oxycombustion as a CO_2 capture technique for WTE plants [4], and Zeman analyzed WTE with post-combustion CO_2 capture based on general design parameters [5] published by the IPCC Special Report on Carbon Dioxide Capture and Storage [10]. Here, we also focus on post-combustion CO_2 capture for WTE facilities, but we use the specifications for the amine-based process, which is currently the most commercialized post-combustion capture technology. In this process, CO_2 is chemically absorbed by an amine solution that is sprayed into the flue gas as it is funneled through a reactor after leaving the furnace. The CO_2-bearing amine solution is then collected and transferred to another reactor, where it is heated to release the CO_2, which is stripped off and compressed into a dense phase for transport and storage (Figure 1). The two major energy penalties in this process are the heat energy required to strip off the absorbed CO_2 and the energy (heat or electricity) required to compress the captured CO_2.

Key terms

Sanitary landfills: Municipal solid waste that is not recycled or reused is ultimately landfilled. The anaerobic decomposition of the biodegradable portion of the municipal solid waste in the landfills generates CH_4 and CO_2, also called biogas. Although biogas can be collected and used a source of energy, the complete recovery of biogas is impossible. Hence, these landfills are source of CH_4 and CO_2 emissions to the atmosphere.

Waste-to-energy: Refers to the combustion of municipal solid waste to generate useful energy. The combustion of waste-to-energy converts all carbon (biogenic and fossil origin) into CO_2. Because CO_2 generated from biogenic carbon is considered to be carbon neutral, and two thirds of municipal solid waste carbon comes from biogenic rather than fossil-fuel sources, net GHG emissions from waste-to-energy have the potential to be carbon negative, reducing CO_2 concentrations in the atmosphere.

Carbon negative: Describes any process that removes CO_2 from the atmosphere. In the case of waste-to-energy coupled with CCS, the carbon comes primarily from biogenic sources such as plant materials and would lead to the carbon negative emissions, because CO_2 is eventually removed from the atmosphere.

CCS: The process for capturing CO_2 from point sources that use carbon-containing fuels such as coal power plants, transporting it to suitable geological storage sites, and storing it underground so that CO_2 is not emitted to the atmosphere.

CO_2 capture technologies: Used to separate CO_2 from other flue gases (gases produced from the oxidation of carbon based fuels) and are classified in three ways: oxycombustion, precombustion and post-combustion. In oxycombustion, fuel is oxidized in oxygen instead of air, and hence the flue gases contain CO_2 and H_2O but not N_2, which otherwise is a major component of the flue gases in conventional combustion. In precombustion capture, the fuel is first gasified primarily into CO and H_2, and the CO is further converted into CO_2. Then, the CO_2 is separated and the H_2 is utilized as a fuel. In post-combustion capture, CO_2 is captured from the flue gases generally by chemical or physical processes.

Methodology & assumptions

GHG emissions from MSW disposal

We evaluate the net GHG emissions (CO_2-e) from using MSW in WTE with and without CO_2 capture. We also compare them to the same emissions from landfill disposal of MSW in which there is no landfill gas recovery, landfill gas recovery with flaring and landfill gas recovery with electricity generation. Our emissions calculations build on previous approaches and use the following assumptions [2,6,104,105]:

- 30% of the MSW is carbon on a wet-weight basis, 66% of which is biogenic and the rest is of fossil origin [6];
- CO_2 emissions from the carbon of biogenic origin are carbon neutral;
- Each Mg of MSW disposed in the landfill generates 100 m^3 of methane in its lifetime [104];
- 50% of the biogas generated from landfills is CH_4 [106];
- CH_4 emissions have 21-times the global warming potential (GWP) of CO_2 (based on a 100-year time horizon);
- Landfill gas recovery systems capture 75% of the biogas generated at a landfill and the rest escapes to the atmosphere (based on the range given by Bahor *et al.* [107]);
- The captured CH_4 in the biogas is released to the atmosphere as CO_2 after either being flared or combusted for electricity generation;
- GHG emissions for the collection and transport of MSW are not considered because these emissions are assumed to be the same for WTE and landfill disposal.

WTE with CCS

For the scenario of WTE with CCS, we assume that WTE plants are established at the five largest landfills in each state and that the plants would incinerate 60% of the waste these landfills receive annually [108]. We base our calculations of the energy produced by incineration on general figures established for the heat content of the MSW and the heat rate of WTE plants [2,4,11]. The values for both are listed in Table 1.

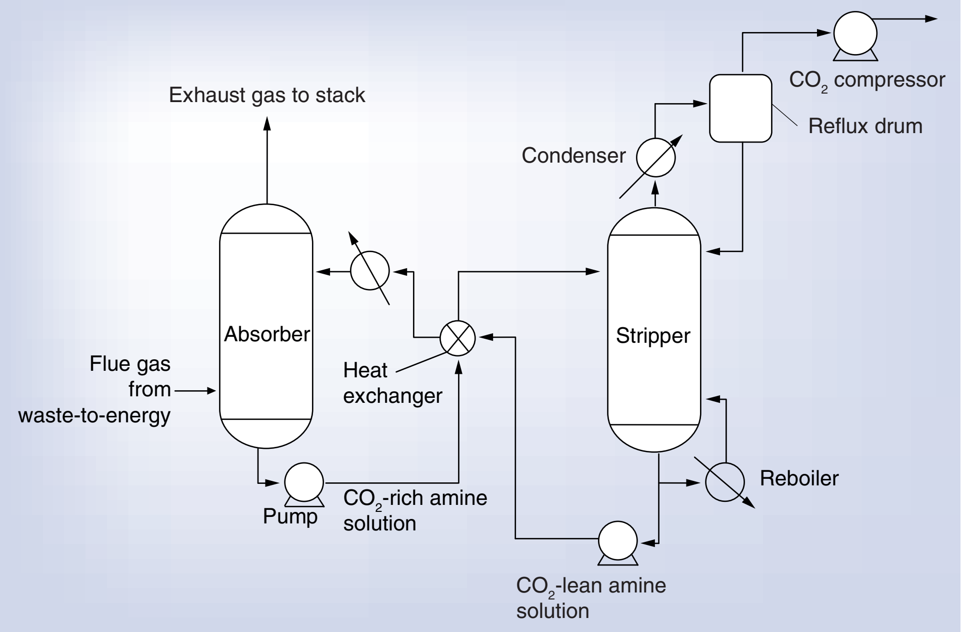

Figure 1. Schematic of amine-based post-combustion CO_2 capture for a waste-to-energy plant. Adapted from [121].

We assume that 90% of the total CO_2 in the flue gases of WTE plants is captured by the amine-based post-combustion process. The operational and design parameters for CO_2 capture are taken from the US National Energy Technology Laboratory estimates for coal and natural gas plants [109]. The primary difference between the capture systems for these two types of plants has to do with the partial pressure of CO_2 in their flue gases. For a subcritical pulverized coal plant (PC-sub), the partial pressure is 13.2%, while for a natural gas combined cycle plant (NGCC) it is 4.1% [109]. Thus to capture the same amount of CO_2 from a NGCC plant, a larger capture reactor is needed along with greater recirculation of the amine solution between the CO_2 absorber and the stripper. This in turn leads to the need for more energy to heat the amine solution in the stripper and extra auxiliary energy to run the capture system. The partial pressure of CO_2 in WTE plants would depend upon several factors, including MSW composition and stoichiometric air-to-fuel ratios. Using the data of Albina *et al.*, we assume the partial pressure of CO_2 in the flue gases from WTE plants to be 8.5%, a value in between that of PC-sub and NGCC plants [110].

We further assume that the energy required to run the CO_2 capture system is a linear function of the partial pressure of CO_2 in the flue gases, and we interpolate the energy based on that currently required by a PC-sub and NGCC plant to run the same capture system **(Table 2)**. We assume that the electricity required to compress the captured CO_2 to 15 MPa prior to transport is the same as that needed by a PC-sub plant per megagram of compressed CO_2. The sum of the energy for the capture system and for the compressor then is the energy penalty to a WTE plant when it is running a CO_2 capture system, and we use this sum to calculate the overall heat rate of WTE–CCS as shown in **Table 1**.

We calculate the GHG emissions from WTE with and without CO_2 capture, and compare them with emissions from landfill disposal. For the electricity generation from landfill gas, we assume that half of the CH_4 captured from the landfill is used for electricity generation and the rest is flared, as not all of the biogas can be used to produce electricity. We assume that the electric generators are internal combustion engines, the most widely used generators for landfill gas in the USA [106]; these are assumed to have a heat rate of 10.55 MJ/kWh (10,000 Btu/kWh) and a capacity factor of 85% [12].

Electricity generated from MSW will reduce net GHG emissions if it replaces electricity generated by other means that produce more emissions. We calculate net GHG emissions as the difference between the emissions from WTE with and without capture and the 2008 average carbon intensity of US electricity generation, which was 0.59 Mg of CO_2/MWh [111].

We do not consider other GHGs emitted from the WTE and landfills besides CO_2 and CH_4. N_2O is the most significant of these due to its high GWP. N_2O is formed in WTE during incineration of waste and is also emitted from the landfills. However, the net effect of these emissions, as a GWP, is less than 1% in WTE systems and approximately 3% for landfills [13,112].

Cost of electricity generation

We calculate the cost of the electricity generation for a 100-MWe size WTE plant. This is large for a typical WTE facility but, as shown below, the capacity can be supported by the amount of MSW being stored in a number of US landfills. The capital cost of a WTE plant depends upon its design, capacity and pollution control equipment. Capital costs typically range from US$7500 to $11,000/kW **(Table 1)** [9,113]. The tipping fees that WTE

Key term

Biogenic origin: A fraction of carbon in municipal solid waste is of biogenic origin, derived from plants and other fresh organic material, and the rest is of fossil origin, derived from fossil fuels. CO_2 emissions from carbon of biogenic origin are potentially carbon neutral because they are derived from recent, photosynthetically derived materials.

Table 1. Descriptions of energy penalties and costs for waste-to-energy plants.

Parameter	WTE	WTE–CCS
Net power output (MWe)	100	42†
Heat content (MJ/kg)	13	13
Net plant HHV efficiency (%)	20	8†
Net plant HHV heat rate (MJ/kWh)	17.94	42.88†
Capacity factor (%)	85%	85%
Annual MSW input (Mg)	1,027,608	1,027,608
CO_2 capture (%)		90
Auxiliary power (MW) – non-CCS	6.25	6.25
Auxiliary power (MW) – CCS:		
▪ Amine system auxiliaries		7.19
▪ CO_2 compression		14.27
▪ CCS steam use (electricity equivalent)		32.05
▪ Other		4.67
Total auxiliary power (MW)	6.25	64.42†
Non-CCS plant cost (US$)	825,000,000	825,000,000
CCS system costs:		
▪ CO_2 removal system ($)		127,866,454
▪ CO_2 compression and drying ($)		10,669,196
Total capital costs ($)	825,000,000	963,535,650
O&M costs:		
▪ O&M costs – non-CCS ($/Mg)	30	30
▪ O&M costs – CCS annual ($)		3,275,960†
Tipping fee ($/Mg)	50	50
Discount rate (%)	10	10
Plant life (years)	25	25
Annualization factor	0.11	0.11

†Calculated/results.
HHV: Higher heating value; MSW: Municipal solid waste; O&M: Operating and maintenance; WTE: Waste-to-energy.

plants charge to dispose of MSW offset some of the plants' operating and maintenance (O&M) costs. Tipping fees in the USA for the year 2008 ranged from $28 to $108/Mg MSW at existing WTE facilities, and from $28 to $85/Mg of MSW at landfills [8]. In this analysis, we assume the plants charge an average tipping fee of $50/Mg.

In the case of WTE plants with CCS, we assume the same heat input capacity as that of a 100-MWe WTE plant. In this way, the base plant size (fuel supply system, combustion system and pollution control equipment) and, hence, the base plant cost, remains the same for both the plants. The costs of CO_2 capture system for WTE–CCS (capital and O&M) is estimated from data compiled by the National Energy Technology Laboratory [109]. These costs are interpolated from those for PC-sub and NGCC plants based on the partial pressure of CO_2 in the flue gases in the same way that the energy penalty for CCS in WTE is estimated (Table 1). For WTE plants with CCS (i.e., WTE–CCS), the costs include those for capturing CO_2 and compressing it to 15 MPa. Any additional CCS costs for CO_2 transport and storage are not considered here.

In order to compare WTE with LFGTE, we also calculate the cost of electricity generation from landfill gas. LFGTE involves the cost for a landfill gas collection system. Capital (C_{cap}) and O&M ($C_{O\&M}$) costs for landfill gas collection systems are derived from the following linear regression equations presented by the US EPA [114]:

- $C_{cap} = 1942.9 * Q_{bio} + 200{,}000;$
- $C_{O\&M} = 459.79 * Q_{bio} + 5141.4.$

Here, C_{cap} and $C_{O\&M}$ are the capital cost and annual operation and maintenance cost of a landfill gas collection system and Q_{bio} is the biogas collected from the landfill in cubic feet per minute. The capital cost and annual O&M costs of generators >0.8 MW are assumed to be $1700/kW and $180/kW, respectively [106]. The total cost of LFGTE then is the cost of the landfill gas recovery system plus the cost of the generators.

We convert the total costs for LFGTE, WTE and WTE–CCS into annual levelized costs for generating electricity using the assumptions that the discount rate from all three plant types is 10% and that the plants have a 25-year life span. The cost of electricity generation is calculated by dividing the annualized costs by the total electricity generated yearly.

We also calculate the cost of CO_2 capture and the cost of carbon negative emissions from WTE–CCS. The cost of CO_2 capture is calculated by dividing the annualized cost of the CO_2 capture system by the annual CO_2 captured. For the cost of carbon negative emissions, the annualized cost of CO_2 capture system is divided by the annual carbon negative emissions.

Table 2. Energy penalty for CO_2 capture.

Auxiliary power use (GJ/Mg of CO_2 capture)	Subcritical PC–CCS [11]	NGCC–CCS [11]	WTE–CCS
Amine system auxiliaries	0.17	0.21	0.19
CO_2 compression	0.38	0.33	0.38
CCS steam use	4.71	4.66	4.71
Other	0.12	0.10	0.12

NGCC: Natural gas combined cycle plant; PC: Pulverized coal; WTE: Waste-to-energy.

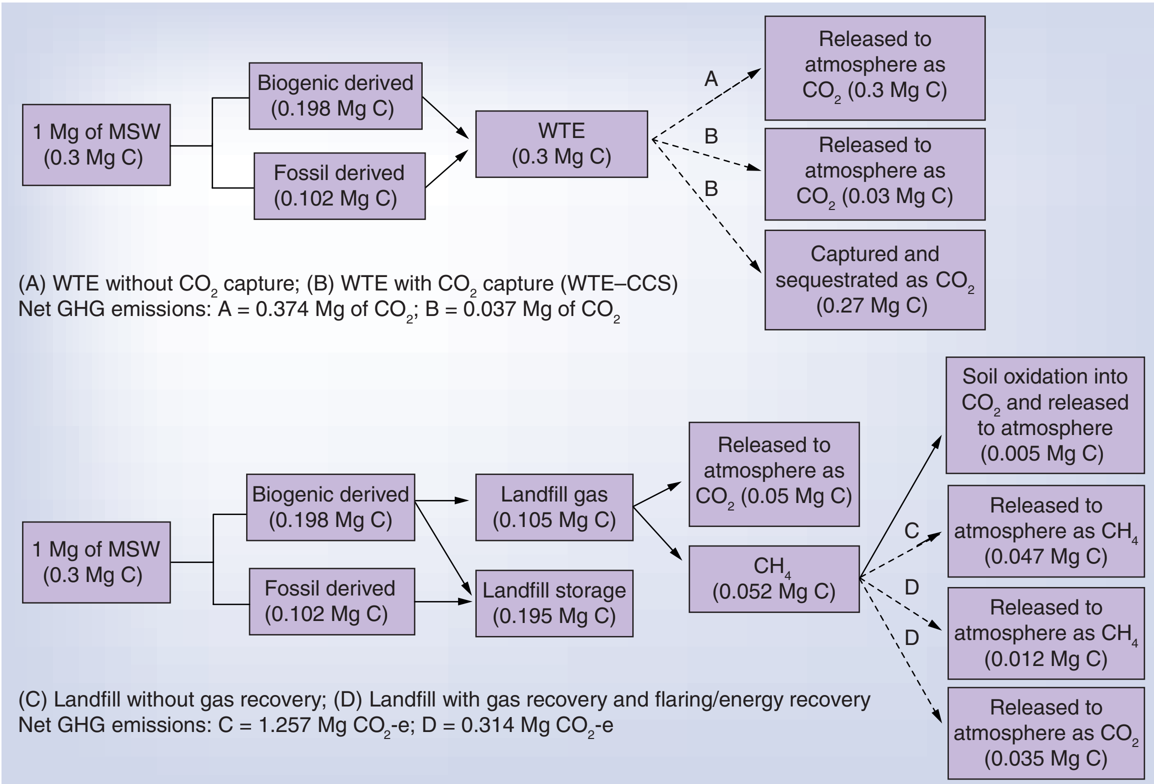

Figure 2. Fate of carbon from 1 Mg of municipal solid waste under different disposal scenarios. The net emissions do not consider the GHG emissions avoided due to the electricity generation from municipal solid waste. MSW: Municipal solid waste; WTE: Waste-to-energy.

Results

Figure 2 depicts the fate of carbon in 1 Mg of MSW under the five disposal scenarios considered: landfilling with no methane capture, landfilling with methane capture, LFGTE, WTE and WTE–CCS. The conversion of carbon into CH_4, CO_2 and its landfill storage is based on the assumptions described in ‘GHG emissions from MSW disposal’. Of these, the WTE and WTE–CCS scenarios result in significantly lower net emissions than the landfill disposal without landfill gas recovery. The GHG emissions from 1 Mg of MSW are 1.257 Mg CO_2-e without landfill gas recovery, whereas GHG emissions from WTE are 0.374 Mg of CO_2. The GHG emissions from landfill disposal approaches WTE only when 70% of the landfill gas is recovered and either flared or utilized for energy generation **(Figure 2)**. Moreover, if the GHG balance includes the average emissions avoided by the electricity generated from waste, the results favor WTE because of its ability to generate more electricity than LFGTE.

When these results are scaled to the amount of MSW received by the five-largest landfill sites in each state, WTE would produce GHG emissions of 30.8×10^6 Mg/year as compared with 88.1×10^6 Mg/year (CO_2-e) from the landfills assuming no landfill gas recovery **(Figure 3)**. However, if 75% of the gas were captured and flared, GHG emissions from the landfills would drop to 22.0×10^6 Mg/year. When the emissions avoided by generating electricity from the waste are considered, emissions drop even further. In the case of LFGTE, the emissions would decrease to 17.1×10^6 Mg/year and, in the case of WTE, net emissions would actually be negative, totaling -7.8×10^6 Mg/year. WTE–CCS is even better, for not only would net emissions be negative, but total plant emissions would be negative as well because approximately 66% of MSW is renewable biomass. In total, WTE–CCS would withdraw 53.8×10^6 Mg of CO_2 from the land–atmosphere carbon cycle; with net CO_2 emissions avoided reaching -70×10^6 Mg/year.

Coincident with reducing net emissions, these WTE facilities would be adding more electric generating capacity to the US power system. We estimate that at least 58 landfill sites have the potential to install WTE plants with capacities of 50 MWe or more, and 11 sites have the potential for >100 MWe **(Figure 4)**. Among states, California has the largest WTE

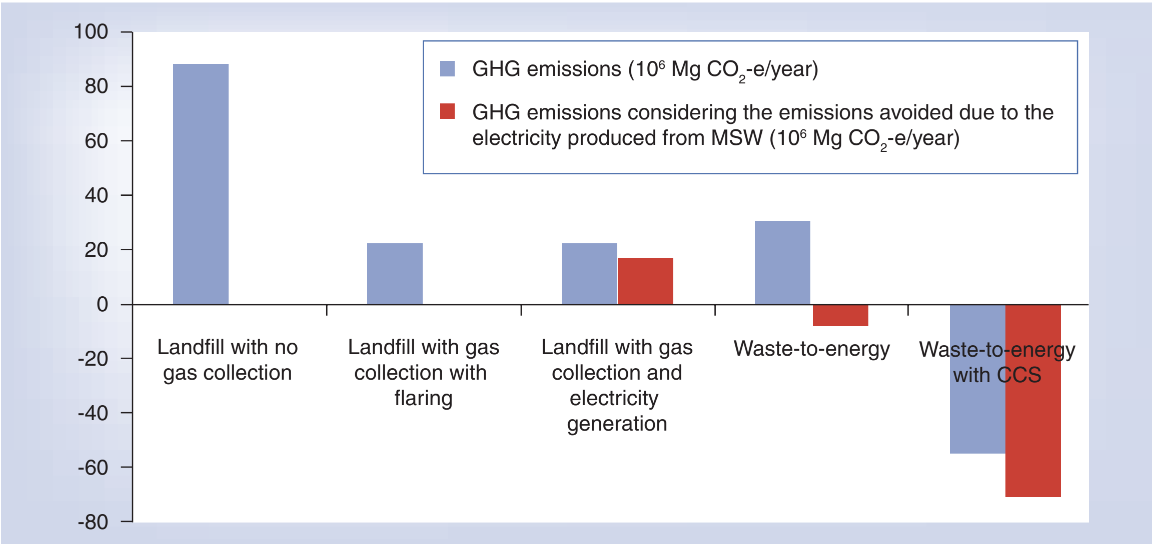

Figure 3. GHG emissions under different disposal options. The emissions are evaluated for 60% of the waste landfilled in the five largest landfill sites in each US state in 2008.
MSW: Municipal solid waste.

potential of >500 MWe. Other states with >300 MWe potential include Illinois, Indiana, Michigan, Ohio, Pennsylvania, Texas and Virginia **(Figure 5A)**. The overall potential for WTE is 8.0 GWe, which would equate to 59.7×10^9 kWh of electricity per year. For WTE–CCS, new generation capacity would be 3.36 GWe, producing up to only 25×10^9 kWh/year due to the energy penalty associated with carbon capture

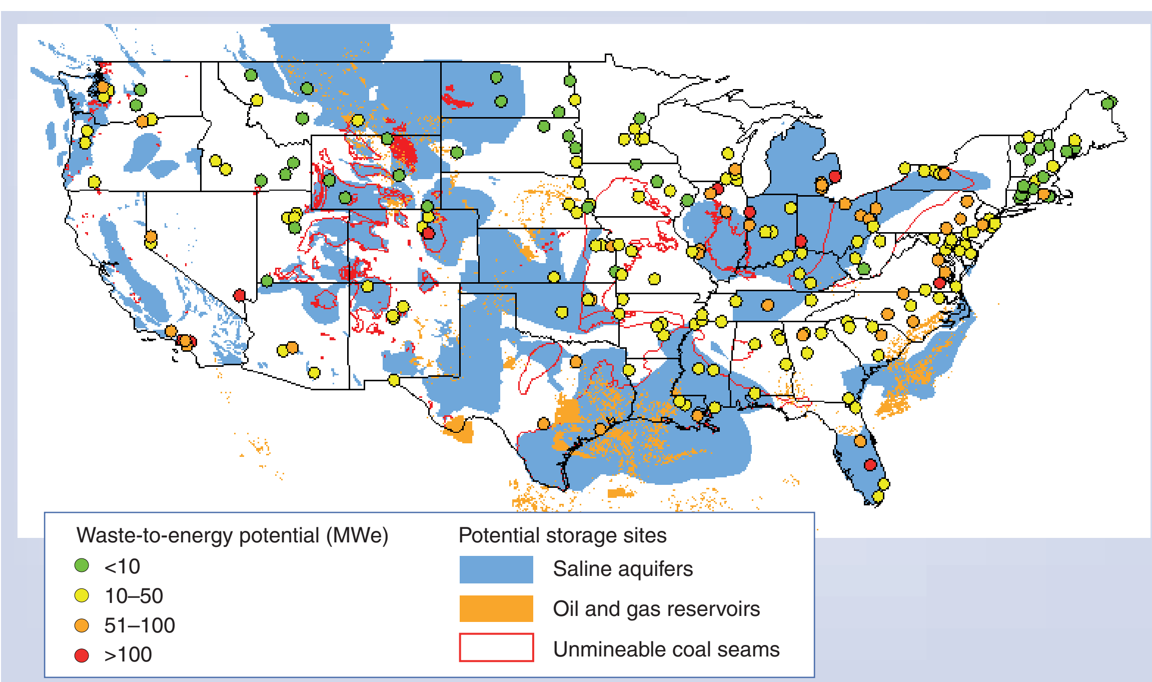

Figure 4. The location of potential waste-to-energy landfill sites with respect to CO_2 storage sites in the USA. The existing five largest landfill sites in each state are assumed to be the potential waste-to-energy sites. The storage sites are based on GIS shape files of the Carbon Sequestration Atlas of the USA and Canada, developed by the National Energy Technology Laboratory of the US Department of Energy [119].

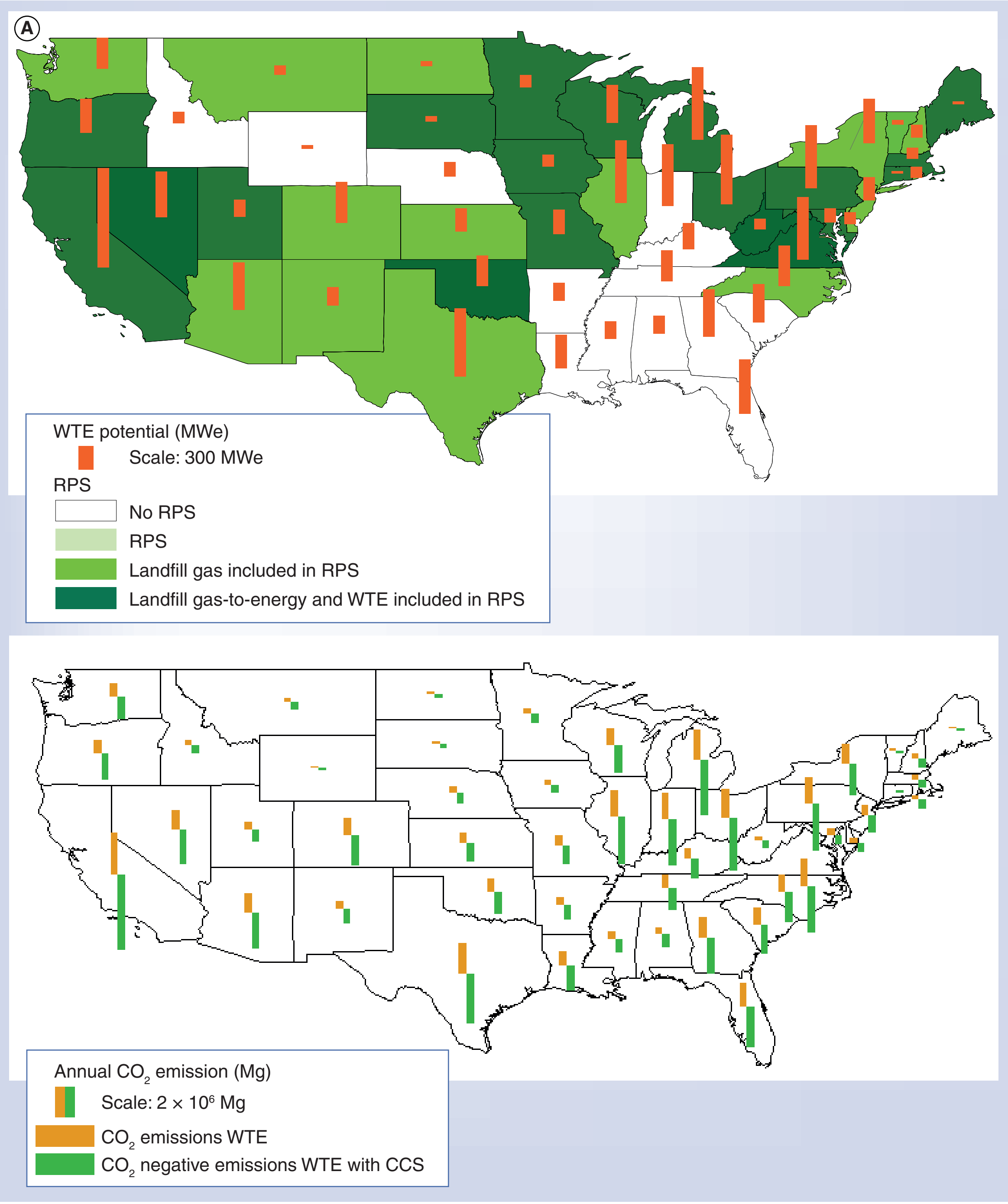

Figure 5. Electricity generation potential and CO_2 emissions if waste from the five largest landfill sites in each state of the USA is utilized to generate electricity by waste-to-energy plants. (A) Electricity generation potential. If CO_2 is captured in these plants, the electricity generation potential would be reduced by 58%. **(B)** CO_2 emissions from these WTE plants with and without CO_2 capture. The CO_2 capture would generate negative carbon emissions of 54×10^6 Mg of CO_2.
RPS: Renewable portfolio standard; WTE: Waste-to-energy.

and compression. By comparison, LFGTE at all the sites could provide a total capacity of up to 3.41 GWe capable of producing up to 25.4×10^9 kWh/year.

The levelized cost of electricity (LCOE) for WTE and WTE–CCS are \$94.5/MWh and \$285.3/MWh, respectively. The increase in the cost of WTE–CCS

Table 3. Levelized cost of electricity generation from various sources.

LFGTE	WTE	WTE–CCS	Wind†	Concentrating solar†	Solar photovoltaic (Utility scale ≥20 MW)†	Natural gas†
66	95	285	90–120	240–290	280–420	50–100

†Levelized cost of electricity, estimates are from [122].
LFGTE: Landfill-gas-to-energy; WTE: Waste-to-energy .

is due in part to the 52% derating of the plant for the CO_2 capture and compression system. The LCOE for the WTE and WTE–CCS are higher than that for LFGTE (Tables 1 & 2). However, the LCOE for WTE still ends up being comparable to that for wind energy, while the LCOE for WTE–CCS compares to that for concentrating solar and approaches the lower limit of that for solar photovoltaic (Table 3).

Values of LCOE are sensitive to capital costs, O&M costs and the waste disposal tipping fees (Figure 6), an important parameter often not considered in WTE analyses. If no tipping fee is charged, the LCOE would be \$163/MWh for the WTE and \$450/MWh for the WTE–CCS. However, if the tipping fee is high enough, then the LCOE could even approach zero. In our analysis, the LCOE will be zero if the tipping fee is \$118/Mg for the case of WTE, and \$137/Mg for WTE–CCS.

In terms of net emissions, WTE plants with or without CCS compare favorably with pulverized coal plants. We estimate the net CO_2 emissions from a WTE to be 0.52 Mg/MWh (Table 4) compared with 0.83 Mg/MWh from a pulverized coal plant [109]. Similarly, the net CO_2 emissions from a WTE–CCS plant are -3.14 Mg/MWh compared with 0.12 Mg/MWh from a pulverized coal plant with CCS, assuming in both cases that 90% of the CO_2 is captured. The cost of CO_2 capture from the WTE–CCS plant is \$58/Mg while the cost of carbon negative emissions is \$93/Mg (Table 4).

Discussion

WTE has the potential to reduce the amount of MSW disposed in landfills while also providing electricity that reduces GHG emissions. We estimate that of the MSW being stored in the five largest landfills in each state, 82.5×10^6 Mg could be used annually for WTE, three-times more than is currently used for this purpose [8]. If the CO_2 from WTE were captured and stored, 54×10^6 Mg of CO_2 could also be removed from the atmosphere each year. The cost of electricity generation from WTE–CCS would likely be higher than that from pulverized coal plants with CCS, but WTE–CCS may be one of a few ways to achieve net negative carbon emissions. Moreover, our results suggest this form of removal would cost less than \$100/Mg of CO_2, which could end up being significantly lower than costs for geoengineering methods for extracting CO_2 from the atmosphere [14].

Our results are based on current technology and the cost estimates available in the published literature. As shown in Figure 6A & B, variations in capital costs and O&M costs could significantly influence the cost of electricity generation from these plants. Also, future improvements in technology could make WTE even more efficient and might also reduce the cost of electricity generation. And while WTE plants are not yet designed with an option for capturing CO_2, there are technologies with lower air/fuel ratios and hence higher CO_2 concentrations in the flue gases that would make WTE–CCS plants cheaper. That said, there are unique challenges to CCS associated with WTE. For example, pollutants in flue gases from WTE, such as HCl and SO_2, could poison the amine solvent used in post-combustion capture by promoting the formation of heat-stable salts that cannot be dissociated even at high temperatures [15]. For example each mole of HCl would poison one mole of monoethanolamine (MEA), the CO_2 absorber in amine scrubbing systems. Similarly each mole of SO_2 could poison two moles of MEA. If so, the concentration of HCl and SO_2 in flue gases may need to be decreased to the order of 10 ppm so as to mitigate MEA poisoning. Dry injection of sodium sorbents is used to remove HCl and SO_2 from the flue gases of waste incinerators, especially in Europe. Since this approach has a removal efficiency of >99% [16], it can be used to fine tune the concentration of HCl and SO_2 in the flue gases. Another approach is

Table 4. Net CO_2 emissions and cost of capture for waste-to-energy facilities.

Plant type	CO_2 emissions (Mg of CO_2/MWh)	Cost of CO_2 capture (US\$/Mg of CO_2)	Cost of CO_2 avoided (\$/Mg of CO_2)	Cost of negative emission (\$/Mg of CO_2)
WTE	0.52			
WTE–CCS	-3.1	58.5	165.3	93.4

WTE: Waste-to-energy.

to gasify the MSW and capture the CO_2 capture before combustion [17], an alternative we did not consider in this analysis.

WTE and WTE–CCS plants also have advantages over other forms of renewable energy such as solar photovoltaic and wind turbines. The latter are intermittent power generators, while WTE and WTE–CCS plants could be used for baseload power [115]. As shown in Table 3, the cost of electricity generation from WTE is also comparable with that produced by wind, while the cost of electricity from the WTE–CCS is comparable to that from concentrating solar photovoltaic, even without considering the potential benefit from WTE–CCS having negative net CO_2 emissions. Moreover, the disposal of MSW is unavoidable, and WTE could reduce future problems of land availability for waste disposal in large cities.

One key to the success of WTE or WTE–CCS will be the tipping fee of MSW, which in our analysis influences the cost of electricity generation considerably. As Figure 6C shows, tipping fees of $120–$140 would drop the LCOE from WTE to zero. Tipping fees in the USA, however, are typically lower than this; the average tipping fee in 2008 for landfilling and WTE was $49/Mg ($28–$85/Mg) and $75/Mg ($28–$108/Mg), respectively [8]. If a landfill tax were imposed, as in the UK (£48/Mg of active waste for 2011) and other EU countries, it would discourage landfilling alone and would promote WTE and WTE–CCS plants.

The success of WTE will also depend on energy policy. For example, 29 states and the District of Columbia currently have a renewable portfolio standard, and seven other states have renewable energy goals that encourage or obligate utility companies to derive a specified portion or percentage of their total electricity from renewable sources (Figure 5A) [116]. Interestingly, all these states consider LFGTE as being renewable, but only 21 of them classify WTE as being renewable, even though it would produce less GHG emissions than LFGTE. A federal renewable portfolio standard that includes WTE would help in promoting the build out of more WTE facilities. For example, according to EU legislation the biodegradable portion of municipal and industrial waste is considered as biomass and hence renewable [117]. This policy, along with the landfill tax policy in most of the countries of Europe, is reflected in the fact that Europe has 446 WTE plants, compared with only 87 in the USA [14,118].

A third critical factor for WTE–CCS would be the cost of CCS. Our estimates of $58/Mg for capture and $93/Mg for carbon negative emissions are based on the assumed performance of a 42 MWe WTE plant with post-combustion, amine-based capture system. This cost could be lower for larger plants, but WTE plants are

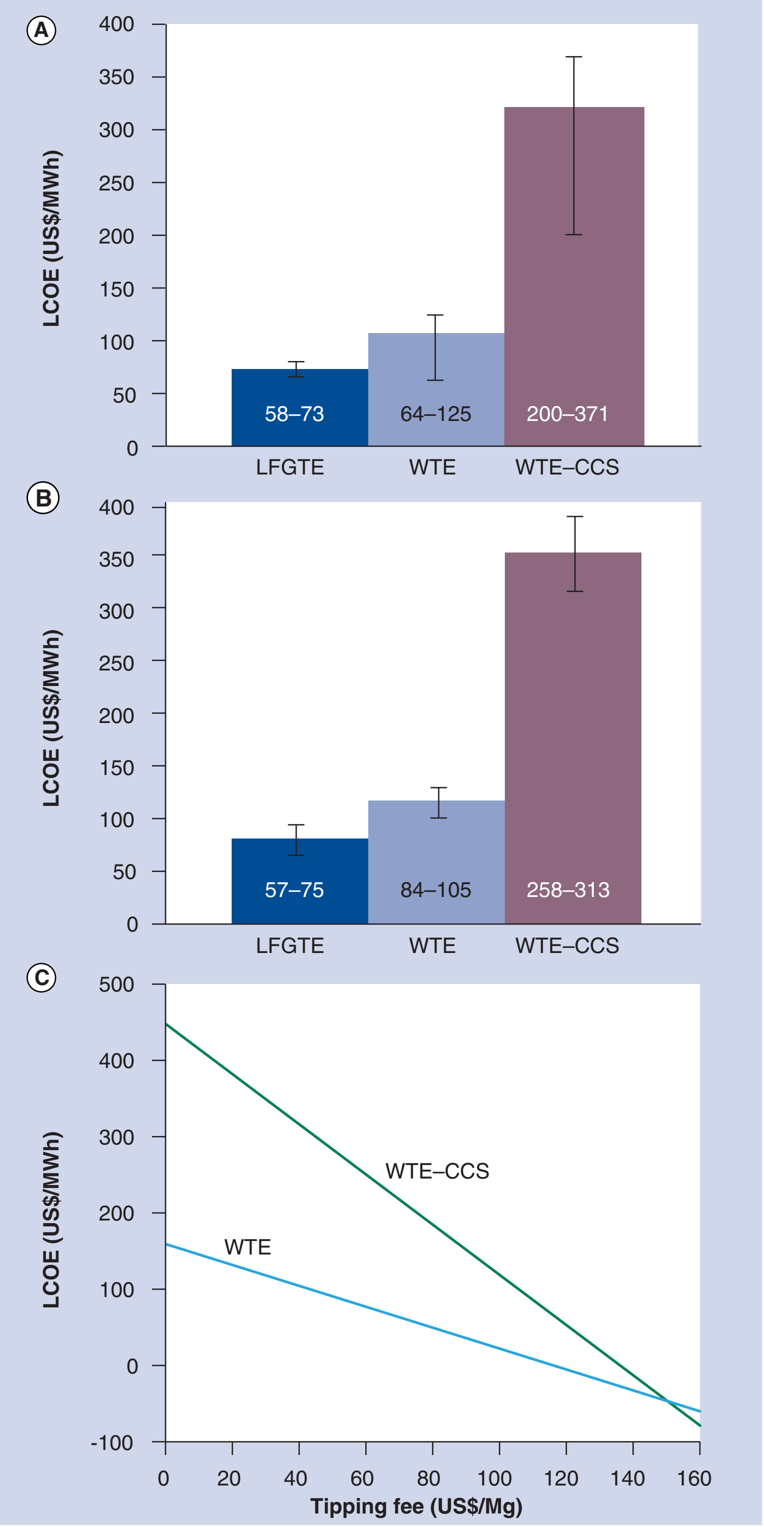

Figure 6. Sensitivity analysis of the levelized cost of electricity generation from waste. (A) Capital cost (± 25%), **(B)** operation and maintenance cost (± 25%) and **(C)** tipping fee (lower electricity costs with higher tipping fees). LCOE: Levelized cost of electricity; LFGTE: Landfill-gas-to-energy; WTE: Waste-to-energy.

smaller than coal plants and so cannot achieve the same type of cost savings on CCS through economies of scale.

The suitability of CCS for any CO_2 source depends on the amount of CO_2 the source produces and its proximity to a viable CO_2 storage site. The amount of CO_2 to be sequestrated from a typical WTE plant is smaller than for a typical coal plant because of its smaller size; therefore, requiring less storage locally. This, in turn, could result in more storage options closer to a WTE plant, reducing CO_2 transport costs. The landfill sites could themselves be used as CO_2 storage sites if the landfills have suitable geology. The storage capacity beneath a WTE plant could also reduce 'not-in-my-backyard' concerns about carbon storage, given that the sites are already storing MSW. Finally, if the plant operators own the landfill property, they may also control the property rights for the pore space for CO_2 storage, eliminating the need for dealing with a third-party.

Figure 4 shows the locations of the potential WTE plants relative to the distribution of possible CO_2 storage sites compiled by the US National Energy Technology Laboratory [119]. These storage sites include deep-saline aquifers, oil and gas reservoirs, and unmineable coal seams [18]. The figure shows that 46% of the potential WTE plants would be situated within 10 km of one of the potential storage sites, and 52% of WTE plants are within 20 km of potential storage sites (Figure 4). Considering only those WTE plants that are within 20 km of potential CO_2 storage sites, the US GHG emissions would be reduced by 33.04×10^6 Mg CO_2 per year and by 44.68×10^6 Mg CO_2 per year when considering the emissions avoided by generating electricity from the waste. Although, these GHG emissions are <1% of the total US emissions, which were 6633.2×10^6 Mg CO_2-e in 2009, this amount of CO_2 can be stored locally without extensive pipeline operations and would reduce the amount of MSW [120]. Furthermore, at least 78% of these sites meet or exceed the threshold limit of 0.1×10^6 Mg CO_2 per year for CCS specified by IPCC [5]. The remaining potential WTE facilities, however, do not have local access to significant known storage, especially potential sites in the US midwest and on the east coast. The cost for WTE–CCS at these locations would likely be greater, and may in fact be higher than the cost of transporting emissions from a typical coal plant, because transportation costs decrease with increasing amounts of CO_2 to be transferred [19].

Future perspective

Implementing WTE in the USA, as has already been done more extensively in Europe, could be a better alternative than landfilling in reducing net GHG emissions. Moreover, WTE–CCS could be a small but important first step in achieving carbon negative footprints in the near future. Although the benefits of WTE are clear, additional work is needed on the feasibility and especially the cost of CCS. However, tipping fees associated with waste disposal may ultimately tip the economic balance in favor of WTE and CCS, implemented together, to obtain carbon negative emissions.

Acknowledgements

We thank R Venditti of the Department of Forest Biomaterials at North Carolina State University (NC, USA) for his helpful suggestions on the manuscript.

Financial & competing interests disclosure

This study was supported by the US Department of Energy through the National Energy Technology Laboratory (DEFE0002197 for RJ and DEFE0001934 for LFP), the Climate Change Policy Partnership, and the Center on Global Change at Duke University. The authors have no other relevant affiliations or financial involvement with any organization or entity with a financial interest in or financial conflict with the subject matter or materials discussed in the manuscript apart from those disclosed.

No writing assistance was utilized in the production of this manuscript.

Executive summary

Background

- Use of municipal solid waste (MSW) to generate useful energy (waste-to-energy [WTE]) would reduce landfill requirements and could reduce GHG emissions from solid-waste management.
- We calculate the energy penalty and cost of CO_2 capture from WTE plants using amine-based post-combustion capture technology.

Methodology & assumptions

- We evaluate the net GHG emissions (CO_2-e) and the electricity generation potential of WTE from MSW based on the waste streams of the five largest landfill sites in each US state.

Results & discussion

- We estimate that at least 58 existing sanitary landfill sites receive enough MSW to fuel WTE plants with capacities of >50 MWe, 11 sites could fuel plants of >100-MWe capacity, and half of all potential sites lie within 20 km of potential underground saline and other storage reservoirs for CO_2.
- We estimate that the cost of CO_2 capture is US\$58/Mg CO_2, resulting in a cost for carbon negative emissions of \$93/Mg CO_2.

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