PLOS CLIMATE

RESEARCH ARTICLE

Waste incinerators undermine clean energy goals

Neil Tangri[1,2*]

1 Global Alliance for Incinerator Alternatives, Berkeley, California, United States of America, **2** Goldman School of Public Policy, University of California Berkeley, Berkeley, CA, United States of America

* ntangri@berkeley.edu

Abstract

A national clean energy standard, modeled upon existing state-level Renewable Portfolio Standards, has been proposed to decarbonize the U.S. electric grid. Most such state policies include municipal solid waste incineration as a form of "renewable" energy, despite incinerators' prominent contributions to air pollution, primarily in environmental justice communities. This study finds that incinerators emit more greenhouse gas emissions per unit of electricity produced (1707 g CO_2e/kWh) than any other power source (range: 2.4 to 991.1 g CO_2e/kWh). They also emit more criteria air pollutants than replacement sources of energy, such as natural gas. Incineration's inclusion in "renewable" or "clean" energy standards is thus counterproductive, as they also divert more than $40 million in subsidies annually from cleaner energy sources. As the electric grid decarbonizes, these disparities will only grow. With most U.S. incinerators nearing their end of life, policy choices about their eligibility for subsidies may well decide whether they shut down or undertake expensive capital improvements to continue operating. Extending incinerators' operational lives by 20 years would result in excess emissions of up to 637.7 million tonnes CO_2e, 61.9 million tonnes NO_x, and 161,200 tonnes SO_2. Conversely, a rapid shutdown of existing incinerators would help decarbonize the electric grid and reduce criteria air pollution, particularly in environmental justice communities, which are disproportionately burdened by environmental health hazards.

Citation: Tangri N (2023) Waste incinerators undermine clean energy goals. PLOS Clim 2(6): e0000100. https://doi.org/10.1371/journal.pclm.0000100

Editor: Laurence L. Delina, The Hong Kong University of Science and Technology, HONG KONG

Received: July 7, 2022

Accepted: March 22, 2023

Published: June 1, 2023

Peer Review History: PLOS recognizes the benefits of transparency in the peer review process; therefore, we enable the publication of all of the content of peer review and author responses alongside final, published articles. The editorial history of this article is available here: https://doi.org/10.1371/journal.pclm.0000100

Data Availability Statement: All data is in the public domain. The primary data source is the Emissions & Generation Resource Integrated Database (eGRID), available at https://www.epa.gov/egrid. Additional data was retrieved from the

1. Introduction

A variety of greenhouse gas (GHG) mitigation policies have been proposed to enable the United States to reach the Paris Agreement goal of zero net emissions by mid-century. The electric grid is widely considered the easiest and quickest sector to decarbonize and the Biden administration has pledged to achieve a climate-neutral electric grid by 2035 [1–3]. A leading candidate for achieving this goal is a national clean electricity standard, modeled upon existing state-level policies [3,4]. These policies, generally known as Renewable Portfolio Standards (RPS), require electric grid operators to buy a minimum percentage of electricity from renewable energy sources. Renewable Energy Credits (RECs) serve to track the amount of renewable electricity produced; as RECs are separable from the electricity supply, parallel REC markets

Facility-Level Information on Greenhouse gases Tool (FLIGHT) at https://ghgdata.epa.gov/ghgp/main.do and from the Energy Information Agency's EIA-860 database at https://www.eia.gov/electricity/data/eia860/.

Funding: This work was supported by Rockefeller Philanthropy Advisers https://www.rockpa.org/ through an organizational grant to GAIA http://no-burn.org. NT is a salaried employee of GAIA. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Competing interests: I have read the journal's policy and the author of this manuscript has the following competing interest: I am employed at GAIA, a non-governmental organization that advocates for zero waste and against the burning of waste in incinerators. The analysis and opinions stated in the paper are entirely the author's own.

have been created, and the surrender of RECs to a regulatory authority does not necessarily correspond to the generation of renewable electricity within that state [5]. Moreover, there is no consistent definition of "renewable": each state determines which energy sources qualify for its RPS. The GHG emissions impact of existing RPS policies is debated: most researchers find significant reductions while a few find minimal effects [6,7]. The inclusion of energy sources with large carbon footprints within the definition of "renewable" may be one reason for the policies' weak mitigation impact.

Due to their air pollution impacts, municipal solid waste incinerators (MSWI or "incinerators") are one of the more controversial technologies subsidized by RPS programs. The US is a large generator of municipal waste– 2.2 kg per person per day–of which 11.8% is incinerated, 50% landfilled, and 32% composted or recycled [8]. Incinerators have frequently attracted the ire of their host communities [9,10]. In addition to greenhouse gas emissions, incinerators are major sources of toxic air emissions including dioxins, lead, mercury, nitrogen and sulfur oxides, particulates, and other organic pollutants of emerging concern [11,12]. In some cities, the incinerator is the single largest source of criteria air pollutants [13]. Nevertheless, the evidence directly linking incinerators to local, adverse health outcomes is mixed [14–16]. This may be due to methodological shortcomings and confounding variables such as socio-economic status, which is a primary determinant of health outcomes [17,18]. Incinerators are primarily (79%) located in communities of color and low-income communities whose residents are subject to multiple, cumulative health impacts [18,19]. This discriminatory pattern of incinerator siting is one of the primary issues that gave rise to the environmental justice movement [20]. Their presence has served to attract other polluting industries and requires large volumes of heavy truck traffic, with its ensuing emissions [19]. While permitting standards consider the facility in isolation, most host communities struggle with multiple environmental health stressors, which exacerbate incinerators' impact. As such, environmental justice movements have frequently targeted incinerators for closure [21].

Incinerator proponents, however, argue that incinerators serve both to treat municipal waste and as a source of "clean" or low-carbon energy [22,23]. For example, Castaldi & Themelis [24] write that, "increasing the usage of WTE [incineration] facilities world wide has the potential to satisfy a large part of the global energy demand while reducing greenhouse gas emissions and providing a safe waste disposal option." Themelis and Millrath [25] conclude, "Since WTE is environmentally better than landfilling and, in addition, it generates electricity thus reducing our dependence on fossil fuels, it should be included in the benefits to be provided to other sources of renewable energy." Michaels [26] opens with the lines, "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." Rather than focus on incineration as a waste management technique these authors emphasize instead its potential to generate "renewable" energy and claims to reducing overall GHG emissions. These arguments rest upon three assertions: 1) the biogenic CO_2 emissions from incinerators are climate neutral; 2) incineration is the only way to avoid landfill methane emissions; and 3) the energy produced by incinerators displaces fossil fuel-based energy.

Incinerators' claims to renewability hinge upon the assertion that biogenic CO_2 emissions, i.e., those from the combustion or decomposition of the biomass component of solid waste, including food waste, paper, cardboard, wood and yard waste, are climate neutral [e.g., 27]. The question of how, and even whether, to count biogenic emissions is controversial. The biomass industry argues that biogenic CO_2 emissions are inherently climate-neutral because they form part of a natural biological cycle; this position has found its way into policy, including the massive COVID relief bill passed in December 2020 [28]. Such arguments ignore the overwhelming evidence that human perturbance of natural carbon cycles, including through deforestation and soil degradation, contribute significantly to atmospheric carbon loading [29,30]. As the radiative forcing of atmospheric CO_2 is virtually identical for biogenic and fossil CO_2, it is imperative to minimize emissions of both [31]. Accurate assessments of the climate impact of energy production thus require accounting for both biogenic and fossil CO_2. In its guidelines for national GHG emissions accounting, the Intergovernmental Panel on Climate Change (IPCC) requires reporting biogenic CO_2 emissions separately from fossil fuel emissions but not including them in the power sector total, as this would lead to double-counting; such emissions are already counted under Agriculture, Forestry, and Other Land Uses [32]. Here, we follow IPCC guidance and report biogenic emissions separately.

The second rationale for considering incineration to be renewable energy centers on methane. Methane is a powerful, short-lived GHG and reducing methane emissions is now a top priority [33]. Landfill methane arises from the anaerobic decomposition of the putrescible component of solid waste in landfills. Incinerator proponents often argue that incinerating waste is the only or primary way to avoid landfill methane emissions [e.g., 24,25,34]. These analyses, while numerous, are generally of poor quality [35]. In fact, the waste management literature contains extensive analysis of a range of approaches to landfill methane mitigation. Besides incineration, these include composting [33,36–41], animal feed [42,43], insect/vermicomposting [44,45]; anaerobic digestion [46–48], mechanical-biological treatment [49–51], improved landfill gas collection [52,53], and biologically active landfill cover [54–56]. Individually, these approaches have been shown to reach 90% efficacy in landfill gas reduction; in combination, they hold the potential to virtually eliminate landfill methane emissions [57]. In any case, such debates about incineration's role in waste management are distinct from the question of what constitutes renewable or low-carbon electricity.

The third leg of the incinerators-as-renewable energy argument is about energy replacement. In analyzing the emissions impact of adding or removing an energy source to the electric grid, it is standard practice to assume one-to-one replacement by other energy sources. In other words, if incinerators were to shut down, their electricity production would have to be compensated by an equal quantity of increased generation from other sources. However, an examination of 50 years of international panel data found that this is often not the case: in practice, alternative energy sources displace on average only 10% of their electricity output [58]. For biomass and waste incineration, no displacement is discernible. Similar dynamics have been observed with biofuels [59]. Reasons for the lack of displacement may include lock-in to the existing electric system, the political and economic power of the fossil fuel industry, elasticity effects, and simply the relatively small electricity output of incinerators.

Nevertheless, incineration is included in 26 of the 42 state-level RPS programs (S1 Table). (For the purposes of this analysis, we refer to the District of Columbia, Guam, the Northern Marianas Islands, Puerto Rico, and the U.S. Virgin Islands, which all have RPS programs, as "states.") Industry analysts claim that the subsidy afforded by RPS programs is critical to the expansion and maintenance of the country's incinerator fleet, which would otherwise be uneconomical to operate [19,60]. Most U.S. incinerators are nearing the end of their expected operating lives and would require major capital investments to continue operations [19]. The decisions to decommission or refurbish incinerators–or to build new ones–may hinge on incineration's inclusion in federal and state RPS programs.

In contrast to extensive discussion of incineration as a waste management strategy, its role in the energy system has received little scrutiny in the academic literature. In this paper, we focus on municipal waste incinerators as an energy source in the context of efforts to decarbonize the electricity sector.

2. Data and methods

We used annual emissions and electricity generation data from the U.S. Environmental Protection Agency's 2018 Emissions and Generation Resource Integrated Database version 2 (eGRID), a database commonly used for power system analysis [61]. For combined heat and power (CHP; also known as cogeneration) plants, we used eGRID's allocation factor to apportion emissions between electricity and heat production. We report fossil carbon dioxide (CO_2), biogenic CO_2, and the gases with high global warming potential (GWP)–methane (CH_4) and nitrous oxide (N_2O)–separately. In addition, we conduct similar analyses for sulfur dioxide (SO_2) and nitrogen oxides (NO_x), non-greenhouse gases included in the eGRID database that are important contributors to poor air quality and acid rain. Mercury emissions are also included in eGRID but, as of 2018, data coverage is too sparse for meaningful analysis [62]. See S1 Text for additional methodological details.

We assess incineration's impact on U.S. electricity grid greenhouse gas emissions by calculating incinerators' excess emissions. We define a plant's excess emissions as the plant's emissions minus the emissions that would be generated by replacement power sources. Previous analyses have found that the climate impact of waste-to-energy is heavily dependent on assumptions made about replacement electricity [35,51,63–65]. In constructing likely scenarios for replacement electricity, several factors need to be considered: geographic area, replacement ratio, and marginal vs. average emissions.

The task of matching electricity generation to demand falls to 73 balancing authorities, each with authority over a section of the U.S. electric grid. However, replacement sources of electricity are not necessarily located within the geographic area of a balancing authority, due to large-scale transfers of electricity between balancing authorities. Accounting for these transfers and their associated emissions is impractical, if not impossible [66]. The Environmental Protection Agency (EPA) has defined subregions (an intermediate geographic area between balancing authorities and regions defined by the North America Electric Reliability Corporation) so as to minimize the import and export of electricity across boundaries [62]. Subregional analysis allows the closest match between electricity demand and associated emissions, so we use the EPA's subregion as the geographic unit of analysis (S1 Fig).

We calculated the excess, or net, emissions from incinerators in 2018 by deducting the emissions associated with replacement energy–both heat and electricity–from each incinerator's emissions. As many CHP incinerators are connected to district heating systems, we assumed that each CHP incinerator would be replaced by a natural gas facility of median emissions intensity with an overall energy output equal to the replaced incinerator's (i.e., 100% replacement). For electricity-only incinerators, we evaluated three scenarios, with replacement coefficients of 0%, 50%, and 100%, to capture the range of possible replacement effects.

Incinerators typically operate 24 hours a day, throughout the year; compared to time-variant generators such as wind, solar, and natural gas "peaker" plants, their electricity output is relatively constant. As such, they are likely to be replaced by sources that reflect the full mix of grid sources, and we use mean rather than marginal emissions intensity to calculate replacement emissions [67].

Average emissions intensity is changing over time, as natural gas and zero-carbon sources replace coal; such changes will need to accelerate if the U.S. is to meet Paris Agreement goals of net zero emissions by 2050. We construct two future decarbonization scenarios [68]. In the "No policy" scenario, each subregion of the grid decarbonizes at 2.3% annually, the rate that best fits the U.S. Power Sector Carbon Index from 2001–2019 [69]. In the "Paris" scenario, we combine emissions data from Grubert's [70] reference scenario for plant retirements with electricity generation data from the Energy Information Agency's reference projections [71]. This results in an annual 9.9% decarbonization rate for fossil CO_2, which we apply to all emissions categories. We do not alter future waste composition, despite the growing proportion of plastic (a fossil fuel) in the waste stream [72], nor do we posit decarbonization for CHP replacement energy.

For incinerators that produce only electricity, these assumptions result in the following formula:

$$X_{g,i,,y} = M_{g,i} - E_i * F_{g,k} * r * d_{s,y} \tag{1}$$

Where $X_{g,i,y}$ indicates the excess emissions of gas g from incinerator i in year y, M the actual emissions, E the electricity produced, $F_{g,k}$ the mean emissions factor for gas g in subregion k containing incinerator i, r the replacement coefficient (0, 0.5 or 1), and $d_{s,y}$ the decarbonization coefficient for scenario s (either "no policy" or "Paris") in year y.

For CHP (cogeneration) incinerators, the formula is:

$$X_{g,i} = M_{g,i} - G_i * F_{g,n} \tag{2}$$

Here, G_i refers to all energy exported by incinerator i, both heat and electricity, and $F_{g,n}$ is the national median emissions factor for gas g from natural gas plants. The rationale behind using a national emissions factor for CHP plants instead of the subregional emissions factor used for electricity-only plants is that, if an electricity-only incinerator is shut down, replacement electricity would be drawn from the local subregion of the grid. If a CHP incinerator is shut down, the most likely replacement source would be a natural gas plant and there is no *prima facie* reason to presume that new plants would vary in efficiency by region.

Throughout the analysis, we have used conservative assumptions–i.e., assumptions that would tend to understate the emissions impact of incinerators. These include the use of 100% replacement of both electricity and heat; the use of 100-year GWPs [73]; stable waste composition; and assuming no decarbonization in the CHP sector through 2050. As such, our estimates of excess emissions from incinerators should be seen as a lower bound.

3. Results

Of the nation's 76 operating incinerators, 69 were analyzed; of these, 56 are electricity-only plants and 13 are CHP facilities. Incinerators are the most emissions-intensive form of power generation: per unit of electricity produced, incinerators emit 1.7 times as much GHGs, 4.8 times as much NO_x but only 0.4 times as much SO_2 as coal, the next most polluting fuel. 46 of 69 (67%) incinerators are equipped with selective catalytic or non-catalytic reduction equipment for NO_x control and 61 (88%) have scrubbers for SO_2 control [74]. In contrast, 77% of coal generation has similar technologies installed [75]. Compared to the national grid average, incinerators emit 3.8 times as much GHGs, 14 times as much NO_x, and 1.3 times as much SO_2 (Figs 1, 2 and S2; Table 1). Coal-fired plants emit 19% more fossil CO_2 than incinerators but negligible biogenic emissions. Biomass plants emit low levels of fossil CO_2 and 17% less biogenic CO_2 than waste incinerators. In eGRID, CO_2 emissions from the combustion of landfill gas, which is primarily methane, are also classified as biogenic. 49% of incinerator CO_2 emissions are classified as biogenic in comparison to 2.8% for the national grid as a whole, reflecting the small role of biomass and biofuels in the nation's electricity system. Waste incinerators stand out as the only generation source that emits large quantities of both fossil and biogenic emissions for each unit of electricity produced.

The electricity mix varies widely by subregion. In 11 of the 15 subregions containing incinerators, incineration is the most GHG-intensive source of electricity (S3 Fig). Exceptions include Northeast Power Coordinating Council (NPCC) New York City/Westchester, where

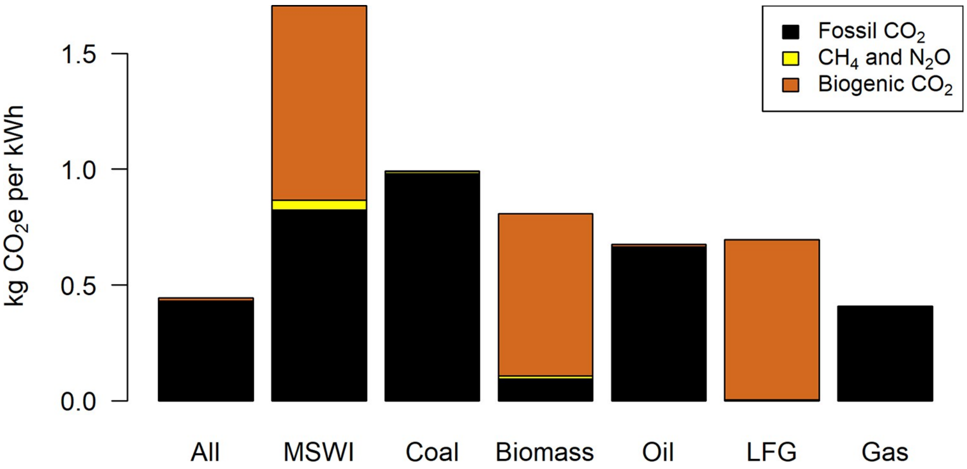

Fig 1. Generation-weighted mean national GHG emissions intensity by major fuel type for electricity. "MSWI" is municipal solid waste incineration, "LFG" is landfill gas, and "Gas" is natural gas.

https://doi.org/10.1371/journal.pclm.0000100.g001

oil has a very high emissions intensity, on par with incineration; and Reliability First Corporation (RFC) Michigan, RFC West, and Southwest Power Pool (SPP) South, where incineration emissions intensities are anomalously low. These low values may be due to issues in the calculation of CHP emissions (see section 4.3).

In 2018, with one exception, every incinerator produced excess emissions of each gas (fossil CO_2, N_2O and CH_4, biogenic CO_2, NO_x) other than SO_2 (Figs 3 and 4). This is true regardless of the energy replacement scenario. The one exception was the Pittsfield facility, which primarily (95.2%) produces heat rather than electricity. In a 100% replacement scenario, its fossil CO_2 emissions were 4.7% less than a natural gas replacement; but this difference is more than made up for by its higher N_2O and CH_4 emissions.

Nationally, incinerators also produced excess SO_2 emissions in 2018, but substantial variability in plant performance and replacement SO_2 intensity produced wide variations in individual excess emissions rates. Notably, Hawaii has very high SO_2 grid intensity due to its

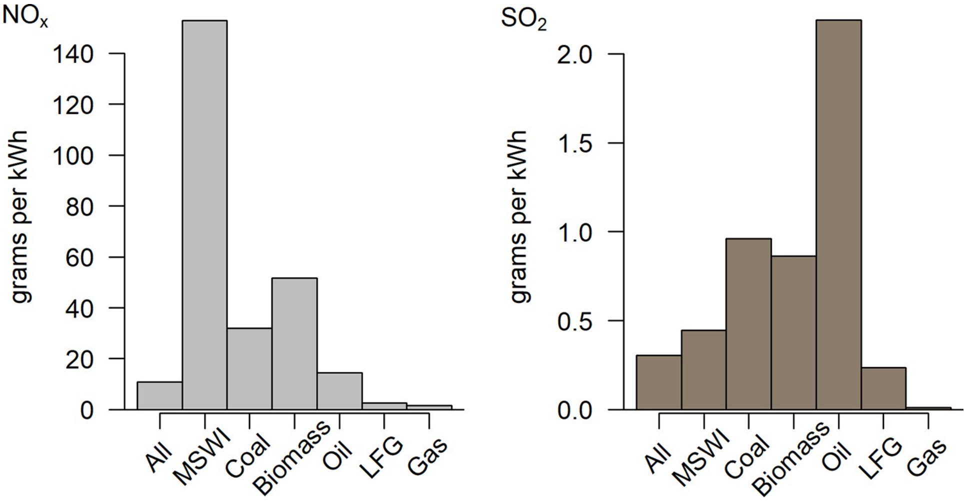

Fig 2. Generation-weighted mean national NO_x and SO_2 emissions intensity by major fuel type for electricity. "MSWI" is municipal solid waste incineration, "LFG" is landfill gas, and "Gas" is natural gas.

https://doi.org/10.1371/journal.pclm.0000100.g002

Table 1. Generation-weighted national electricity emissions intensity by major fuel type in grams (CO_2e for CH_4, N_2O) per kWh.

	All	MSWI	Coal	Biomass	Oil	LFG	Gas	Noncom
Fossil CO_2	428.6	822.9	981.6	95	660.2	4.4	406.2	2.4
$CH_4 + N_2O$	2.9	42.6	8.5	13.4	3.7	0.8	0.5	0
Biogenic CO_2	12.7	841.7	1.0	699.9	11.9	689.8	1.2	0
GHGs	444.2	1707.2	991.1	808.2	675.8	695.0	407.9	2.4
NO_x	10.9	152.9	31.9	51.7	14.6	2.6	1.6	0
SO_2	0.3	0.4	1.0	0.9	2.2	0.2	0.0	0
Plants	8590	69	336	264	662	338	1603	5247
Electricity	100%	0.3%	28.8%	1.0%	0.6%	0.2%	33.5%	34.9%

"GHGs" is the sum of all greenhouse gases. "Plants" is the number of facilities. "Electricity" is the percentage of grid power supplied, including electricity from cogeneration (CHP) facilities. "Noncom" is all non-combustion sources. Percentages do not total 100% because of rounding.

https://doi.org/10.1371/journal.pclm.0000100.t001

unique reliance on oil (69% of generation) and thus its incinerator produces substantially less SO_2 emissions than ostensible replacement sources (-1111 tonnes in 2018 under 100% energy replacement). On the other hand, just nine heavy emitters produce all the national excess emissions. Removing these ten outliers would reduce incinerators' excess SO_2 emissions nationally by 75%.

The average age of incinerators operating at the beginning of 2021 is 32 ± 5 years; 48 incinerators are over the age of 30. Only one incinerator–Palm Beach #2 –has begun operations since 1995; its estimated life extends through 2050. Retiring the current fleet of incinerators at end-of-life, estimated to be 35 years, will incur 157.1 million tonnes CO_2e, 16.8 million tonnes NO_x, and 39,700 tonnes SO_2 in excess emissions under the "no policy" scenario to 2050 (Fig 5, Table 2). In the Paris scenario, excess GHG emissions increase by 10.1 million tonnes, almost all fossil CO_2; and excess SO_2 emissions increase by 5900 tonnes. Extending each functioning incinerator's life by 20 years will incur 585.7 million tonnes CO_2e, 61.0 million tonnes NO_x and 125,500 tonnes SO_2 additional emissions under the "no policy" scenario and 637.7 million tonnes CO_2e, 61.9 million tonnes NO_x and 161,200 tonnes SO_2 under the Paris scenario.

4. Discussion

4.1 Incineration is a high-carbon power source

The intensity and excess emissions analyses indicate that incineration is the most emissions-intensive form of electricity production and its removal from the grid would improve overall grid performance. Even under conservative assumptions–that electricity-only incinerators are replaced by a mix of sources reflecting the 2018 average for each subregion, and CHP incinerators are replaced by natural gas–every category of emissions but SO_2 would be reduced in every subregion, and SO_2 would be reduced nationally. In fact, incinerators' contribution to the electric grid is minimal (0.3%) and could easily be replaced by zero-carbon energy sources. This is particularly likely as incinerator removal would free up RPS subsidies to expand zero-carbon sources. As the grid decarbonizes, the benefits of incinerator shutdowns will further increase. Incineration cannot therefore be considered a "low-carbon" energy source, as it is currently designated in many state laws.

While it is clear that removing incinerators would help decarbonize the electric grid, the impact on emissions in the waste management sector is less clear, and largely depends on the replacement waste management strategy. Replacing incinerators with landfills could lead to a rise in GHG emissions, particularly methane, depending on various factors including landfill

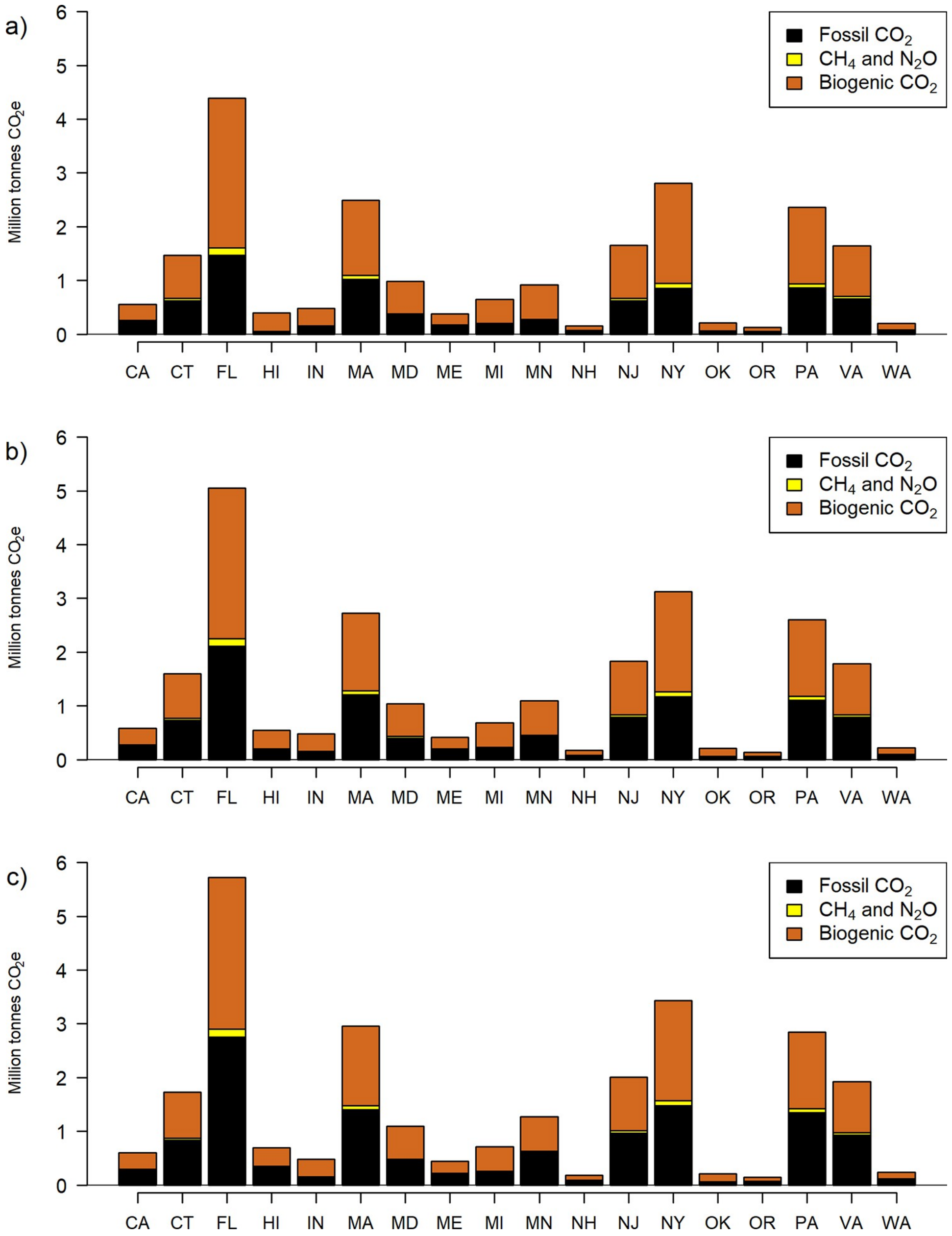

Fig 3. Excess GHG emissions from incinerators in 2018 by state for three electricity replacement scenarios: a) 100% replacement; b) 50% replacement; and c) 0% replacement. CHP incinerators are replaced at 100% of energy in all three scenarios. Only states with incinerators are shown.

https://doi.org/10.1371/journal.pclm.0000100.g003

gas capture rates [65]. Landfill methane emission rates are not well-constrained, so there is considerable uncertainty about the potential impact of greater landfilling [76,77]. On the other hand, a waste management strategy based primarily on composting and recycling, as is now required by California law, would reduce waste sector emissions considerably [39,63]. San Francisco, for example, already recycles or composts more than 75% of its waste; [78,79]. Other countries have had even greater success: Thiruvananthapuram (India) recycles and composts over 80% of its waste; Ljubljana (Slovenia) has reduced waste going to landfill by 95%; and the entire country of South Korea diverts 94% of its organics into animal feed and

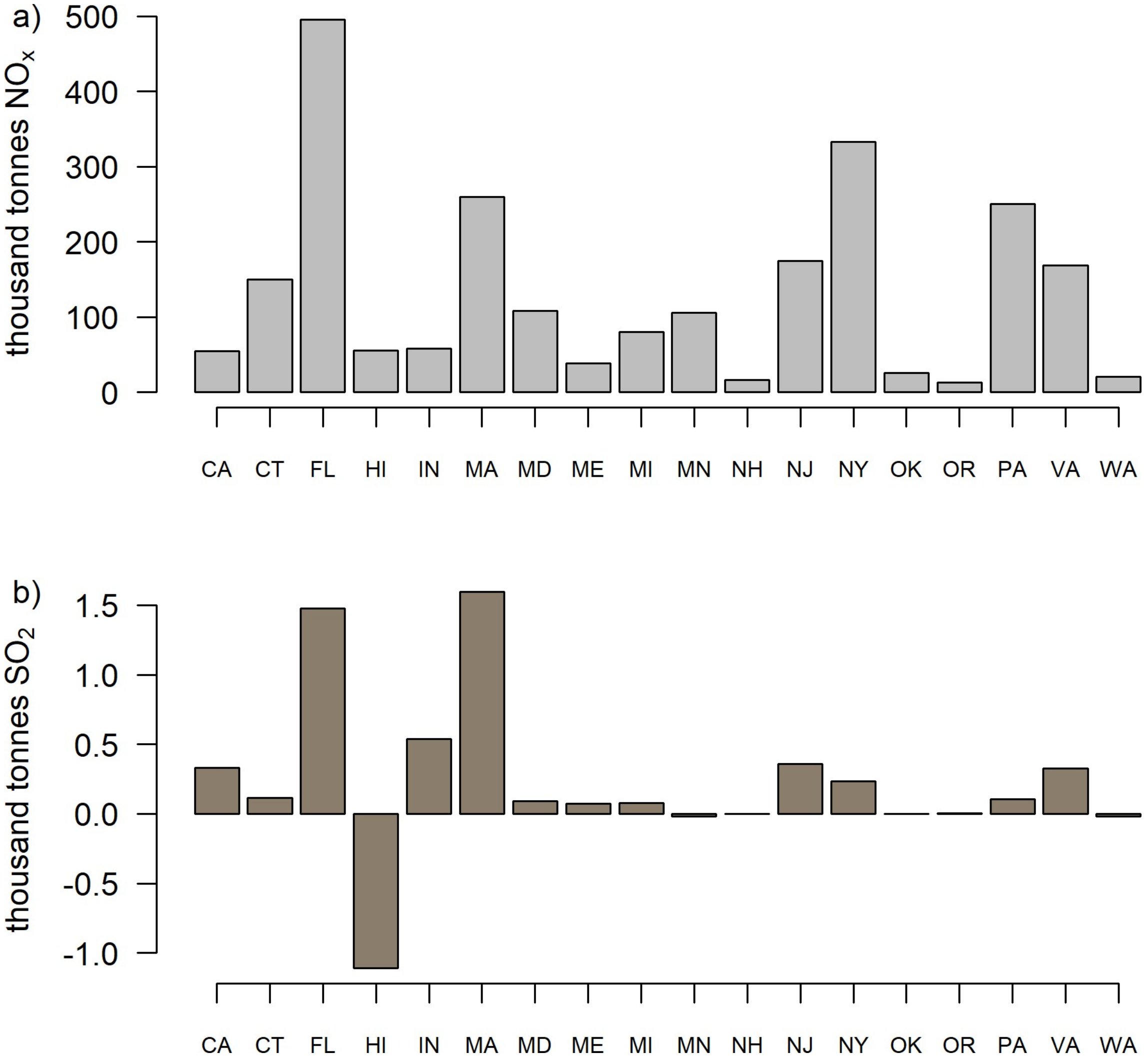

Fig 4. Excess NO_x (top) and SO_2 (bottom) emissions from incinerators in 2018 by state, under a 100% energy replacement scenario. Negative excess emissions indicates that incinerators emit less of the pollutant than replacement energy sources.

https://doi.org/10.1371/journal.pclm.0000100.g004

compost. [43,80,81]. Another advantage of recycling and composting over incineration is that these approaches generate 10–60 times as much employment [82].

Excess NO_x and SO_2 emissions track excess GHG emissions well, with $r = 0.97$, $p << 0.001$ (NO_x with fossil CO_2) and $r = 0.73$, $p << 0.001$ (SO_2 with fossil CO_2) on a state-by-state basis. This indicates that incinerator removal would produce considerable co-benefits to host communities. Indeed, on this question, beneficial climate policy and beneficial environmental justice policy are indistinguishable.

4.2 Sensitivity analysis

Consistent with earlier studies, the choice of replacement energy scenario made a dramatic difference in the excess emissions of fossil CO_2 and SO_2. However, it had little impact on other excess emissions. Compared with a 100% replacement scenario, the 0% replacement scenario increased excess fossil CO_2 emissions by 59%, CH_4 and N_2O by 3%, biogenic CO_2 by 2%, NO_x by 3%, and SO_2 by 80% (S2 Table). This is due to the fact that, in 2018, replacement energy sources are major sources of fossil CO_2 and SO_2 but emit minimal levels of the other gases.

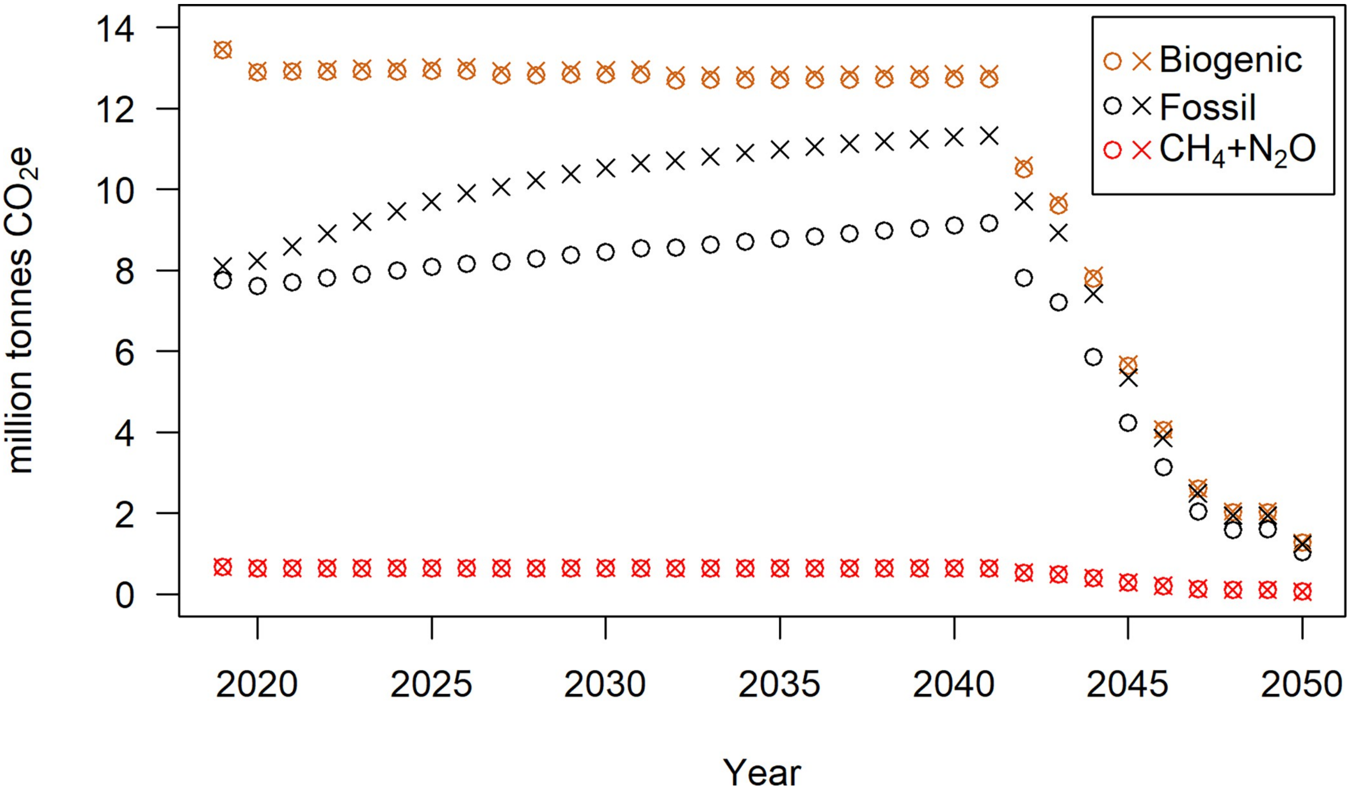

Fig 5. Annual excess GHG emissions resulting from extending incinerators' operating lives by 20 years. Open circles indicate the no policy scenario and crosses the Paris scenario, both with 100% energy replacement. The scenarios are almost identical for biogenic, N_2O, and CH_4 emissions.

https://doi.org/10.1371/journal.pclm.0000100.g005

The primary factor driving excess emissions to 2050 is the lifespan of incinerators. Extending the incinerator fleet's operating life by 20 years increases total emissions by 3 to 4 times (average: 3.67) in each emissions category. By contrast, the choice of decarbonization scenario is significant but not large: in comparison with the "no policy" scenario, the faster, "Paris" pathway increases excess emissions by 6.5% in the end-of-life case and 8.9% in the extended life case. Indeed, as the 2018 analysis shows, incinerators produce excess emissions even without grid decarbonization. State-to-state variation in the magnitude of excess emissions is primarily due to variability in the emissions intensity of the replacement energy and whether the incinerator is a CHP facility. Nevertheless, every incinerator produces excess GHG emissions

Table 2. Excess incinerator emissions under four scenarios to 2050.

Closure:	**End of Life**	**End of Life**	**Extended**	**Extended**
Decarbonization scenario:	**No policy**	**Paris**	**No policy**	**Paris**
Fossil CO_2	58.0	67.7	228.1	277.4
N_2O and CH_4	4.7	4.7	17.0	17.2
Biogenic CO_2	94.3	94.7	340.6	343.1
NO_x	16.8	17.0	61.0	61.9
SO_2	39.7	45.8	125.5	161.2
All GHGs	157.1	167.2	585.7	637.7

All data in million tonnes (CO_2e for N_2O, CH_4) except SO_2, which is in thousand tonnes. End of life is estimated at 35 years; "Extended" adds an additional 20 years.

https://doi.org/10.1371/journal.pclm.0000100.t002

and therefore every state's GHG emissions intensity is higher than it would be without incinerators. These results are consistent with those of Tabata [83], who analyzed 727 power-producing incinerators in Japan and found that only five did not produce excess fossil CO_2 emissions.

4.3 CHP plants

Our analysis raises questions about eGRID's reporting of thermal output from CHP plants. CHP plants are generally more energy-efficient than electricity-only plants and therefore show lower emissions intensity. For example, Pratt and Lenaghan [72] report that Scotland's electricity-only incinerators are 61% more emissions intensive than its heat-only incinerator; Healy [84] concludes that CHP can deliver approximately 20% savings in emissions intensity for a grid intensity of ~0.45 kg CO_2/kWh; Kelly [85] estimates 21% lower emissions intensity from CHP; while Jarre [86] finds only marginal differences in emissions intensity between gas-fired CHP and electricity-only plants. However, our analysis shows that electricity-only plants are on average 3.5 to 4 times more emissions-intensive than CHP plants. The magnitude of this difference is highly anomalous.

Among CHP plants, we would expect that facilities that dedicate more of their energy output to electricity generation would be less efficient and thus more emissions-intensive. Yet the data show the opposite: emissions intensity is negatively correlated with electricity allocation across fuel types (Fig 6). The discrepancy in emissions intensity between plants that devote at least 90% of their energy output to electricity and those that produce only electricity is particularly stark (Table 3). The reason for these inconsistencies is not clear, but may lie in the methodology for calculating plants' heat and/or steam output. In the eGRID database, the useful thermal output is not measured but estimated from fuel consumption and electricity production; uniform efficiency factors are applied to all facilities, obscuring significant real-world variations in efficiency [62]. A systematic overestimation of the heat/steam exported would

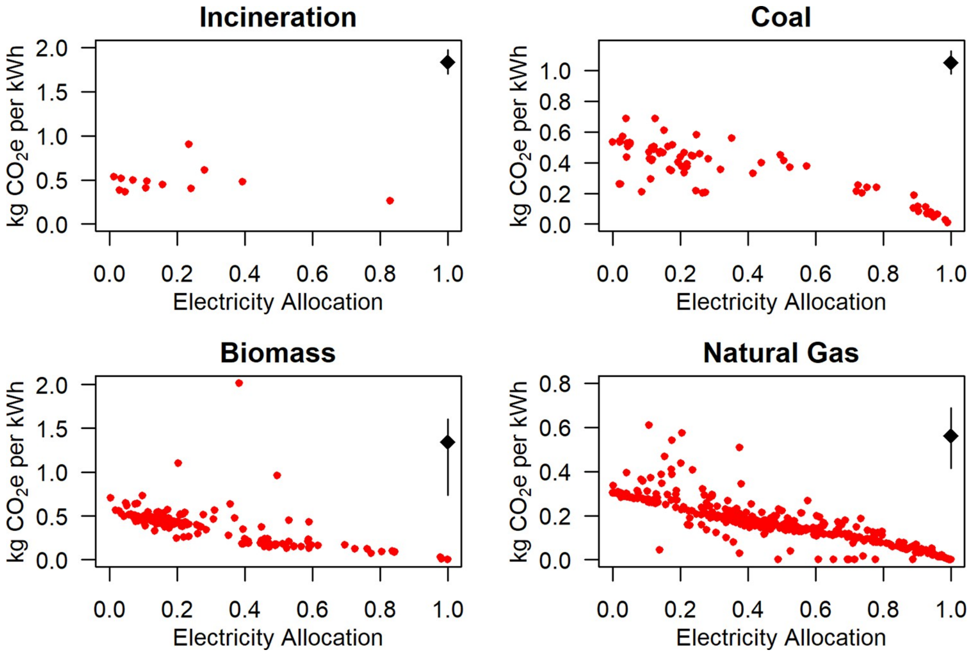

Fig 6. Relationship between energy allocation to electricity and emissions intensity for four fuel types. Each red dot indicates a CHP plant. Black diamonds and lines indicate the median value and interquartile range for electricity-only plants.

https://doi.org/10.1371/journal.pclm.0000100.g006

Table 3. Total GHG emissions intensity, in kg CO_2e/kWh, for plants that export only electricity (top row); CHP plants that use 90% or more of their energy for electricity production (middle row); and all CHP plants (bottom row).

Energy production	MSWI	Coal	Biomass	Natural Gas
100% electricity	1.92	1.10	1.28	0.74
90%+ electricity	n/a	0.06	0.01	0.02
All CHP plants	0.48	0.36	0.40	0.17

Total GHG emissions intensity is the sum of fossil CO_2, biogenic CO_2, CH_4, and N_2O emitted.

https://doi.org/10.1371/journal.pclm.0000100.t003

explain both discrepancies. It would also result in over-allocating emissions to heat/steam production, producing artificially low figures for electricity emissions intensity. To test this hypothesis and rectify any reporting bias, we suggest that the Energy Information Agency collect actual measurements of steam and heat output from CHP plants. Regardless of these discrepancies, incinerators still perform poorly compared to other cogeneration facilities.

4.4 Role of renewable energy subsidies

One of the aims of RPS programs is to diversify energy sources by incentivizing the construction of new renewable energy capacity [7]. In the case of incineration, this has failed: incinerator construction in the U.S. all but halted in the mid-1990s, just as state-level RPS laws became widespread. However, analysts do credit RECs with extending the operating lifespan of existing incinerators [19,60].

REC sales data are fragmented and not public, so it is difficult to assess the financial impact of RPS programs [5]. We estimate the value of REC sales to the incinerator industry at $41 to $44 million in 2018 (see Appendix for details). Removing incinerators from existing RPS programs would free up substantial subsidies for zero-emissions forms of power generation.

At an average age of 32 years, most of the U.S. incinerator fleet is nearing retirement age. 31 incinerators retired between 2000 and 2020, at an average age of 25 ± 6 years. In the next few years, most incinerator operators will have to decide whether to decommission their facilities or invest extensive capital in refurbishment to extend their lifespans. Waste industry analyses suggest that the availability of subsidies, in particular inclusion in state- or a national-level RPS program, would be the deciding factor in most decommissioning decisions [13,19,87]. To evaluate the impact of continuing to subsidize waste incineration, we calculated the excess emissions of each incinerator to the end of its expected operating life, which we took to be 35 years, and the additional excess emissions that would result from extending each incinerator's operations for another 20 years. The results indicate that extending the operating life of incinerators would be counterproductive to the aim of decarbonizing the electric grid. On the other hand, excluding incinerators from existing RPS programs might prompt many of them to close early. Even if replaced by fossil fuel plants, this would still result in reduced emissions.

Another effect of new subsidies would be to encourage the construction of new incinerators. Given the age of the existing fleet, one might expect new incinerators to be more efficient, with implications for the emissions intensity of the electricity produced. However, the little evidence available does not support this conjecture: the emissions intensity of the one incinerator built in the 21st century, Palm Beach #2, (1662.6 g CO_2e/kWh) is only marginally lower than the national average (1707.2 g CO_2e/kWh).

5. Conclusions and policy implications

Incinerators are the most emissions-intensive form of generating electricity in the U.S. today. This is true regardless of the methodology employed (such as omitting biogenic emissions, using a different timescale for GWP, or analyzing subregions separately). As such, they are the last energy source that should be incentivized through renewable or clean energy policies. Incineration's inclusion in current, state-level RPS programs has not led to a build-out of incineration but may well be keeping alive the existing incinerator fleet; it has certainly diverted subsidies from non-combustion energy sources that would have lowered overall grid emissions. As these incinerators age, the availability of state and federal subsidies may be the deciding factor in whether or not to prolong their operational lives. To lower emissions, legislators should remove incineration from existing RPS and other subsidy programs, and avoid including them in any future federal subsidy program such as a clean energy standard. Simultaneously, improved waste treatment strategies are needed to ensure that incinerator closures do not result in increased landfill methane emissions. With these measures in place, incinerator closures would result in both a cleaner electric grid and less air pollution in environmental justice communities.

Hugo Guzmán conceived of this project and laid the groundwork. John Ribeiro-Broomhead, Lizbeth Flores, Doun Moon, and Alexandra Rollings contributed invaluable research assistance. Travis Johnson at EPA rapidly responded to questions and corrected errors in the eGRID database.

Supporting information

S1 Fig. Map of eGRID subregions used in this analysis. Source: USEPA.
(TIF)

S2 Fig. GHG emissions intensity at the plant level. (cf. generation-weighted data in Fig 1). CH_4 and N_2O emissions are not depicted. MSWI is incineration, LFG is landfill gas, and Gas is natural gas. Heavy line indicates the median value, boxes the interquartile range, and whiskers the outliers.
(TIF)

S3 Fig. Generation-weighted mean subregional GHG emissions intensity by major fuel type for electricity. "MSWI" is municipal solid waste incineration, "LFG" is landfill gas, and "Gas" refers to natural gas. Purple numbers indicate the number of plants in the named subregion. See map (S1 Fig) for subregions.
(TIF)

S1 Table. State-level jurisdictions with RPS programs. Sources: State statutes; Database of State Incentives for Renewables & Efficiency [Internet]. N.C. Clean Energy Technology Center; Available from: https://www.dsireusa.org/; Cleanwashing: How States Count Polluting Energy Sources as Renewable. Food and Water Watch; 2018 Jul.
(DOCX)

S2 Table. 2018 Excess emissions from incinerators for three energy replacement scenarios: 100% replacement, 50% replacement, and no replacement. "Change" indicates the change in excess emissions between the no replacement and 100% replacement scenarios. GHGs is the total of all greenhouse gases. Data in million tonnes (CO_2e for CH_4, N_2O) except SO_2 which is in thousand tonnes.
(DOCX)

S3 Table. Incinerators excluded from the analysis.
(DOCX)

S4 Table. Non-eGRID incinerators added to the analysis. Emissions data from the Facility Level Information on GreenHouse gases Tool (FLIGHT; U.S. Environmental Protection

Agency; 2020. Available from: https://ghgdata.epa.gov/ghgp/main.do). Steam production for Pittsfield and Pope/Douglas from FLIGHT. Niagara electricity generation from the Energy Information Agency's Open Data platform (Available from https://www.eia.gov/opendata). Remaining data calculated with EIA formulae and nameplate capacity.
(DOCX)

S1 Text. Methodological Notes.
(DOCX)

Author Contributions

Conceptualization: Neil Tangri.

Data curation: Neil Tangri.

Formal analysis: Neil Tangri.

Methodology: Neil Tangri.

Software: Neil Tangri.

Visualization: Neil Tangri.

Writing – original draft: Neil Tangri.

Writing – review & editing: Neil Tangri.

References

1. Biden J. The Biden Plan to Build a Modern, Sustainable Infrastructure and an Equitable Clean Energy Future [Internet]. Joe Biden for President: Official Campaign Website. [cited 2021 Jan 22]. Available from: https://joebiden.com/clean-energy/.
2. Bistline J, Abhyankar N, Blanford G, Clarke L, Fakhry R, McJeon H, et al. Actions for reducing US emissions at least 50% by 2030. Science. 2022 May 27; 376(6596):922–4. https://doi.org/10.1126/science.abn0661 PMID: 35617382
3. Lawson A. Clean Energy Standards: Selected Issues for the 117th Congress [Internet]. Congressional Research Service; 2021 Nov [cited 2022 Jun 19]. Report No.: R46691. Available from: https://crsreports.congress.gov/product/pdf/R/R46691.
4. Solving the Climate Crisis: The Congressional Action Plan for a Clean Energy Economy and a Healthy and Just America [Internet]. U.S. House Select Committee on the Climate Crisis; 2020 Jun [cited 2021 Jan 26]. Available from: https://climatecrisis.house.gov/report.
5. Mack JH, Gianvecchio N, Campopiano MTM, Logan S. All RECs Are Local: How In-State Generation Requirements Adversely Affect Development of a Robust REC Market. The Electricity Journal. 2011 May 1; 24(4):8–25.
6. Barbose G, Wiser R, Heeter J, Mai T, Bird L, Bolinger M, et al. A retrospective analysis of benefits and impacts of U.S. renewable portfolio standards. Energy Policy. 2016 Sep 1; 96:645–60.
7. Upton GB, Snyder BF. Funding renewable energy: An analysis of renewable portfolio standards. Energy Economics. 2017 Aug 1; 66:205–16.
8. USEPA. Advancing Sustainable Materials Management: 2018 Fact Sheet. 2020 Dec;25.
9. Temper L, Demaria F, Scheidel A, Del Bene D, Martinez-Alier J. The Global Environmental Justice Atlas (EJAtlas): ecological distribution conflicts as forces for sustainability. Sustain Sci. 2018 May 1; 13 (3):573–84.
10. Walsh EJ, Warland R, Smith DC. Don't Burn it Here: Grassroots Challenges to Trash Incinerators. Penn State Press; 1997. 318 p.
11. Allsopp M, Costner P, Johnston P. Incineration and human health: state of knowledge of the impacts of waste incinerators on human health. Amsterdam: Greenpeace Research Laboratories; 2001.
12. Li C, Yang L, Wu J, Yang Y, Li Y, Zhang Q, et al. Identification of emerging organic pollutants from solid waste incinerations by FT-ICR-MS and GC/Q-TOF-MS and their potential toxicities. Journal of

Hazardous Materials. 2022 Apr 15; 428:128220. https://doi.org/10.1016/j.jhazmat.2022.128220 PMID: 35016122

13. McAnulty H. A Dirty Waste—How Renewable Energy Policies Have Financed the Unsustainable Waste-to-Energy Industry. Boston College Law Review. 2019 Jan 29; 60(1):385.
14. Ashworth DC, Elliott P, Toledano MB. Waste incineration and adverse birth and neonatal outcomes: a systematic review. Environment International. 2014 Aug 1; 69:120–32. https://doi.org/10.1016/j.envint.2014.04.003 PMID: 24831282
15. Cole-Hunter T, Johnston FH, Marks GB, Morawska L, Morgan GG, Overs M, et al. The health impacts of waste-to-energy emissions: a systematic review of the literature. Environ Res Lett. 2020 Dec; 15 (12):123006.
16. Tait PW, Brew J, Che A, Costanzo A, Danyluk A, Davis M, et al. The health impacts of waste incineration: a systematic review. Australian and New Zealand Journal of Public Health. 2020; 44(1):40–8. https://doi.org/10.1111/1753-6405.12939 PMID: 31535434
17. Bevc CA, Marshall BK, Picou JS. Environmental justice and toxic exposure: Toward a spatial model of physical health and psychological well-being. Social Science Research. 2007 Mar 1; 36(1):48–67.
18. Martuzzi M, Mitis F, Forastiere F. Inequalities, inequities, environmental justice in waste management and health. European Journal of Public Health. 2010 Feb 1; 20(1):21–6. https://doi.org/10.1093/eurpub/ckp216 PMID: 20061348
19. Baptista AI, Perovich A. U.S. Municipal Solid Waste Incinerators: An Industry in Decline. The New School Tishman Environment and Design Center; 2019 May.
20. Bullard RD. Race and Environmental Justice in the United States Symposium: Earth Rights and Responsibilities: Human Rights and Environmental Protection. Yale J Int'l L. 1993; 18(1):319–36.
21. Behrsin I. Green Energy from Garbage? A Case Study of Municipal Solid Waste's Contested Inclusion in Maryland's Renewable Portfolio Standard. Case Studies in the Environment. 2019 Dec 31; 3(1):1–7.
22. Brown M. Is waste a source of renewable energy? [Internet]. Isonomia. 2014 [cited 2021 Jan 26]. Available from: https://www.isonomia.co.uk/is-waste-a-source-of-renewable-energy/
23. Grosso M, Motta A, Rigamonti L. Efficiency of energy recovery from waste incineration, in the light of the new Waste Framework Directive. Waste Management. 2010 Jul 1; 30(7):1238–43. https://doi.org/10.1016/j.wasman.2010.02.036 PMID: 20347289
24. Castaldi MJ, Themelis NJ. The Case for Increasing the Global Capacity for Waste to Energy (WTE). Waste Biomass Valor. 2010 Mar 1; 1(1):91–105.
25. Themelis NJ, Millrath K. The Case for WTE as a Renewable Source of Energy. In American Society of Mechanical Engineers Digital Collection; 2008 [cited 2022 May 5]. p. 15–22. Available from: https://computingengineering-asmedigitalcollection-asme-org.stanford.idm.oclc.org/NAWTEC/proceedings/NAWTEC12/3736X/15/302978
26. Michaels T. Waste Not, Want Not: The Facts Behind Waste-to-Energy. Energy Recovery Council; 2009 Apr.
27. Kong D, Shan J, Iacoboni M, Maguin SR. Evaluating greenhouse gas impacts of organic waste management options using life cycle assessment. Waste Manag Res. 2012 Aug 1; 30(8):800–12. https://doi.org/10.1177/0734242X12440479 PMID: 22588112
28. Cuellar H. Consolidated Appropriations Act [Internet]. H.R. 133 Dec 27, 2020. Available from: https://www.congress.gov/bill/116th-congress/house-bill/133.
29. Ciais P, Sabine CL, Bala G, Bopp L, Brovkin V, Canadell J, et al. Carbon and other biogeochemical cycles. In: Climate change 2013: the physical science basis Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press; 2014. p. 465–570.
30. Searchinger TD, Hamburg SP, Melillo J, Chameides W, Havlik P, Kammen DM, et al. Fixing a Critical Climate Accounting Error. Science. 2009 Oct 23; 326(5952):527–8.
31. Waste and Climate Change: Global Trends and Strategy Framework. Osaka/Shiga: United Nations Environment Programme; 2010.
32. Garg A, Weitz MM. 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 2: Energy. Intergovernmental Panel on Climate Change; 2019.
33. Ravishankara AR, Kuylenstierna JCI, Michalopoulou E, Höglund-Isaksson L, Zhang Y, Seltzer K, et al. Global Methane Assessment: Benefits and Costs of Mitigating Methane Emissions. Nairobi: United Nations Environment Programme; 2021.
34. Michaels T. Waste Not, Want Not: The Facts Behind Waste-to-Energy. Energy Recovery Council; 2009 Apr.

35. Astrup TF, Tonini D, Turconi R, Boldrin A. Life cycle assessment of thermal Waste-to-Energy technologies: Review and recommendations. Waste Management. 2015 Mar 1; 37:104–15. https://doi.org/10.1016/j.wasman.2014.06.011 PMID: 25052337

36. Barton JR, Issaias I, Stentiford EI. Carbon–Making the right choice for waste management in developing countries. Waste Management. 2008 Jan 1; 28(4):690–8. https://doi.org/10.1016/j.wasman.2007.09.033 PMID: 18053701

37. Brown S. Greenhouse gas accounting for landfill diversion of food scraps and yard waste. Compost Science & Utilization. 2016 Jan 2; 24(1):11–9.

38. Favoino E, Hogg D. The potential role of compost in reducing greenhouse gases. Waste Manag Res. 2008 Feb 1; 26(1):61–9. https://doi.org/10.1177/0734242X08088584 PMID: 18338702

39. Nordahl SL, Devkota JP, Amirebrahimi J, Smith SJ, Breunig HM, Preble CV, et al. Life-Cycle Greenhouse Gas Emissions and Human Health Trade-Offs of Organic Waste Management Strategies. Environ Sci Technol. 2020 Aug 4; 54(15):9200–9. https://doi.org/10.1021/acs.est.0c00364 PMID: 32628836

40. Qdais HA, Wuensch C, Dornack C, Nassour A. The role of solid waste composting in mitigating climate change in Jordan: Waste Management & Research [Internet]. 2019 Jun 20 [cited 2020 Mar 4]; Available from: https://journals-sagepub-com.stanford.idm.oclc.org/doi/10.1177/0734242X19855424.

41. Smith A, Brown K, Ogilvie S, Rushton K, Bates J. Waste management options and climate change. European Commission DG Environment; 2001.

42. Dou Z, Toth JD, Westendorf ML. Food waste for livestock feeding: Feasibility, safety, and sustainability implications. Global Food Security. 2018 Jun 1; 17:154–61.

43. Kim MH, Kim JW. Comparison through a LCA evaluation analysis of food waste disposal options from the perspective of global warming and resource recovery. Science of The Total Environment. 2010 Sep 1; 408(19):3998–4006. https://doi.org/10.1016/j.scitotenv.2010.04.049 PMID: 20580812

44. Diener S, Zurbrügg C, Tockner K. Conversion of organic material by black soldier fly larvae: establishing optimal feeding rates. Waste Manag Res. 2009 Sep 1; 27(6):603–10. https://doi.org/10.1177/0734242X09103838 PMID: 19502252

45. Singh RP, Singh P, Araujo ASF, Hakimi Ibrahim M, Sulaiman O. Management of urban solid waste: Vermicomposting a sustainable option. Resources, Conservation and Recycling. 2011 May 1; 55(7):719–29.

46. De Clercq D, Wen Z, Gottfried O, Schmidt F, Fei F. A review of global strategies promoting the conversion of food waste to bioenergy via anaerobic digestion. Renewable and Sustainable Energy Reviews. 2017 Nov 1; 79:204–21.

47. Mao C, Feng Y, Wang X, Ren G. Review on research achievements of biogas from anaerobic digestion. Renewable and Sustainable Energy Reviews. 2015 May 1; 45:540–55.

48. Pham TPT, Kaushik R, Parshetti GK, Mahmood R, Balasubramanian R. Food waste-to-energy conversion technologies: Current status and future directions. Waste Management. 2015 Apr 1; 38:399–408. https://doi.org/10.1016/j.wasman.2014.12.004 PMID: 25555663

49. Bayard R, de Araújo Morais J, Ducom G, Achour F, Rouez M, Gourdon R. Assessment of the effectiveness of an industrial unit of mechanical–biological treatment of municipal solid waste. Journal of Hazardous Materials. 2010 Mar 15; 175(1):23–32. https://doi.org/10.1016/j.jhazmat.2009.10.049 PMID: 19913357

50. Gioannis GD, Muntoni A, Cappai G, Milia S. Landfill gas generation after mechanical biological treatment of municipal solid waste. Estimation of gas generation rate constants. Waste Management. 2009 Mar 1; 29(3):1026–34. https://doi.org/10.1016/j.wasman.2008.08.016 PMID: 18954969

51. Smith A, Brown K, Ogilvie S, Rushton K, Bates J. Waste management options and climate change. European Commission DG Environment; 2001.

52. Powell JT, Townsend TG, Zimmerman JB. Estimates of solid waste disposal rates and reduction targets for landfill gas emissions. Nature Clim Change. 2016 Feb; 6(2):162–5.

53. Themelis NJ, Ulloa PA. Methane generation in landfills. Renewable Energy. 2007 Jun 1; 32(7):1243–57.

54. Barlaz MA, Green RB, Chanton JP, Goldsmith CD, Hater GR. Evaluation of a Biologically Active Cover for Mitigation of Landfill Gas Emissions. Environ Sci Technol. 2004 Sep 1; 38(18):4891–9. https://doi.org/10.1021/es049605b PMID: 15487801

55. Bogner J, Meadows M, Czepiel P. Fluxes of methane between landfills and the atmosphere: natural and engineered controls. Soil Use and Management. 1997; 13(s4):268–77.

56. Park JK, Chong YG, Tameda K, Lee NH. Applying methane and carbon flow balances for determination of first-order landfill gas model parameters. Environmental Engineering Research. 2020; 25(3):374–83.

57. Methane Matters: A comprehensive approach to methane mitigation. Changing Markets Foundation, Environmental Investigation Agency, Global Alliance for Incinerator Alternatives; 2022 Mar.

58. York R. Do alternative energy sources displace fossil fuels? Nature Climate Change. 2012 Jun; 2 (6):441–3.

59. Hochman G, Rajagopal D, Zilberma. The Effect of Biofuels on Crude Oil Markets. AgBioForum [Internet]. 2010 [cited 2021 Jan 26];13(2). Available from: https://pubag.nal.usda.gov/catalog/286715.

60. Behrsin I. Controversies of justice, scale, and siting: The uneven discourse of renewability in Austrian waste-to-energy development. Energy Research & Social Science. 2020 Jan 1; 59:101252.

61. USEPA. Emissions & Generation Resource Integrated Database (eGRID) [Internet]. 2020. Available from: https://www.epa.gov/egrid.

62. USEPA. The Emissions & Generation Resource Integrated Database: Technical Support Document for eGRID with Year 2018 Data. 2020 Jan.

63. Morris J, Scott Matthews H, Morawski C. Review and meta-analysis of 82 studies on end-of-life management methods for source separated organics. Waste Management. 2013 Mar 1; 33(3):545–51. https://doi.org/10.1016/j.wasman.2012.08.004 PMID: 22964362

64. Schott ABS, Wenzel H, Jansen J la C. Identification of decisive factors for greenhouse gas emissions in comparative life cycle assessments of food waste management–an analytical review. Journal of Cleaner Production. 2016 Apr 15; 119:13–24.

65. Vergara SE, Damgaard A, Horvath A. Boundaries matter: Greenhouse gas emission reductions from alternative waste treatment strategies for California's municipal solid waste. Resources, Conservation and Recycling. 2011 Dec 1; 57:87–97.

66. Ryan NA, Johnson JX, Keoleian GA. Comparative Assessment of Models and Methods To Calculate Grid Electricity Emissions. Environ Sci Technol. 2016 Sep 6; 50(17):8937–53. https://doi.org/10.1021/acs.est.5b05216 PMID: 27499211

67. Ryan NA, Johnson JX, Keoleian GA, Lewis GM. Decision Support Algorithm for Evaluating Carbon Dioxide Emissions from Electricity Generation in the United States. Journal of Industrial Ecology. 2018; 22(6):1318–30.

68. Business as unusual. Nature Energy. 2017 Sep 12; 2(9):1–1.

69. Schivley G, Azevedo I, Samaras C. Assessing the evolution of power sector carbon intensity in the United States. Environ Res Lett. 2018 Jun; 13(6):064018.

70. Grubert E. Fossil electricity retirement deadlines for a just transition. Science. 2020 Dec 4; 370 (6521):1171–3. https://doi.org/10.1126/science.abe0375 PMID: 33273092

71. U.S. Energy Information Administration. Annual Energy Outlook 2020 [Internet]. 2020 Jan [cited 2021 Jan 26]. Available from: https://www.eia.gov/outlooks/aeo/pdf/aeo2020.pdf.

72. Pratt K, Lenaghan M. The climate change impacts of burning municipal waste in Scotland: Technical Report. Zero Waste Scotland; 2020 Oct.

73. Myhre G, Shindell D, Bréon FM, Collins W, Fuglestvedt J, Huang J, et al. Anthropogenic and Natural Radiative Forcing. In: Climate Change 2013: The Physical Science Basis Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press; 2013.

74. U.S. Energy Information Agency. Form EIA-860 detailed data with previous form data (EIA-860A/860B) [Internet]. 2018 [cited 2022 Oct 1]. Available from: https://www.eia.gov/electricity/data/eia860/.

75. 2018 Power Sector Programs–Progress Report [Internet]. United States Environmental Protection Agency; 2018 p. 100. Available from: https://www3.epa.gov/airmarkets/progress/reports/index.html.

76. Duren RM, Thorpe AK, Foster KT, Rafiq T, Hopkins FM, Yadav V, et al. California's methane super-emitters. Nature. 2019 Nov; 575(7781):180–4. https://doi.org/10.1038/s41586-019-1720-3 PMID: 31695210

77. National Academies of Sciences, Engineering, and Medicine. Improving Characterization of Anthropogenic Methane Emissions in the United States. Vol. h. Washington, DC, USA: The National Academies Press; 2018.

78. Silva A, Rosano M, Stocker L, Gorissen L. From waste to sustainable materials management: Three case studies of the transition journey. Waste Management. 2017 Mar 1; 61:547–57. https://doi.org/10.1016/j.wasman.2016.11.038 PMID: 27955907

79. Zaman AU, Lehmann S. The zero waste index: a performance measurement tool for waste management systems in a 'zero waste city.' Journal of Cleaner Production. 2013 Jul 1; 50:123–32.

80. Oblak E. The Story of Ljubljana [Internet]. Zero Waste Europe; 2019 [cited 2022 May 28]. (Zero Waste Case Studies). Report No.: 5. Available from: https://zerowasteeurope.eu/wp-content/uploads/2019/10/zero_waste_europe_cs5_ljubljana_en.pdf

81. Status of solid and liquid waste management. Thiruvananthapuram Municipal Corporation; 2019.

82. Ribeiro-Broomhead J, Tangri N. Zero Waste and Economic Recovery: The Job Creation Potential of Zero Waste Solutions [Internet]. Global Alliance for Incinerator Alternatives; 2021 Feb. Available from: http://zerowasteworld.org/zerowastejobs.

83. Tabata T. Waste-to-energy incineration plants as greenhouse gas reducers: A case study of seven Japanese metropolises. Waste Manag Res. 2013 Nov 1; 31(11):1110–7. https://doi.org/10.1177/0734242X13502385 PMID: 24025369

84. Healy DP. Influence of the carbon intensity of electricity on carbon savings from CHP. Building Research & Information. 2012 Jun 1; 40(3):317–26.

85. Kelly KA, McManus MC, Hammond GP. An energy and carbon life cycle assessment of industrial CHP (combined heat and power) in the context of a low carbon UK. Energy. 2014 Dec 1; 77:812–21.

86. Jarre M, Noussan M, Poggio A. Operational analysis of natural gas combined cycle CHP plants: Energy performance and pollutant emissions. Applied Thermal Engineering. 2016 May 5; 100:304–14.

87. Karidis A. The 50 states of waste: How waste-to-energy definitions vary across the nation. Waste Dive [Internet]. 2016 Mar 24 [cited 2021 Jan 26]; Available from: https://www.wastedive.com/news/the-50-states-of-waste-how-waste-to-energy-definitions-vary-across-the-nat/416197/.