Journal of Benefit-Cost Analysis (2023), 14: 2, 275–297
doi:10.1017/bca.2023.16

CAMBRIDGE UNIVERSITY PRESS

ARTICLE

Ex Ante Costs Versus Ex Post Costs of the Large Municipal Waste Combustor Rule

Cynthia Morgan[1] and Carl A. Pasurka Jr[2]

[1]Office of Policy, U.S. Environmental Protection Agency (1809T), Washington, DC, USA
[2]Schar School of Policy and Government, George Mason University, Arlinigton, VA 22201
Corresponding author: Carl A. Pasurka; Email: CPASURKA@GMU.EDU

Keywords: air regulation; compliance costs; municipal waste combustor; retrospective cost analysis

JEL classifications: Q52; Q53; Q58

Abstract
This article compares the U.S. Environmental Protection Agency's (EPA) ex ante cost analysis of its 1995 Large Municipal Waste Combustor (MWC): New Source Performance Standards and Emissions Guidelines rule to an ex post assessment of its cost. Unlike many retrospective cost analyses, where ex post assessments are limited due to lack of data on compliance costs, this case study is unique because we located and used plant-level survey data from the U.S. Department of Energy and Governmental Advisory Associates in a comparison of ex ante and ex post costs of individual MWCs. We find the ex post capital expenditures for nitrogen oxide control systems are typically lower than the EPA ex ante estimates, while the ex post capital expenditures for mercury control systems tend to be higher than the EPA ex ante estimates. Finally, while we find a few outliers, the average ratio of ex post to ex ante capital expenditures for particulate matter and sulfur dioxide emissions control is near unity.

1. Introduction

In 2014, the U.S. Environmental Protection Agency (EPA) published the results of an ex post evaluation of the costs of five regulations (Simon & Blomquist, 2014; U.S. EPA, 2014). Similar to previous evaluations of federal regulations, these assessments used a case study approach that examined the relationship between ex ante and ex post costs. What differentiated the EPA's case studies from earlier ones is that the EPA developed a conceptual framework for its ex post assessments. The key components of this framework include defining the regulated universe, baseline technologies, methods of compliance, and their compliance costs.[1] This framework provides a systematic way to evaluate the general

[1] See Table 1.2 in US EPA (2014) for a summary of the conceptual framework including the cost components as well as questions posed for the ex post assessment.

accuracy of ex ante estimates and to identify the factors associated with discrepancies between ex ante and ex post costs. Among the reasons ex ante and ex post costs may differ are unanticipated changes in costs of inputs, costs of emerging abatement technologies, changes in market conditions, and technological innovation (U.S. EPA, 2014, Morgenstern, 2015).

We use this conceptual framework in our article to compare ex ante cost estimates to the actual ex post costs incurred by large municipal waste combustor plants at the time of the December 2000 compliance date of the EPA's Large Municipal Waste Combustor (MWC): New Source Performance Standards and Emissions Guidelines rule. The MWC rule was randomly selected from 42 "economically significant" rules the EPA promulgated between 1995 and 2005.[2] This retrospective analysis of the MWC rule adds to the inventory of ex post cost evaluations conducted by the EPA (Simon & Blomquist, 2014; U.S. EPA, 2014; Wolverton *et al.,* 2018). The goal of these evaluations is to identify factors that lead to differences between ex ante and ex posts costs to inform improvements to the EPA's ex ante cost analyses. For example, if unanticipated changes are repeatedly found to be the reason ex ante costs are over-or underestimated, then the EPA can use this information to expand the uncertainty analyses often conducted in their ex ante assessment of costs.

Municipal waste combustors (U.S. EPA, 1994*b*) are waste-to-energy plants that generate energy from combusting municipal solid waste (MSW). Combusting MSW generates pollutants, such as particulate matter and metals, that are released into the air. The EPA is required to regulate emissions of hazardous and criteria pollutants from MWCs under Sections 111 and 129 of the Clean Air Act (CAA). As a result, the EPA proposed emission standards and guidelines for the following categories of pollutants generated by new and existing MWC units: (i) organics (including dioxins/furans), (ii) metals (cadmium, lead, mercury (Hg), particulate matter (PM)), and (iii) acid gases (sulfur dioxide (SO_2) and hydrogen chloride (HCl)). The final rule, which plants had to comply with no later than December 2000, sought to reduce emissions of these air pollutants by approximately 145,000 tons per year.

This case study is unique because, unlike most previous case studies that evaluate aggregate ex ante and ex post costs, we compare ex ante and ex post costs of *individual* MWC plants operating in 2000. At the time of the rulemaking, the EPA developed cost estimates using a set of model plant categories that represented existing and new MWCs. Using characteristics of individual MWCs affected by the rule, we assign each MWC to a model plant category and compare the model plant's ex ante cost estimates to the reported capital costs of air pollution control devices (APCD) installed in response to the rule. We undertake this evaluation using two surveys – one public and one private – that collected data from MWCs on the type of APCDs installed, the year an APCD was installed, and its cost.

The remainder of this article is organized in the following manner. Section 2 outlines the impetus and timeline for the regulatory action associated with the rule, and Section 3 discusses the EPA ex ante cost estimates. Section 4 describes the information available for the ex post analysis, while Section 5 compares the ex ante and ex post cost estimates for each MWC plant. Finally, Section 6 summarizes the article.

[2] A regulation is economically significant if it has costs or benefits of $100 million or more in any single year. The costs and benefits must be assessed for rules that are economically significant as required by Executive Order 12866.

https://doi.org/10.1017/bca.2023.16 Published online by Cambridge University Press

2. Timeline for regulatory action

The original MWC rule, promulgated in 1991, established new source performance standards (NSPS) for new MWC plants and emission guidelines (EG) for existing MWC plants. These standards and guidelines are applied to large MWCs with capacities above 225 megagrams per day (Mg/day) (approximately 250 tons per day (tpd)). However, the rule faced many legal challenges that led to several revisions which required the EPA to develop NSPS and emission guidelines for both large and small MWC facilities,[3] more restrictive performance standards, and a schedule for revising the 1991 standards and guidelines.

The final MWC rule was promulgated in December 1995 with standards for new sources that supplemented the 1991 NSPS, and more stringent guidelines for existing sources than the 1991 guidelines. The technologies installed to meet the 1991 emissions limits could still be used to meet the 1995 emission limits but now, MWCs were also required to install supplemental technology to reduce Hg and fugitive ash emissions.

3. Ex ante cost estimation

The U.S. EPA (1995) estimated 72 MWC plants would be subject to the NSPS provisions of the rule in 2000. Of these plants, 48 would be subject to the 1991 NSPS and 24 would be subject to the 1995 NSPS. The EPA also projected an additional 179 MWC plants would be subject to the 1995 EG for existing MWCs. In the economic analysis conducted in support of the MWC rule, the EPA did not develop cost estimates for individual MWC plants. Instead, it developed a set of cost estimates based on model plants that reflected the characteristics of the regulated plants. The U.S. EPA (1994*a*) created 16 model plant categories for existing MWC plants and 11 categories for NSPS MWC plants to represent the universe of regulated MWC plants. Model plants for existing MWC plants were based on representative characteristics of existing plants, while the model plants for NSPS plants were based on characteristics of recently built plants, that is, plants under construction (UC) at the time the rule was written.

At the onset of the rulemaking process, the EPA initially intended to regulate all MWC plants but legal challenges ultimately altered the size of the regulated universe. Even if ex post cost data were available for all MWCs, comparing aggregate ex ante and ex post compliance costs would not be informative because of two unanticipated changes that occurred between the promulgation date in 1995 and the 2000 compliance date. First, a 1997 court vacatur of the 1995 MWC rule required the EPA to promulgate separate rules for small and large MWC units. As a result, the number of plants covered by the new large MWC rule was a subset of the plants subject to the 1995 MWC rule. And then, the number of large plants affected by the rule was smaller than predicted due to canceled construction plans and plant closures that occurred after 1991. It follows that, unless ex post costs per plant were substantially higher than ex ante costs per plant, the decline in the number of MWC plants subject to the rule would result in aggregate ex post costs being lower than aggregate ex ante cost estimates.

While only a subset of the original MWC plants had to comply with the 1995 final rule, the control technologies that would achieve the emission limits for the targeted pollutants did

[3] MWC plants with aggregate plant capacity above 35 Mg/day.

https://doi.org/10.1017/bca.2023.16 Published online by Cambridge University Press

not change. The model plant categories used to estimate plant-level compliance costs from the economic analysis conducted to support the 1991 rulemaking still applied to this subset of large MWCs. However, the aggregate ex ante compliance costs estimated in the economic analysis no longer accurately reflected total compliance costs because of the overall changes to the regulated universe of MWC plants. As a result, our retrospective assessment focuses on individual MWC plants.

3.1. Main drivers of ex ante cost estimates

The main drivers of plant-level ex ante costs were the characteristics used to define the model plant categories and the respective equations used to estimate capital and operating costs for new and existing MWC plants. The model plants captured design characteristics such as combustion technologies, APCD, and capacity. For existing MWCs, the EPA assigned a combustion technology, capacity, and baseline APCD to each model plant category. The model plant category for NSPS MWCs is distinguished only by its combustion technology and capacity.

While the standards and guidelines for new and existing MWCs did not mandate specific technologies, the U.S. EPA (1994*a*) set maximum achievable control technology, or MACT, standards and guidelines for new and existing MWC plants based on control technologies that would meet emission limits. The EPA found that emissions limits could be achieved if new MWCs used a spray dryer (SD) and fabric filter (FF) configuration (i.e., SD/FF), while existing MWCs could comply with limits by retrofitting with either a SD/FF configuration or a SD and electrostatic precipitator (ESP) configuration (i.e., SD/ESP) to reduce dioxin/furans, SO_2, PM, and metals. The technology limits for Hg and NO_x emissions were set based on MWCs using activated carbon injection (CI) for controlling Hg emissions and selective noncatalytic reduction (SNCR) to control NO_x emissions (U.S. EPA, 1995). Contingent on the model plant baseline APCD, the EPA assigned one or more of these control technologies to each model plant category to meet emission limits. The estimated incremental capital and annual operating costs were the difference between this APCD configuration compared to the baseline control technology.

3.2. Main sources of uncertainty in ex ante cost estimates

For the 1995 rule, the EPA did not estimate the number of planned MWCs whose construction might be canceled or the number of existing plants that might shutdown due to the regulation. At the time the rule was promulgated, the U.S. EPA (1995) acknowledged new data suggested fewer MWCs were being constructed, which would reduce the aggregate costs of meeting the standards. The EPA also recognized that if the regulation raised tipping fees, that is, fees paid to dispose waste, then some MWCs might switch to less costly options for disposing municipal waste. For any of these scenarios, aggregate costs and emissions would be lower than reported in the economic analysis of the rule. The EPA recognized its estimates potentially misestimated the effect of the rule, and as a result, it characterized the estimated impacts of the final rule as the worst-case scenario when implementing the new standards.

https://doi.org/10.1017/bca.2023.16 Published online by Cambridge University Press

4. Information available to conduct ex post evaluation

We use a combination of MWC inventories complied by the EPA and non-EPA sources to identify the names and characteristics of the large MWCs subject to the 1995 final rule. The 1991 EPA inventory of MWC plants (see Fenn & Nebel, 1992) was used to identify the baseline universe of MWCs.[4] Two subsequent inventories assembled by the EPA were used to identify which MWC units were subject to the large MWC rule in 1995 and by the 2000 compliance date. The revised 1995 inventory of large MWC units (Cone & Kane, 1997), which incorporated changes resulting from the 1997 court vacatur, identified the universe of large MWCs at the time the 1995 rule was promulgated, while the 2000 inventory of large MWC units (Huckaby, 2002*a*) reported the universe of large MWCs on the effective date of the revised large MWC rule.

The EPA inventories of MWCs were supplemented with information from several non-EPA sources. First, Governmental Advisory Associates, Inc. (GAA) published several directories of municipal waste facilities (Berenyi & Gould, 1988, 1991, 1993; Berenyi, 1997, 2006) that provided information on the start-up year, plant shutdowns, and APCDs installed at MWCs.[5] Kiser (1990, 1992) published another set of directories with information on the operating status, capacity, and APCDs installed at each plant. Finally, the Energy Recovery Council (ERC) occasionally publishes directories of waste-to-energy plants – the most recent was published in 2018 (ERC, 2018). The ERC inventories provide information on the combustor type, installed APCDs, and the year the plant started operating.

To identify plants subject to NSPS, we used information from the EPA's Office of Compliance and Enforcement (OECA) Supporting Statement for their 2001 information collection request (ICR), that collected data on plants subject to the NSPS provisions of the MWC rule. The Supporting Statement for the 2001 ICR estimated seven plants were subject to NSPS provisions (U.S. EPA, 2001).

An important contribution of this study is the identification and use of two independent surveys – one public and one private – that collected air pollution abatement cost data from MWCs.[6] The public source of ex post cost estimates is the EIA-767 "Steam-Electric Plant Operation and Design Report" survey (U.S. Department of Energy, n.d.), and its successor, the EIA-860 "Annual Electric Generator" report (U.S. DOE, 2013). These annual surveys request information on (i) the installed costs and operating costs for flue-gas desulfurization (FGD) units which remove SO_2 emissions using spray dry scrubbing coupled with baghouses (FFs), and (ii) the installed costs of flue-gas particulate (FGP) collectors that remove particulate matter from the flue gas. While the EIA-767 survey collected information on whether nitrogen oxide or mercury abatement technologies were installed, only the EIA-860 survey includes questions about the cost of those technologies. We augment the EIA data with a private source of data on capital expenditures by MWCs. The capital expenditure data

[4] The EPA used the database compiled by Fenn and Nebel (1992) to identify and characterize MWC plants that would be subject to the guidelines. In addition to plant name and location, the database captured information on current APCD, construction and start-up dates, and combustor type.

[5] These inventories also provide information on the cancelations of planned MWCs.

[6] All 66 MWCs report some information on the GAA survey. However, it should be noted that while there is information on additional capital costs incurred by a MWC, there appears to be no specific question about capital expenditures associated with air pollution control equipment. For the 2013 EIA survey, responses are reported from 56 of the 66 MWCs covered in our analysis.

https://doi.org/10.1017/bca.2023.16 Published online by Cambridge University Press

collected by the GAA (Berenyi, 2006) includes the type of APCD(s) installed, the year of their installation, and costs of the device(s).

5. Ex post assessment of compliance costs

In this section, we use the EPA's conceptual framework to compare ex ante and ex post values for MWC plants and, when possible, identify potential factors leading to differences between the estimates. The key components of the conceptual framework are the number of regulated MWCs, baseline APCDs used by MWCs, the APCDs used for compliance, and the cost of those control devices installed to comply with the rule. Table 1 provides a summary of our overall findings by each component in our assessment, including sources of ex post information, how ex ante and ex post costs are estimated, as well as potential reasons for differences between ex ante and ex post compliance costs.

5.1. Regulated universe

Recall the EPA expected 179 existing plants and 72 new plants would be subject to the 1995 rule. But changes to the original 1991 rule resulted in a decrease in the regulated universe. When the rule was promulgated in 1995, only 128 MWC plants were operating, of which 81 plants were classified as large (Cone & Kane, 1997). The 1997 court vacatur resulted in the reclassification of 18 plants from the large to small plant category. As a result, the revised 1995 inventory lists 63 large plants and 65 small plants (Cone & Kane, 1997). However, at the time of compliance with the rule, the 2000 inventory of large MWCs (Huckaby, 2002*a*) lists 66 MWC plants subject to the EG. The increase from 63 to 66 large MWC plants between 1995 and 2000 resulted from (i) the addition of four, new large plants, (ii) the closure of seven large plants, (iii) the reclassification of three plants from the large MWC category to the small MWC category, and (iv) the reclassification of nine plants from the small to large MWC category.[7,8] The name, location (by state), and plant characteristics of the 66 large MWC plants operating in 2000 are listed in Table 2.

By comparing plants from the 2000 EPA MWC inventory to the 1991 EPA MWC inventory, we identified seven plants subject to NSPS. These plants are shown in Table 2 with NSPS in parentheses next to the facility name. For several plants, we modified the classification listed in the 1991 inventory, which affected whether a plant was classified as NSPS. For example, Union County RRF (NJ), was included in the 1991 EPA inventory of existing MWC plants. However, because both the 1995 and 2000 EPA inventories state construction on Union County (NJ) started in 1992, we include it as a new source subject to subpart Ea.[9] Another plant, Hudson Falls (NY), is not listed in the 1991 EPA MWC inventory. While the 1995 EPA inventory does not provide a construction date, it lists the startup date as 1992, while other sources (Berenyi & Gould, 1988, 1991; Kiser, 1990) list its startup date in either 1990 or 1991. Based on this information, we decided to classify the

[7] For a description of these plants, see Supplementary Table A.9.

[8] The nine MWC plants were initially classified as large MWCs, then reclassified as small MWCs due to the 1997 court vacatur (Cone & Kane, 1997), and then reclassified as a large MWC in the 2000 large MWC inventory.

[9] Additional sources (Kiser, 1992; Berenyi & Gould, 1993) corroborated that the plant was under construction after 1991.

https://doi.org/10.1017/bca.2023.16 Published online by Cambridge University Press

Table 1. *Summary of the retrospective cost analysis.*

Components of the cost estimates			Sources of ex post information	Assessment (ex post compared to ex ante)	Potential reasons for differences between ex ante and ex post costs
Regulated universe	Types of plants	Large MWC plants (capacity greater than 250 tons/day)	Fenn and Nebel; Cone and Kane; Huckaby	Existing MWCs – fewer New MWCs – fewer	Changes to the original 1991 rule resulted in the separation of large and small MWCs; reduced number of regulated MWCs.
	Number of plants	Existing MWC plants New MWC plants			
Methods of compliance	Main pollutants targeted: PM, SO_2, NO_x, Hg	APCD – FGD, FGP, SCNR, and CI	Berenyi and Gould; Berenyi; U.S. DOE, EIA Form 860; Fenn and Nebel	MWC plants installed (ex post) the expected technologies to reduce emissions of PM, SO_2, Hg, and NO_x	
Ex post compliance costs per MWC plant	EPA used model plant categories to estimate ex ante costs for new and existing MWC plants	Assessment compares ratio of ex post to ex ante capital costs	EIA-767; EIA-860; Berenyi	APCD to reduce PM and SO_2 (FGD and FGP), mean ratio of 1.16, ex ante and ex post capital costs are similar in magnitude. APCD to reduce NO_x (SCNR), mean ratio of 0.50, ex post capital costs are less than ex ante costs. APCD to reduce Hg (CI), mean ratio of 4.74, ex post capital costs significantly higher than ex ante costs.	Both SCNR and CI were emerging technologies, just beginning to be adopted in United States when the ex ante costs values were estimated.

Table 2. *Characteristics of 66 large MWCs operating in 2000.*

State	Facility name	Plant ID	Model plant	Combustion technology (in 2000)	Baseline APCD	2000 APCD
AL	Huntsville Solid Waste-to-Energy Facility	N/A	5	MB/WW	(ESP)	SD/FF/CI/SNCR
CA	Commerce Refuse-to-Energy Facility	10090	6	MB/WW	SD/FF/SNCR[a,b]	SD/FF/SNCR
CA	Southeast Resource Recovery Facility (SERRF)	50837	5	MB/WW	SD/FF/SNCR[a,b]	SD/FF/SNCR
CA	Stanislaus County Resource Recovery Facility	50632	5	MB/WW	SD/FF/SNCR[a,b]	SD/FF/CI/SNCR
CT	Bristol Resource Recovery Facility	50648	5	MB/WW	SD/FF[b]	SD/FF/CI/SNCR
CT	Mid-Connecticut Resource Recovery Facility	54945	7	RDF	SD/FF[a]	SD/FF/SNCR
CT	Riley Energy Systems of Lisbon Connecticut Corp.	54758	(NSPS) 2	MB/WW	—*	SD/FF/CI/SNCR
CT	Southeastern Connecticut Resource Recovery Facility	10646	5	MB/WW	(ESP)	SD/FF/CI
CT	Wheelabrator Bridgeport Company, L.P.	50883	4	MB/WW	SD/FF[a]	SD/FF/CI
FL	Hillsborough County Resource Recovery Facility	50858	5	MB/WW	ESP[a]	SD/FF/CI/SNCR
FL	Lake County Resource Recovery Facility	50629	6	MB/WW	(ESP)	SD/FF/CI/SNCR
FL	Lee County Resource Recovery Facility	52010	(NSPS) 2	MB/WW	—*	SD/FF/CI/SNCR
FL	McKay Bay Refuse-to-Energy Facility	50875	5	MB/WW	ESP[a]	SD/FF/CI/SNCR
FL	Miami-Dade County Resource Recovery Facility	10062	7	RDF	ESP[a]	SD/FF/CI/SNCR
FL	North County Resource Recovery Facility	50071	7	RDF	SD/ESP[b]	SD/ESP
FL	Pasco County Resource Recovery Facility	50666	5	MB/WW	(ESP)	SD/FF/CI/SNCR
FL	Pinellas County Resource Recovery Facility	50884	4	MB/WW	ESP[a]	SD/FF/CI/SNCR
FL	Wheelabrator North Broward, Inc.	54033	4	MB/WW	(ESP)	SD/FF/SNCR

https://doi.org/10.1017/bca.2023.16 Published online by Cambridge University Press

Table 2. *Continued*

State	Facility name	Plant ID	Model plant	Combustion technology (in 2000)	Baseline APCD	2000 APCD
FL	Wheelabrator South Broward, Inc.	50887	4	MB/WW	(ESP)	SD/FF/SNCR
GA	Montenay Savannah Operations, Inc.	N/A	6	MB/WW	ESP[a]	SD/FF/CI/SNCR
HI	Honolulu Resource Recovery Venture – HPOWER	49846	7	RDF	(ESP)	SD/ESP
IN	Indianapolis Resource Recovery Facility	50647	4	MB/WW	SD/FF[c]	SD/FF/CI/SNCR
MA	Haverhill Resource Recovery Facility	50661	4	MB/WW	SD/ESP[c]	SD/FF/CI/SNCR
MA	*SEMASS Resource Recovery Facility*	*50290*	*7*	*RDF*	*SD/ESP (units 1–2)*[a]	*Units 1–2: SD/ESP/FF/CI (COHPAC)*
			(NSPS) 6		*— (unit 3)****	*Unit 3: SD/FF/SNCR*
MA	Wheelabrator Millbury Inc.	50878	5	MB/WW	SD/ESP[a]	SD/ESP/CI/SNCR
MA	Wheelabrator North Andover Inc.	50877	5	MB/WW	ESP[a]	SD/FF/CI/SNCR
MA	Wheelabrator Saugus, J.V.	50880	5	MB/WW	ESP[a]	SD/FF/CI/SNCR
MD	Baltimore Refuse Energy Systems Company (BRESCO)	10629	4	MB/WW	ESP[a]	SD/ESP/CI/SNCR
MD	Montgomery County Resource Recovery Facility	50657	(NSPS) 3	MB/WW	—*	SD/FF/CI/SNCR
ME	Greater Portland Resource Recovery Facility	50225	6	MB/WW	SD/ESP[b]	SD/ESP/CI/SNCR
ME	Maine Energy Recovery Company	10338	8	RDF	SD/FF[a]	SD/FF/SNCR
ME	Penobscot Energy Recovery Corp.	50051	8	RDF	SD/FF[a]	SD/FF
MI	Central Wayne Energy (unit 3 is large MWC)	54804	(NSPS) 1	MB/WW	—**	SD/FF/CI/SNCR
MI	Greater Detroit Resource Recovery Facility	10033	7	RDF	ESP[a]	SD/FF
MI	Kent County Waste-to-Energy Facility	50860	5	MB/WW	(ESP)	SD/FF/CI/SNCR

Table 2. *Continued*

State	Facility name	Plant ID	Model plant	Combustion technology (in 2000)	Baseline APCD	2000 APCD
MN	Great River Energy – Elk River Station	2039	8	RDF	SD/FF[b]	SD/FF
MN	Hennepin Energy Resource Co.	10013	5	MB/WW	SD/FF[c]	SD/FF/CI/SNCR
MN	Xcel Energy – Red Wing Steam Plant	1926	8	RDF	ESP[a]	DSI/FF
MN	Xcel Energy – Wilmarth Plant (Mankato)	1934	8	RDF	ESP[a]	SD/FF/SNCR
NC	New Hanover County-Wastec (unit 3 is large MWC)	50271	6	MB/WW	(ESP)	SD/FF/CI/SNCR
NH	Wheelabrator Concord Company, L.P.	50873	6	MB/WW	DSI/FF[d]	SD/FF/CI/SNCR
NJ	Camden Resource Recovery Facility	10435	5	MB/WW	(ESP)	SD/ESP/CI/SNCR
NJ	Essex County Resource Recovery Facility	10643	4	MB/WW	(ESP)	SD/ESP/CI/SNCR
NJ	Union County Resource Recovery Facility	50960	(NSPS) 3	MB/WW	—*	SD/FF/CI/SNCR
NJ	Wheelabrator Gloucester Company, L.P.	50885	6	MB/WW	(ESP)	SD/FF/CI/SNCR
NY	Babylon Resource Recovery Facility	50649	5	MB/WW	SD/FF[a]	SD/FF/CI/SNCR
NY	Hempstead Resource Recovery Facility	10642	4	MB/WW	SD/FF[c]	SD/FF/SNCR
NY	Huntington Resource Recovery Facility	50656	5	MB/WW	(ESP)	SD/FF/CI/SNCR
NY	Niagara Falls Resource Recovery Facility	50472	4	MB/WW	ESP[a]	SD/FF/CI/SNCR
NY	Onondaga County Resource Recovery Facility	50662	(NSPS) 2	MB/WW	—*	SD/FF/CI/SNCR
NY	Wheelabrator Hudson Falls Inc.	10503	6	MB/WW	(ESP)	SD/ESP/CI
NY	Wheelabrator Westchester Company, L.P.	50882	4	MB/WW	ESP[a]	SD/FF/CI/SNCR
OK	Walter B. Hall RDD (Tulsa)	50660	5	MB/WW	ESP[a]	SD/FF/CI/SNCR
OR	Marion County Solid Waste-to-Energy Facility	50630	6	MB/WW	SD/FF[a]	SD/FF/CI/SNCR
PA	Delaware Valley Resource Recovery Facility	10746	12	MB/RC	(ESP)	SD/FF
PA	Lancaster County Resource Recovery Facility	50859	5	MB/WW	(ESP)	SD/FF/CI/SNCR

***Table 2.** Continued*

State	Facility name	Plant ID	Model plant	Combustion technology (in 2000)	Baseline APCD	2000 APCD
PA	Montenay Energy Resources of Montgomery County, Inc.	54625	5	MB/WW	(ESP)	SD/FF/CI/SNCR
PA	Wheelabrator Falls Inc.	54746	(NSPS) 3	MB/WW	—*	SD/FF/CI/SNCR
PA	York Resource Recovery Center/Montenay York	50215	12	MB/RC	SD/FF[b]	SD/FF/CI/SNCR
SC	Montenay Charleston Resource Recovery Inc.	10344	5	MB/WW	SD/ESP[d]	SD/ESP/CI
TN	Nashville Thermal Transfer Corp	50209	5	MB/WW	ESP[a]	SD/FF/CI/SNCR
VA	Alexandria/Arlington Resource Recovery Facility	50663	5	MB/WW	ESP[a]	SD/FF/CI/SNCR
VA	I-95 Energy-Resource Recovery Facility	50658	4	MB/WW	(ESP)	SD/FF/CI/SNCR
VA	Southeastern Public Service Authority of Virginia	54998	7	RDF	ESP[a]	SD/FF
WA	Spokane Regional Solid Waste Disposal Facility	50886	5	MB/WW	(ESP)	SD/FF/CI/SNCR
WI	Xcel Energy French Island Generating Plant	4005	8	RDF	EGB[a]	SD/FF***

Note: Plant ID refers to DOE/EIA ORIS Plant Code. See Morgan and Pasurka (2021, Table 1) for more detailed information about this table. Baseline APCD configurations: (ESP) – plants whose started construction prior to 1990, but started operation in 1990 or later are assumed to have ESP as baseline APCD.

Abbreviations: COHPAC, compact hybrid particulate collector; DSI, dry sorbent injection; EGB, electrified gravel bed.

[a]Berenyi and Gould (1988);

[b]U.S. DOE, EIA Form 860 (2013);

[c]Berenyi (2006);

[d]Fenn and Nebel (1992) are sources of baseline APCD configurations.

*NSPS (subject to subpart Ea).

**NSPS (subject to subpart Eb).

***According to the EIA-860, French Island (WI) installed SD/FF APCDs in 2002. When calculating ex ante and ex post costs for French Island, we use the SD/FF configuration reported by GAA and EIA-860 as its 2000 APCD configuration instead of the 2000 APCD configuration of DSI/EGB reported by Huckaby (2002*a*, *b*).

Source: Huckaby (2002*a*, *b*) for Total Plant Capacity, Combustion Technology, and 2000 APCD.

Hudson Fall plant as an existing MWC. Finally, the SEMASS Resource Recovery Facility (MA) added a third boiler in 1993 that is subject to NSPS. And one new unit – unit 3 of the Central Wayne (MI) plant – appears to also be subject to NSPS in 2000.[10] Hence, it is the eighth plant in Table 2 with units classified as NSPS.

5.2. Baseline information

For each existing model plant, the EPA assigned one or more APCD that served as its baseline APCD. The baseline APCDs for model plants were either ESP, SD/ESP, or SD/FF, the control technologies designed to control PM and SO_2 emissions. Even though the rule proposed in 1989 and finalized in 1991 underwent modifications from legal challenges, the control technologies the EPA used to set the emission limits of the rule never changed. As a result, APCDs installed on or before December 20, 1989, are the baseline APCDs used in our assessment. Approximately 30% of existing MWC plants were under construction prior to December 20, 1989, and did not start operating until the early 1990s. While we do not have data on the baseline APCDs for these plants, we know they needed to comply with existing standards under the Clean Air Act. The permits they received from the state authorizing their construction and operation would have specified the pollution control equipment needed to meet emission limits. At the time of construction, these plants would have needed to install ESP to comply with existing standards under the Clean Air Act for PM and SO_2. For our analysis, these plants are assigned ESPs as their baseline APCD configuration.

The baseline APCDs for each plant are reported in Table 2. While baseline APCDs identified in the 1991 EPA inventory for MWCs operating prior to 1989 varied, most plants were using ESP technology to control PM and SO_2 emissions. However, the baseline APCD for 15 plants was SD/FF.[11] Given the APCDs in use at the time of the 1989 rulemaking were either ESP or SD/FF, the baseline APCD the EPA used for their existing model plant categories appear to comport with what most MWC plants were using at the time. Only three plants in California had installed SNCR, the technology used to reduce NO_x emissions, prior to 1990.[12] Although the 1991 EPA inventory does not list APCD devices to control Hg or NO_x emissions, we assume the SNCR units installed at these MWCs are part of the baseline and not counted as costs of the MWC rule.

5.3. Compliance costs

For the ex post assessment of compliance costs for each MWC plant, we assign the 67 large MWC plants in Table 2 to one of the model plant categories using four characteristics: (i) existing or NSPS plant, (ii) combustion technology, (iii) capacity, and (iv) baseline

[10] In 1996, the U.S. EPA (1996*b*) determined that if any units of the Central Wayne (MI) plant underwent a waste-to-energy conversion, they would be subject to NSPS.

[11] The sources for the baseline APCDs of MWCs that were operating as of December 20, 1989 are discussed in the endnotes of Table 2.

[12] Information on baseline APCDs to control NO_x releases are from Berenyi and Gould (1988), and EIA Form 860 (U.S. DOE, 2013).

https://doi.org/10.1017/bca.2023.16 Published online by Cambridge University Press

APCD.[13,14] The MWC plants using mass burn waterwall (MB/WW) or mass burn rotary combustor (MB/RC) combustion technology are assigned to a small, mid-size, or large model plant category based on their combustion capacity. The MWC plants using refuse-derived fuel (RDF) combustion technology are assigned to either RDF (large) or RDF (small) model plants based on their combustion capacity. The assigned model plant category for each of the 67 large MWCs are found in Table 2.

From the EIA and GAA surveys, we have information on the APCD installed, the year it was installed and the reported capital cost of the technology. Because we only have capital cost data, our ex post assessment for existing MWCs compares the ex ante capital costs associated with the assigned model plant category to the ex post capital costs of APCD installed by 2000. The difference in costs represents the compliance costs of the rule for the MWC plant. Ex ante costs for new and existing MWC plants that install SNCR and CI are also based on the model plant category to which the MWC is assigned.

5.4. SO_2 and PM capital expenditures (EIA)

As shown in Table 2, of the 59 existing MWC plants, 15 plants using SD/FF did not change their APCD configuration between 1991 and 2000.[15] While the 1991 inventory lists a SD/FF configuration for Union County (NJ), because it is classified as new MWC, it is not included among the 15 plants. Another four plants listed SD/ESP as their baseline APCDs and maintained that configuration through December 2000. Because these 19 plants made no changes to their baseline APCDs, they incur no capital costs related to the MWC rule for reducing SO_2 and PM emissions.

Of the remaining 40 existing MWC plants, 10 plants submitted neither FGD nor FGP capital cost data on their EIA survey form, 23 plants submitted both FGD and FGP data, five plants submitted only FGD data, and two plants submitted only FGP data. Because the seven plants that submitted only FGD or only FGP data were already using the other device, these plants are included in the analysis. Of the eight NSPS MWC plants, only one plant, Montgomery County (MD), submitted no data, while the other seven submitted data for both FGD and FGP costs. As a result, we can compare ex ante and ex post capital costs for 30 existing and 7 NSPS MWC plants.[16]

Instead of providing absolute ex ante and ex posts capital costs for these 37 plants, we present ratios of ex post to ex ante capital costs. The ratios for FGD and FGP systems are summarized in Table 3. Seventeen of the 37 MWCs have ratios greater than unity, while the other 20 MWCs have a ratio less than one. The mean ratio of 1.16 indicates that, on average, ex post and ex ante capital costs are similar in magnitude. However, the maximum and minimum ratios suggests that for some plants, there are substantial discrepancies between ex ante and ex post costs. The MWCs with the highest ratios are Delaware Valley (PA) and

[13] Morgan and Pasurka (2021) provide a detailed explanation of how MWCs are assigned to model plant categories.

[14] For the purposes of the FGD, FGP, CI, and SNCR ex post analysis, SEMASS (MA) is treated as two MWCs. For SEMASS, units 1–2 are treated as an existing MWC, while unit 3 is treated as an NSPS MWC. Hence, ex ante cost estimates are presented for 59 existing MWCs and 8 NSPS MWCs.

[15] The costs of implementing good combustion practices (GCP) are assumed to be imbedded in the ex post capital cost data collected by EIA and GAA.

[16] For ex ante and ex post capital costs of the 37 MWC plants, see Table 8 in Morgan and Pasurka (2021).

https://doi.org/10.1017/bca.2023.16 Published online by Cambridge University Press

Table 3. *Comparison of ex ante and ex post capital costs FGD and FGP (PM and SO_2).*

No. of MWCs	
Ex post > Ex ante	17
Ex post < Ex ante	20
Ex post/Ex ante	
Mean	1.16
Median	0.90
Minimum	0.01
Maximum	3.43

Source: EIA-860, 2013 and EIA-767, 2006.

Lake County (FL), with ratios of 3.43 and 3.00, respectively, while Greater Detroit (MI) has the lowest ratio of 0.01. It is worth noting that Greater Detroit reports $813,000 as the sum of its ex post costs for FGD and FGP. While we are unable to confirm, it is possible the plant misreported this cost value on the EIA Survey.

5.5. Mercury and NO_x capital expenditures (GAA and EIA)

Both EIA and GAA (Berenyi, 2006) collect data on the year of installation and costs of NO_x and Hg control systems. From GAA, we have ex post capital costs of SNCR systems for 11 MWC plants and ex post capital costs of CI systems for 19 MWC plants, where six of these plants reported ex post costs for both SNCR and Cl systems.[17] Eight additional MWC plants that installed both SNCR and CI systems reported their combined ex post capital costs on the GAA survey. From EIA, we have the ex post capital costs of SNCR systems for 34 plants and CI systems for 33 plants, of which 28 MWCs reported costs for both SNCR and CI systems.[18]

The comparison of the ratios of ex post to ex ante capital costs using data from GAA is summarized in Table 4. Of the 19 MWCs reporting capital expenditures for Hg abatement, 18 have ratios greater than unity. A mean ratio of 4.74 for the 19 MWCs suggests the reported ex post capital costs for Hg abatement are significantly higher than the predicted ex ante costs. Only Essex (NJ), with a ratio of 0.60, has an ex post value less than its ex ante cost estimate. For most plants, the EPA estimated ex ante costs of $310,000 for carbon injection to reduce Hg emissions. However, costs reported by GAA ranged from $0.19 to $1.78 million.[19]

For the 11 MWCs reporting capital expenditures for NO_x abatement, 10 have ratios less than unity. The mean ratio of 0.50 indicates the ex post costs of NO_x abatement are not as costly as predicted by the EPA. The ex ante costs ranged from $1.36 to $5.32 million, while the ex post costs reported by GAA ranged from $0.68 to $1.91 million.

[17] SEMASS is excluded because the ex ante cost estimates for model plant number 7 were nil (see Table 10 in Morgan & Pasurka, 2021).

[18] For ex ante costs and GAA and EIA ex post costs, see Morgan and Pasurka (2021, Table 10).

[19] GAA and EIA capital expenditure data are converted to 1990 dollars using the Chemical Engineering Plant Cost Index (see Vatavuk, 2002).

https://doi.org/10.1017/bca.2023.16 Published online by Cambridge University Press

Table 4. *Comparison of ex ante and ex post capital costs (Hg and NO_x).*

No. of MWCs	CI (Hg)	SNCR (NO_x)	CI + SNCR (combined)	CI + SNCR (8 MWCs combined and 6 MWCs – report separate Cl and SNCR)
Ex post > Ex ante	18	1	2	4
Ex post < Ex ante	1	10	6	10
Ex post/Ex ante				
Mean	4.74	0.50	0.74	0.85
Median	3.84	0.37	0.70	0.73
Minimum	0.60	0.17	0.40	0.28
Maximum	19.55	1.34	1.28	2.26

Source: Berenyi (2006).

The ratios are less than unity for two of the eight MWCs reporting a combined capital expenditure value for Hg and NO_x control equipment. For comparison, we combined the ex post costs for the six MWCs that report separate cost values for Hg and NO_x abatement and found the magnitude of costs is similar to combined ex posts costs reported by the eight MWCs. While we are unable to confirm our hypothesis because we are comparing sums, the similarity in the sums of ex post costs suggest costs for Hg abatement were higher than expected, while the costs of NO_x abatement were lower than expected for these eight MWC's.

The ratios of ex post costs to ex ante cost for Hg and NO_x control equipment using data from the EIA are shown in Table 5. The ratios from EIA follow a similar pattern as the ratios found using data reported by GAA. Of the 33 MWCs reporting capital expenditures for Hg abatement, all have ex post to ex ante ratios greater than unity. The mean ratio is 7.60 with reported costs ranging from \$0.22 to \$10.66 million. The MWCs with the highest ratios are Haverhill (MA) and Union County (NJ), with ratios of 34.38 and 27.97, respectively. It is worth noting both MWCs report the same ex post costs for both Hg and NO_x abatement, raising questions of potential misreporting.

Of the 34 MWCs reporting capital expenditures for NO_x abatement, 29 have ex post to ex ante ratios less than unity. The mean ratio is 0.69 for the 34 MWCs, with reported ex post costs ranging from \$36,000 to \$11.65 million. For the five MWCs that reported ex post costs higher than ex ante costs, ex post costs ranged from \$5.46 to \$11.65 million. Again, it is worth noting three of the five MWCs (Haverhill (MA), Union County (NJ), and Alexandria/Arlington (VA)) report identical ex post costs for Hg and NO_x abatement, again raising questions of potential misreporting.

For some plants, capital expenditure data are reported by both sources. While the magnitude of the difference between the ex ante and ex post costs may differ, the direction of the difference is usually the same. In fact, of the 26 ex post cost values reported for either SNCR or Cl systems separately or combined on both surveys, the direction of the difference between ex post and ex ante costs diverges between the two data sources for only three MWCs (Bristol, Essex, and Lake County). That is, if the ex post costs reported on GAA are

https://doi.org/10.1017/bca.2023.16 Published online by Cambridge University Press

Table 5. *Comparison of ex ante and ex post capital costs (Hg and NO_x).*

No. of MWCs	CI(Hg)	SNCR(NO_x)
Ex post > Ex ante	33	5
Ex post < Ex ante	0	29
Ex post/Ex ante		
Mean	7.60	0.69
Median	4.68	0.42
Minimum	1.57	0.01
Maximum	34.38	2.19

Source: EIA-860, 2013.

higher than ex ante costs, then the ex post costs reported for the same plant are lower than the ex ante costs on EIA, and vice versa.

Summarizing, the ratios indicate that ex post capital costs are almost always greater than ex ante capital costs for Hg controls, whereas ex post capital costs are almost always less than ex ante capital costs for NO_x controls. Why did the EPA substantially underestimate the capital costs of Hg controls and overestimate the cost of NO_x controls? In both cases, there are compelling reasons why the EPA may have misestimated the costs. First, the use of activated carbon to remove mercury was new to the United States. At the time the rule was promulgated, the EPA assumed plants would inject activated carbon into the flue gas of their APCD to reduce mercury emissions. The carbon would capture the mercury, which would be collected on a FF and disposed. Because a plant would use existing capital equipment to capture mercury, it was believed the associated incremental capital cost would be low. One plant in British Columbia reported that their preliminary capital cost estimates of installing a carbon absorption system was $200,000 (1990 dollars) (Nebel & White, 1991).

Even though it appeared the cost of using carbon adsorption might be low, it was unclear if and how other factors would influence the overall cost of reducing mercury emissions. For example, the costs of using carbon absorption varied per ton of municipal waste combusted and the amount of mercury in the waste being incinerated. As Shaub (1993) showed, the mercury content of incinerated waste varied based on the consumer products being disposed. Shaub stated the cost of using carbon absorption ranged from $0.50 to $1.00 per ton of MSW combusted. Hence, if the mercury content in waste combusted was between 0.5 and 5.0 g/ton, then the cost to control mercury emissions ranged between $100,000 and $2,000,000 per ton of mercury removed. Given this range of costs, Shaub argued the cost of removing mercury using carbon injection was uncertain and required further investigation. Unfortunately, we were unable to determine the EPA's assumptions regarding mercury content in the waste, but the evidence suggests the costs of using carbon adsorption for mercury removal were significantly higher than the EPA anticipated ex ante.[20]

[20] While Shaub provides a range of costs, we are unable to compare our ex post data to his estimates because we lack plant-level information on the tons of mercury emitted. Furthermore, it is not clear whether his estimates include only the capital costs of carbon absorption.

https://doi.org/10.1017/bca.2023.16 Published online by Cambridge University Press

Like the mercury control technology, there were also uncertainties associated with the cost of installing a SNCR system at the time the MWC rule was promulgated. Selective noncatalytic reduction is an add-on post-combustion APCD (FFs and spray dryers remove some NO_x) that reduces NO_x to N_2 without the use of a catalyst. It requires the injection of a reducing agent such as ammonia or urea into the furnace that reacts with the NO_x to form N_2. While the capital costs associated with using ammonia tend to be lower, urea has several advantages over ammonia. For example, urea is less toxic and less volatile, which means it can be handled and stored more safely. The capital cost to install or retrofit a combustor with the SNCR technology typically increases as the size of the plant increases (as measured by combustion capacity). However, the capital cost can vary with the difficulty associated with retrofitting the current APCD system, the reducing agent used, and method of residual disposal.

In late 1980s, three MM/WW California plants installed SNCR technology using ammonia as the reducing agent (U.S. EPA, 1989*b*). Information from these three California plants were used to develop algorithms to estimate costs of SNCR devices for the model plants used by the EPA in its economic analysis. The costs varied across combustion technology and plant capacity. By the mid-1990s several additional MWCs had installed SNCR devices, and several used urea as opposed to ammonia as the reagent (White *et al.,* 1994). For plants using ammonia, many used aqueous ammonia instead of anhydrous ammonia. Aqueous ammonia is less volatile but requires a larger storage tank, which leads to slightly higher capital costs. However, we could locate no estimates of differences in capital costs between systems using the two reagents.

Using information from MWCs with installed SNCR systems, White *et al.* (1994) developed cost estimates for three model combustors (100, 400, and 750 tpd) using MB/WW combustion and aqueous ammonia as the reagent. Comparing the capital cost per ton for these three model combustors to the capital costs of the same model combustors from a report released in the late 1980s (US EPA, 1989*b*), model plant costs decreased. However, it should be noted that at the time of the 1994 study, new technologies, such as furnace temperature monitoring and ammonia monitoring, were being tested as ways to improve the performance of SNCR and lower the costs of the technology.

Given that the NO_x and Hg abatement technologies the EPA expected MWCs to employ were just beginning to be adopted in the United States, the assumptions used to develop the cost estimates for each model plant may not have captured all costs of the technologies. While limited, the evidence suggests the model plant cost equations did not adequately capture the capital costs associated with carbon injection and SNCR. Unfortunately, the data needed to evaluate the design parameters of the model plant are not available (US EPA, 1989*a*), so we are unable to quantitatively assess which elements of the capital cost equations were higher or lower than the EPA predicted.

5.6. Total capital expenditures across APCD

Instead of reporting capital expenditures for the individual abatement technologies, GAA (Berenyi, 2006) reports total capital expenditures for FGD and FGP for 10 MWC plants as well as total expenditures for FGD, FGP, SNCR, and CI systems for an additional 10 MWCs. The summary statistics for these MWCs are reported in Table 6. For the 10 MWC plants reporting combined cost estimates for FGD and FGP systems, nine have ex post to ex ante ratios greater than unity. For the 10 MWC plants reporting combined

Table 6. *Comparison of ex ante and ex post aggregate capital costs for existing MWCs.*

No. of MWCs	FGD + FGP	FGD + FGP + SNCR+CI
Ex post > Ex ante	9	5
Ex post < Ex ante	1	5
Ex post/Ex ante		
Mean	1.69	1.07
Median	1.67	1.09
Minimum	0.22	0.30
Maximum	2.68	1.63

Source: Berenyi (2006).

costs for their FGD, FGP, SNCR, and CI systems, five have ex post to ex ante ratios greater than one.[21]

For the 10 plants reporting capital expenditures for FGD and FGP systems, we identified eight that also report capital cost data on the EIA survey. The combined capital expenditures for FGD and FGP reported by GAA for three plants – Hillsborough County (FL), Saugus (MA), and Wilmarth (MN) – are lower than the sum reported on the EIA survey, while the combined expenditures reported by the other five plants – McKay Bay (FL), SEMASS (units 1–2) (MA), Greater Detroit (MI), Alexandria/Arlington (VA), and Southeastern Public Service (VA) – are higher than the sum reported on the EIA survey.[22]

While there are differences between the reported values on GAA and EIA for Saugus (MA), Wilmarth (MN), and Alexandria/Arlington (VA), the discrepancies are not substantial. However, the differences are more significant for the other five MWCs. For example, Hillsborough County (FL) reported the same capital cost value for FGD and FGP on EIA. The sum reported by GAA is similar to the cost reported on EIA for either FGD or FGP. Given the similarities, it is possible Hillsborough reported its combined costs for FGD or FGP as the individual costs of FGD and FGP, respectively, on the EIA Survey. Finally, the costs reported by GAA for McKay Bay (FL), SEMASS (units 1–2) (MA), Greater Detroit (MA), and Southeastern Public Service (VA) are more than double the cost reported by EIA. Unfortunately, we were unable to find any explanation for the large discrepancy between the costs reported by the two surveys.

Of the 10 plants reporting combined costs for their FGD, FGP, SNCR, and CI systems on the GAA survey, six also reported ex post capital costs for each technology (FGD, FGP, SNCR, and CI systems) on the EIA survey. Summing the EIA ex post capital costs of these APCDs, four plants – Haverhill (MA), North Andover (MA), Concord (NH), and Westchester (NY) – report total costs on the EIA survey that are 25–58% higher than the combined costs reported by GAA. On the other hand, the combined costs reported on the EIA survey by Pinellas County (FL) and Baltimore (MD) are 7 and 24% less, respectively, than the combined costs reported by GAA. Again, we were unable to explain the discrepancies between the reported costs.

[21] For GAA ex post costs, see Table 13 in Morgan and Pasurka (2021).
[22] See Tables 8 and 13 in Morgan and Pasurka (2021).

https://doi.org/10.1017/bca.2023.16 Published online by Cambridge University Press

5.7. Pictorial summary of the data

Figures 1–3 show box and whisker plots of the ex post to ex ante cost ratios for the various APCDs using the EIA and GAA data. These plots offer a pictorial summary of the characteristics of the ratio of ex post to ex ante costs including the mean (represented by an *x*), median (shown by a horizontal line), the interquartile range (IQR) (shown by the box), the outer range (shown by the whiskers) and any outliers (shown by dots). These graphs convey information about variation in the data and allow side-by-side comparisons of the ratios generated by EIA and GAA data that are not captured by our tables.

Figure 1 depicts the side-by-side comparison of the boxplot of the ratio of ex post to ex ante costs of FGD and FGP systems for the EIA and GAA data. As can be seen by the boxes, there is little overlap between the ratios for the two sources of data. The IQR range, representing the middle 50% of ex post to ex ante cost ratios, is higher for the GAA data. The length of the whiskers, representing the outer range of values – excluding outliers, show the spread of the EIA data is slightly larger.[23] As shown by the length of the upper whisker, the range beyond the upper quartile is much larger for the EIA data, while the range beyond the lower quartile is much larger for GAA, as shown by the length of the lower whisker. That is, the ratio using the EIA data is right-skewed or positively skewed while the ratio using the GAA data is left-skewed or negatively skewed.

For Hg controls (see Figure 2), the side-by-side comparison shows the dispersion of the ratios, as depicted by the IQR, is not as large for the GAA data compared to the EIA data. That is, the length of the box is smaller. Unlike the ratios calculated using GAA data, the EIA data yields ratios that are skewed to the right. Figure 3 shows a similar picture for the cost ratios associated with NO_x pollution controls. As shown by the length of the IQR box, the

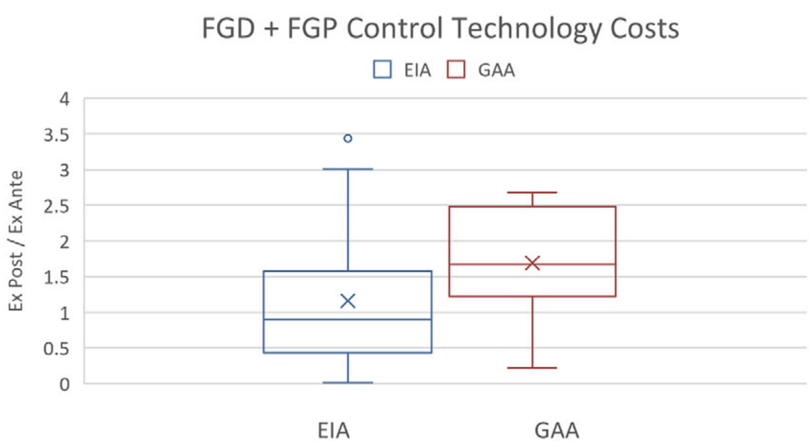

Figure 1. *Box and Whisker plot of the ratio of ex post to ex ante technology costs for FGD and FGP.*

[23] The upper and lower whiskers represent variability outside the upper and lower quartiles and any data point outside the whiskers is considered an outlier. An outlier is a data point that is a numerical distance from the rest of the data – 1.5 times the IQR above the upper quartile and below the lower quartile.

https://doi.org/10.1017/bca.2023.16 Published online by Cambridge University Press

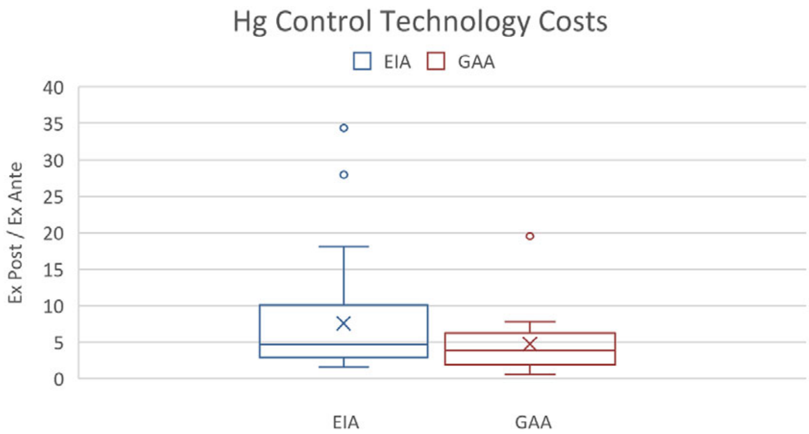

Figure 2. Box and Whisker plot of the ratio of ex post to ex ante technology costs for Hg.

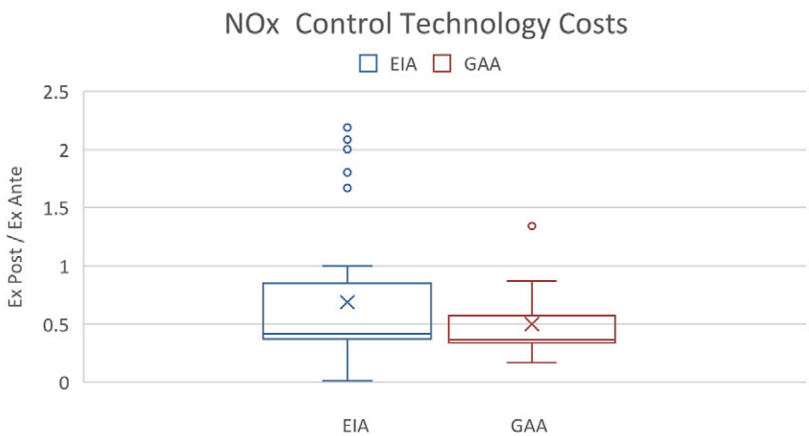

Figure 3. Box and Whisker plot of the ratio of ex post to ex ante technology costs for NO_x.

ratio of ex post to ex ante costs exhibits larger dispersion for the EIA data than GAA data. The EIA data also have more outliers (outside the upper whisker), yet the data are skewed to the left as shown by the lower whisker. As can be seen by the horizontal line, the median ratio is similar for both datasets, while the mean ratio is much higher using the EIA data due to the outliers.

6. Overall implications and study limitations

We compare the projected ex ante capital costs of model plants to the actual ex post capital costs reported by MWCs to comply with the large municipal waste combustor rule. Using characteristics of individual MWC plants, we assign each of the large MWCs operating in 2000 to a model plant category developed by the EPA in their ex ante cost analysis of the rule. Our ex post capital cost plant-level data are from the U.S. Department of Energy

https://doi.org/10.1017/bca.2023.16 Published online by Cambridge University Press

EIA-767 and EIA-860 annual surveys of pollution abatement expenditures incurred by steam-electric power plants, and data on MWC plant capital expenditures from occasional surveys undertaken by GAA. Using these data, we present ratios of ex post capital expenditures to ex ante capital expenditures predicted for the model plant. In addition, when both surveys report data for the same plant, we compare variation in differences between ex post and ex ante costs across surveys. When possible, we identify potential factors contributing to differences between the ex post and ex ante estimates.

For the 37 new and existing MWCs that installed both FGD and FGP systems to reduce PM and SO_2 emissions and reported the costs of these systems on the EIA survey, the ex posts capital costs are higher than the ex ante costs for 17 plants and lower for 20 plants. Even though the results vary among plants, the mean of the ratios of ex post to ex ante costs is near unity indicating that, in general, the EPA estimated similar capital costs as reported by plants. Both FGD and FGP systems have been commercially available and installed as an end-of-pipe technology to reduce PM and SO_2 emissions since the 1970s. Given that the EPA has well-developed cost equations/models that are continually being updated to capture advances in these technologies, it is not surprising that the EPA's ex ante estimates of capital costs are similar in magnitude to reported costs.

However, analysis of the data on reported costs for Hg and NO_x abatement indicates that the EPA underestimated compliance costs of Hg control and overestimated compliance costs of NO_x control. During the late 1990s, both SNCR and CI were new technologies used in the United States. Although only a subset of MWCs report ex post capital costs for their installed APCDs, the findings for SCNR and CI technologies used to reduce NO_x and Hg emissions highlight how the expected costs of technologies change as they become more widely used for emission control. The EPA developed cost equations for model plants using data on these technologies that were still in the early stages of operation and whose performance was still being optimized. While the EPA used the best available information at the time, as the technologies were adopted on a larger scale in response to the rule, the evidence suggests the realized costs diverged from the expected costs.[24]

While this case study presents evidence on how one environmental regulation affected an industry, our findings underscore the point that the accuracy of ex ante cost estimates may be limited when the assessments are based on emerging technologies. This retrospective analysis highlights the risks of underestimating or overestimating compliance costs when relying on engineering models or model plants that incorporate information on new technologies. Because it is not always possible to anticipate how the cost of these technologies will change as they are more widely adopted, one possibility is to conduct additional sensitivity analyses around key cost parameters to explore the effects of this uncertainty when estimating the ex ante compliance costs.

Acknowledgments. We wish to thank S. Miller and A. Fraas for helpful comments on an earlier draft of this article that was presented at the 2018 conference of the Society for Benefit-Cost Analysis in Washington, DC. We also wish to thank N. Simon, L. Sorrels, and C. Spells for helpful comments on a later draft of this article. Any errors, opinions, or conclusions are those of the authors and should not be attributed to the U.S. Environmental Protection Agency.

[24] Based on data the EPA obtained from MWCs that adopted these technologies, these MWCs achieved the emission limits for the NO_x and Hg.

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/bca.2023.16.

References

Berenyi, Eileen B. 1997. *The Municipal Waste Combustion Industry in the United States, 1997–98 Resource Recovery Yearbook and Directory*, 7th Ed. Westport, CT: Governmental Advisory Associates.

Berenyi, Eileen B. 2006. *2005–2006 Municipal Waste Combustion in the United States, Yearbook and Directory*, 8th Ed. Westport, CT: Governmental Advisory Associates.

Berenyi, Eileen B., and Robert N. Gould. 1988. *1988–89 Resource Recovery Yearbook, Directory & Guide*, 4th Ed. Westport, CT: Governmental Advisory Associates.

Berenyi, Eileen B., and Robert N. Gould. 1991. *1991 Resource Recovery Yearbook, Directory & Guide*, 5th Ed. Westport, CT: Governmental Advisory Associates.

Berenyi, Eileen B., and Robert N. Gould. 1993. *1993–94 Resource Recovery Yearbook, Directory & Guide*, 6th Ed. Westport, CT: Governmental Advisory Associates.

Cone, Laurie, and Colleen Kane 1997. "Large and Small MWC Units in the 1995 MWC Inventory Database," July 7 Memo from Eastern Research Group, Inc. to Walt Stevenson (Docket A-90-45, Item VI-B-2).

Energy Recovery Council. 2018. "2018 Directory of Waste-to-Energy Facilities." Available at https://gwcouncil.org/2018-directory-of-waste-to-energy-facilities-energy-recovery-council/.

Fenn, Denise, and Kris Nebel. 1992. "MWC Database," March 9 Memo from Radian Corporation to Walt Stevenson, EPA (Docket A-90-45, Item II-B-8). Available at https://www.regulations.gov/document/EPA-HQ-OAR-2003-0072-0196.

Huckaby, Jason. 2002a. "2000 National Inventory of Large Municipal Waste Combustion (MWC) Units," June 12 Memo from Eastern Research Group, Inc. to Walt Stevenson, EPA (Docket A-90-45, Item VIII-B-6). Available at https://www.regulations.gov/document/EPA-HQ-OAR-2003-0072-0182.

Huckaby, Jason. 2002b. "National Emissions Trends for Large Municipal Waste Combustion Units (Years 1990 to 2005)," June 17 Memo from Eastern Research Group, Inc. to Walt Stevenson, EPA (Docket A-90-45, Item VIII-B-7). Available at https://www.regulations.gov/document/EPA-HQ-OAR-2003-0072-0044.

Kiser, Jonathan. 1990. "A Comprehensive Report on the Status of Municipal Waste Combustion." *Waste Age*, *21* (11): 100–159.

Kiser, Jonathan. 1992. "The 1992 Municipal Waste Combustion Guide." *Waste Age*, *23*(11): 99–117. Available at https://p2infohouse.org/ref/08/07787.pdf.

Morgan, Cynthia, and Carl Pasurka. 2021. "Ex Ante Costs vs. Ex Post Costs of the Large Municipal Waste Combustor Rule." NCEE Working Paper, #2021-01. Available at https://www.epa.gov/sites/default/files/2021-04/documents/2021-01.pdf.

Morgenstern, Richard D. 2015. "The RFF Regulatory Performance Initiative: What Have We Learned?" Resources for the Future Discussion Paper #15–47. Available at https://www.rff.org/publications/working-papers/the-rff-regulatory-performance-initiative-what-have-we-learned/.

Nebel, Kristina L., and David M. White 1991. "A Summary of Mercury Emissions and Applicable Control Technologies for Municipal Waste Combustors." Prepared for Walter Stevenson and Michael Johnston, EPA. Available at https://www.regulations.gov/document/EPA-HQ-OAR-2003-0072-0121.

Shaub, Walter M. 1993. "Mercury Emissions from MSW Incinerators: An Assessment of the Current Situation in the United States and Forecast of Future Emissions." *Resources, Conservation and Recycling*, *9*: 31–59. https://doi.org/10.1016/0921-3449(93)90032-B.

Simon, Nathalie, and Glenn Blomquist (Eds.) 2014. "Retrospective Analysis of the Costs of EPA Regulations [Special Issue]." *Journal of Benefit-Cost Analysis*, *5*(2): 173–193. https://doi.org/10.1017/S2194588800000737.

U.S. Department of Energy, Energy Information Administration. 2013. "Annual Electric Generator Report," EIA Form 860. Available at https://www.eia.gov/electricity/data/eia860/.

U.S. Department of Energy, Energy Information Administration. 2006 "Steam-Electric Plant Operation and Design Report," EIA Form 767. Available at https://www.eia.gov/electricity/data/eia767/.

U.S. Environmental Protection Agency. 1989a. *Municipal Waste Combustors – Background Information for Proposed Standards: III(b) Model Plant Description and Cost Report*, EPA-450/3–89-27b. Available at https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=2000JFUA.PDF.

U.S. Environmental Protection Agency. 1989b. *Municipal Waste Combustors – Background Information for Proposed Standards: Control of NO_x Emissions*, EPA-450/3-89-27d. Available at https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P10074CN.PDF.

U.S. Environmental Protection Agency. 1994a. *Economic Impact Analysis for Proposed Emission Standards and Guidelines for Municipal Waste Combustors*, EPA-450/3-91-029. Available at https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=2000MT8O.PDF.

U.S. Environmental Protection Agency. 1994b. "Emission Guidelines: Municipal Waste Combustors." *Federal Register*, *59*(181): 48228–48258. Available at https://www.govinfo.gov/content/pkg/FR-1994-09-20/html/94-22343.htm.

U.S. Environmental Protection Agency. 1995. "Standards of Performance for New Stationary Sources and Emission Guidelines for Existing Sources." *Federal Register 60*(243): 65387–65436. Available at https://www.govinfo.gov/content/pkg/FR-1995-12-19/pdf/95-30257.pdf.

U.S Environmental Protection Agency. 1996. Correspondence of October 11, 1996 from George T. Czerniak, Jr., Chief, Air Enforcement and Compliance Assurance Branch, Air and Radiation Division, to Greg Aldrich, Wayne County Department of Environment. Available at https://www.regulations.gov/document/EPA-HQ-OAR-2004-0306-0015.

U.S. Environmental Protection Agency. 2001. SF-83 Supporting Statement for "NSPS for Municipal Waste Combustors (Subparts Ea and Eb)." Docket ID Number EPA-HQ-OECA-2003-0087-0005. Available at https://www.regulations.gov/document/EPA-HQ-OECA-2003-0087-0005.

U.S. Environmental Protection Agency. 2014. "Retrospective Study of the Costs of EPA Regulations: A Report of Four Case Studies," Report 240-F-14-001. Available at https://www.epa.gov/sites/default/files/2017-09/documents/ee-0575_0.pdf.

Vatavuk, William. 2002. "Updating the CE Plant Cost Index." *Chemical Engineering*, *109*(1): 62–70. Available at https://chemeng.queensu.ca/courses/CHEE332/files/UpdatingtheCEPlantCostIndex.pdf.

White, D., K. Nebel, M. Gundappa, and K. Ferry. 1994. "NO_x Control Technologies Applicable to Municipal Waste Combustion." U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-94/208. Available at https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100P73S.PDF.

Wolverton, A., A. Ferris, and N. Simon. 2018. "Retrospective Evaluation of the Costs of Complying With Light-Duty Vehicle Surface Coating Requirements." *Journal of Benefit-Cost Analysis*, *10*(1): 39–64. https://doi.org/10.1017/bca.2018.25.

Cite this article: Morgan, C., and C. A. Pasurka Jr. 2023. "Ex Ante Costs Versus Ex Post Costs of the Large Municipal Waste Combustor Rule." *Journal of Benefit-Cost Analysis* 14: 275–297, doi:10.1017/bca.2023.16