Supplemental Information

Characterization of end-of-pipe controls in support of the manuscript "Marginal abatement cost curve for NOx that incorporates control measures, renewable electricity, energy efficiency and fuel switching"

Dan Loughlin

End-of-pipe NOx controls were added to the database to represent the maximum reduction options for industrial, residential, commercial and off-highway sources. The control characterizations were derived from the file All_Poll_All_Sectors_US_DetSTratRslt_NOX_Cntrls.xlsx, which was created by OAQPS' David Misenheimer as part of the Ozone NAAQS RIA process. Using pivot tables and a state-to-MARKAL region crosswalk, the average percent reduction and cost-per-ton-of-pollutant-treated for controls within each MARKAL region and SCC[1] aggregation level were calculated, one through four.

Next, a crosswalk that links MARKAL's emission control technologies to the most relevant control characterizations was constructed. The crosswalk is provided in **Table 1**. The resulting control efficiencies and cost-per-ton-of-emissions-treated for each MARKAL category are shown in **Tables 2 and 3**, respectively.

Although All_Poll_All_Sectors_US_DetSTratRslt_NOX_Cntrls.xlsx lists controls that would make up a "maximum control strategy," there are many sources within the inventory that are not represented in the file. Some of these sources do not have any controls available. For others, OAQPS assumes that controls cannot be implemented cost-effectively because the source is too small. To prevent MARKAL from placing controls on these sources, All_Poll_All_Sectors_US_DetSTratRslt_NOX_Cntrls.xlsx was compared with a 2025 inventory and the fraction of regional NOx emissions at each SCC tier that is controllable was estimated.

Inventory data were obtained from the file 2025_NOx_state_scc_summary.xlsx, which summarized state-level emissions by SCC for the 2025 modeling inventory used in the Ozone NAAQS RIA. This file was obtained from OAQPS' Alison Eyth on 4/18/14. Using a pivot table, we aggregated these by region and SCC tier. Comparing the emissions in each tier provided an estimate of the percentage of the emissions in that category that are subject to control. Where there was no data for a particular category-region combination, it was assumed that 20% of the emissions were subject to control. This percentage was a typical low value for categories for which data could be calculated. The percentages were mapped to MARKAL controls, and the result is shown in **Table 4**.

For questions regarding this study, please contact Dan Loughlin at loughlin.dan@epa.gov.

[1] There are approximately 10,000 source classification codes, or SCCs, within the EPA emission inventory. The codes are organized in a hierarchy which is defined as tiers or levels. Typically four levels are used, providing more specific information with each level.

Table 1. Crosswalk between MARKAL control categories and SCC-level control characterizations.

MARKAL control applied to:		Matching SCC category			
Fuel	From	Tier 1	Tier 2	Tier 3	Tier 4
coal	boilers	External combustion boilers	Industrial	Bituminous/Subbituminous coal	[all]
coal	turbines	Internal combustion engines	Industrial	Natural gas	[all turbines]
coal	process heaters	Industrial processes	In-Process Fuel Use	Bituminous/Subbituminous coal	[all]
coal	other	Stationary fuel combustion	Industrial	Bituminous/Subbituminous coal	[all]
gas	boilers	External combustion boilers	Industrial	Natural gas	[all]
gas	engines	Internal combustion engines	Industrial	Natural gas	[all engines]
gas	turbines	Internal combustion engines	Industrial	Natural gas	[all turbines]
gas	process heaters	Industrial processes	Petroleum Industry	Process Heaters	[all with gas in name]
gas	other	Stationary fuel combustion	Industrial	Distillate oil	[all]
distillate	boilers	External combustion boilers	Industrial	Distillate oil	[all]
distillate	engines	Internal combustion engines	Industrial	Distillate oil	[all engines]
distillate	turbines	Internal combustion engines	Industrial	Natural gas	[all turbines]
distillate	process heaters	Industrial processes	Miscellaneous manufacturing industries	Distillate (No 2)	Process heaters
distillate	other	Stationary fuel combustion	Industrial	Distillate oil	[all]
fuel oil	boilers	External combustion boilers	Industrial	Residual oil	[all]
fuel oil	engines	Internal combustion engines	Industrial	Residual/crude oil	[all]
fuel oil	Petroleum industry	Industrial processes	Process heaters	Oil-fired	[all]
fuel oil	other	Stationary fuel combustion	Industrial	Distillate oil	[all]
other	boilers	External combustion boilers	Industrial	Distillate oil	[all]
other	engines	Internal combustion engines	Industrial	Distillate oil	[all engines]
other	turbines	Internal combustion engines	Industrial	Natural gas	[all turbines]
other	process heaters	Industrial processes	Miscellaneous manufacturing industries	Distillate (No 2)	Process heaters
other	other	Stationary fuel combustion	Industrial	[all]	[all]
diesel	off-highway diesel	Off-highway vehicle diesel	Mobile sources	[all]	[all]
various	residential	Stationary fuel combustion	Residential	[all]	[all]
various	commercial	[all matching]	Commercial/Institutional	[all]	[all]
various	refineries	Industrial processes	Petroleum Industry	[all]	[all]
various	facility heat	External combustion boilers	Space Heaters	[all]	[all]
various	Coking	Industrial processes	Primary Metal Production	By-Product Coke Manufacturing	[all]

Table 2. Characterization of control costs by MARKAL control category and region, derived from the set of maximum controls in each state, as specified by OAQPS in the process of developing the Ozone NAAQS RIA.

MARKAL control category		Average cost	Average regional cost ($k/tonne)								
Fuel	Type	$k/tonne	1	2	3	4	5	6	7	8	9
coal	boilers	$ 2.63	$ 2.78	$ 3.03	$ 3.17	$ 2.27	$ 2.64	$ 1.63	$ 2.75	$ 2.99	$ 4.59
coal	turbines	$ 0.66	$ 0.66	$ 0.66	$ 0.66	$ 0.66	$ 0.66	$ 0.66	$ 0.66	$ 0.66	$ 0.66
coal	process heaters	$ 4.06	$ 4.06	$ 2.29	$ 3.28	$ 4.06	$ 4.06	$ 4.59	$ 4.59	$ 0.46	$ 4.06
coal	other	$ 0.16	$ 0.16	$ 0.16	$ 0.16	$ 0.16	$ 0.16	$ 0.16	$ 0.16	$ 0.16	$ 0.16
gas	boilers	$ 5.36	$ 4.99	$ 3.28	$ 5.97	$ 5.82	$ 5.39	$ 5.55	$ 5.28	$ 5.47	$ 5.62
gas	engines	$ 0.41	$ 0.14	$ 0.35	$ 0.34	$ 0.53	$ 0.54	$ 0.26	$ 0.45	$ 0.34	$ 0.41
gas	turbines	$ 0.66	$ 3.78	$ 1.09	$ 1.30	$ 0.85	$ 1.64	$ 0.83	$ 1.09	$ 0.48	$ 0.36
gas	process heaters	$ 6.42	$ 6.42	$ 6.42	$ 5.11	$ 6.42	$ 6.42	$ 6.42	$ 6.59	$ 6.42	$ 6.42
gas	other	$ 0.14	$ 0.14	$ 0.14	$ 0.14	$ 0.14	$ 0.14	$ 0.14	$ 0.14	$ 0.14	$ 0.14
distillate	boilers	$ 10.33	$ 10.33	$ 10.33	$ 10.33	$ 10.33	$ 10.33	$ 10.33	$ 10.33	$ 10.33	$ 10.33
distillate	engines	$ 2.56	$ 3.00	$ 3.00	$ 3.00	$ 3.00	$ 3.00	$ 3.38	$ 3.00	$ 3.00	$ 1.94
distillate	turbines	$ 0.66	$ 0.66	$ 0.66	$ 0.66	$ 0.66	$ 0.66	$ 0.66	$ 0.66	$ 0.66	$ 0.66
distillate	process heaters	$ 1.76	$ 1.76	$ 1.76	$ 1.76	$ 1.76	$ 1.76	$ 1.76	$ 1.76	$ 1.76	$ 1.76
distillate	other	$ 0.09	$ 0.09	$ 0.09	$ 0.09	$ 0.09	$ 0.09	$ 0.09	$ 0.09	$ 0.09	$ 0.09
fuel oil	boilers	$ 3.41	$ 2.56	$ 2.99	$ 3.41	$ 3.41	$ 4.64	$ 5.24	$ 3.85	$ 3.41	$ 1.95
fuel oil	engines	$ 4.87	$ 4.87	$ 4.87	$ 4.87	$ 4.87	$ 4.87	$ 4.87	$ 4.87	$ 4.87	$ 4.87
fuel oil	turbines	$ 0.66	$ 0.66	$ 0.66	$ 0.66	$ 0.66	$ 0.66	$ 0.66	$ 0.66	$ 0.66	$ 0.66
fuel oil	process heaters	$ 2.10	$ 2.10	$ 2.10	$ 2.10	$ 2.10	$ 2.10	$ 2.10	$ 2.10	$ 2.10	$ 2.10
fuel oil	other	$ 0.09	$ 0.09	$ 0.09	$ 0.09	$ 0.09	$ 0.09	$ 0.09	$ 0.09	$ 0.09	$ 0.09
other	boilers	$ 10.33	$ 10.33	$ 10.33	$ 10.33	$ 10.33	$ 10.33	$ 10.33	$ 10.33	$ 10.33	$ 10.33
other	engines	$ 2.56	$ 2.56	$ 2.56	$ 2.56	$ 2.56	$ 2.56	$ 2.56	$ 2.56	$ 2.56	$ 2.56
other	turbines	$ 0.66	$ 0.66	$ 0.66	$ 0.66	$ 0.66	$ 0.66	$ 0.66	$ 0.66	$ 0.66	$ 0.66
other	process heaters	$ 1.76	$ 1.76	$ 1.76	$ 1.76	$ 1.76	$ 1.76	$ 1.76	$ 1.76	$ 1.76	$ 1.76
other	other	$ 0.14	$ 0.09	$ 0.15	$ 0.16	$ 0.15	$ 0.16	$ 0.16	$ 0.09	$ 0.10	$ 0.08
diesel	Off-highway diesel	$ 0.31	$ 0.21	$ 0.22	$ 0.27	$ 0.32	$ 0.22	$ 0.25	$ 0.26	$ 0.25	$ 0.74
miscl	Residential	$ 0.69	$ 0.34	$ 0.50	$ 0.86	$ 0.86	$ 0.78	$ 0.86	$ 0.86	$ 0.85	$ 0.71
miscl	Commercial	$ 0.79	$ 0.67	$ 0.65	$ 0.87	$ 0.86	$ 0.53	$ 0.93	$ 0.98	$ 1.11	$ 0.82
miscl	Refineries	$ 5.42	$ 5.42	$ 4.09	$ 4.24	$ 3.74	$ 5.42	$ 6.88	$ 5.70	$ 3.74	$ 6.62
miscl	Facility heat	$ 3.56	$ 3.56	$ 3.56	$ 3.56	$ 3.56	$ 3.56	$ 3.56	$ 3.56	$ 3.56	$ 3.56
miscl	Coking	$ 1.58	$ 1.58	$ 1.58	$ 1.58	$ 1.58	$ 1.58	$ 1.58	$ 1.58	$ 1.58	$ 1.58

Table 3. Characterization of control efficiencies by MARKAL control category and region, derived from the set of maximum controls in each state, as specified by OAQPS in the process of developing the Ozone NAAQS RIA.

MARKAL control category		Average reduction	Regional reduction, %								
Fuel	Type	%	1	2	3	4	5	6	7	8	9
coal	boilers	85%	71%	84%	85%	71%	87%	87%	83%	86%	87%
coal	turbines	74%	74%	74%	74%	74%	74%	74%	74%	74%	74%
coal	process heaters	79%	79%	90%	90%	79%	79%	80%	80%	50%	79%
coal	other	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%
gas	boilers	85%	91%	85%	88%	89%	80%	83%	85%	78%	90%
gas	engines	68%	29%	58%	58%	83%	83%	48%	72%	59%	69%
gas	turbines	74%	68%	68%	68%	68%	68%	71%	69%	69%	78%
gas	process heaters	79%	79%	79%	89%	79%	79%	79%	79%	79%	79%
gas	other	7%	7%	7%	7%	7%	7%	7%	7%	7%	7%
distillate	boilers	91%	91%	91%	91%	91%	91%	91%	91%	91%	91%
distillate	engines	80%	80%	80%	80%	80%	80%	77%	80%	80%	80%
distillate	turbines	74%	74%	74%	74%	74%	74%	74%	74%	74%	74%
distillate	process heaters	80%	80%	80%	80%	80%	80%	80%	80%	80%	80%
distillate	other	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%
fuel oil	boilers	62%	50%	53%	62%	62%	63%	69%	69%	62%	69%
fuel oil	engines	67%	67%	67%	67%	67%	67%	67%	67%	67%	67%
fuel oil	turbines	74%	74%	74%	74%	74%	74%	74%	74%	74%	74%
fuel oil	process heaters	76%	76%	76%	76%	76%	76%	76%	76%	76%	76%
fuel oil	other	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%
other	boilers	91%	91%	91%	91%	91%	91%	91%	91%	91%	91%
other	engines	80%	80%	80%	80%	80%	80%	80%	80%	80%	80%
other	turbines	74%	74%	74%	74%	74%	74%	74%	74%	74%	74%
other	process heaters	80%	80%	80%	80%	80%	80%	80%	80%	80%	80%
other	other	7%	5%	7%	7%	7%	7%	8%	5%	6%	5%
diesel	Off-highway diesel	6%	5%	5%	6%	7%	5%	6%	6%	6%	13%
miscl	Residential	41%	25%	38%	44%	44%	42%	44%	44%	44%	48%
miscl	Commercial	56%	55%	55%	57%	57%	51%	61%	59%	66%	54%
miscl	Refineries	84%	84%	90%	89%	90%	84%	85%	82%	90%	86%
miscl	Facility heat	80%	80%	80%	80%	80%	80%	80%	80%	80%	80%
miscl	Coking	60%	60%	60%	60%	60%	60%	60%	60%	60%	60%

Table 4. Rule penetration estimates, derived from comparing information about the set of maximum controls and the 2025 modeling inventory.

MARKAL control category		Regional Rule Penetration, %								
Fuel	Type	1	2	3	4	5	6	7	8	9
coal	boilers	100%	93%	51%	60%	96%	96%	95%	79%	100%
coal	turbines	20%	20%	20%	20%	20%	20%	20%	20%	20%
coal	process heaters	20%	20%	20%	20%	20%	20%	20%	20%	20%
coal	other	20%	20%	20%	20%	20%	20%	20%	20%	20%
gas	boilers	23%	30%	25%	23%	44%	40%	66%	20%	48%
gas	engines	51%	33%	80%	85%	85%	84%	56%	41%	51%
gas	turbines	100%	100%	100%	100%	100%	100%	100%	100%	100%
gas	process heaters	20%	20%	20%	20%	20%	20%	26%	20%	20%
gas	other	20%	20%	20%	20%	20%	20%	20%	20%	20%
distillate	boilers	20%	20%	20%	20%	20%	20%	48%	20%	20%
distillate	engines	61%	33%	22%	21%	28%	44%	10%	17%	54%
distillate	turbines	100%	100%	100%	100%	100%	100%	100%	100%	100%
distillate	process heaters	20%	20%	20%	20%	20%	20%	20%	100%	20%
distillate	other	12%	18%	8%	2%	2%	2%	2%	14%	63%
fuel oil	boilers	12%	12%	12%	12%	12%	12%	12%	12%	12%
fuel oil	engines	20%	20%	20%	20%	20%	20%	20%	20%	100%
fuel oil	turbines	20%	20%	20%	20%	20%	20%	20%	20%	20%
fuel oil	process heaters	20%	20%	20%	20%	20%	20%	20%	20%	20%
fuel oil	other	20%	20%	20%	20%	20%	20%	20%	20%	20%
other	boilers	20%	20%	20%	20%	20%	20%	20%	20%	20%
other	engines	20%	20%	20%	20%	20%	20%	20%	20%	20%
other	turbines	20%	20%	20%	20%	20%	20%	20%	20%	20%
other	process heaters	20%	20%	20%	20%	20%	20%	20%	20%	20%
other	other	21%	46%	60%	48%	51%	51%	77%	61%	73%
diesel	Off-highway diesel	66%	67%	75%	93%	75%	79%	82%	82%	72%
miscl	Residential	78%	81%	67%	46%	51%	38%	61%	61%	72%
miscl	Commercial	20%	43%	55%	43%	56%	48%	66%	60%	61%
miscl	Refineries	20%	52%	32%	7%	20%	28%	28%	2%	22%
miscl	Facility heat	20%	20%	20%	0%	25%	20%	20%	14%	0%
miscl	Coking	20%	94%	7%	20%	55%	99%	20%	20%	20%