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WHITE PAPER: NOX EMISSION CONTROLS FOR STATIONARY SOURCES IN THE LADCO REGION

White Paper: NOx Emission Controls For Stationary Sources in the LADCO Region

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Appendix A. All LADCO Reviewed Technologies NOx Emission Reductions
Appendix B. Emission Units by White Paper Group

1.0 INTRODUCTION

In this white paper, we document the analysis of candidate stationary source nitrogen oxides (NOx) emission control measures that may be considered by state and local agencies in the Lake Michigan Air Directors Consortium (LADCO) to reduce emissions from ozone precursors. Emission reductions in addition to those resulting from on-the-books (OTB) regulations may be necessary to meet state implementation plan (SIP) requirements and to demonstrate attainment of ozone standards.

The candidate stationary source NOx emission control measures identified herein are for evaluation purposes only. The LADCO member states have not yet determined which stationary sources will be subject to additional control requirements or which control measures will be adopted. Therefore, inclusion of a source category or candidate control measure herein does not represent a commitment or decision by any agency to adopt that measure.

The stationary source groupings and control measures evaluated under chapters 2 through 11 were selected by LADCO members. Each chapter includes an analysis of the selected stationary source groupings and control measures; emission reductions across all control measures (i.e., including control measures not selected for evaluation in this white paper) are provided in Appendix A.

Each section below includes a source category analysis with the following content: summary table, source category description, candidate control measures description, estimated emission reductions, estimated cost-effectiveness, geographic applicability, responsible agency, implementation schedule, implementation feasibility, and public acceptance discussion.

The emissions estimate for controls were based on available information on existing controls and the incremental improvement with additional controls. We did not have base year control information for many sources. When actual control information was not available we used default control information by SCC. The achievable reductions are dependent on this information and further collection of existing control information will improve these estimates.

The analysis below present results by LADCO state (with the exception of Indiana (IN)) and by ozone nonattainment area (NAA). For Indiana, results are presented for the Chicago, IN ozone NAA only. The ozone NAAs considered herein are listed below.

- Allegan, MI[1]
- Berrien, MI
- Chicago, IL[2]
- Chicago, IN
- Chicago, WI[3]
- Cincinnati, OH[4]
- Cleveland, OH
- Columbus, OH
- Detroit, MI
- Door, WI
- Manitowoc County, WI
- Muskegon, MI

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[1] Michigan

[2] Illinois

[3] Wisconsin

[4] Ohio

- Northern Milwaukee/Ozaukee, WI
- Sheboygan, WI
- St. Louis, IL

Ramboll evaluated the selected control measures to estimate potential NOx emission reductions with implementing these control measures. Ramboll started from the EPA 2016v1[5] non-electric generating unit (non-EGU) inventory and applied selected control measures for each stringency scenario. Ramboll applied applicable control measure control efficiency estimates to the 2016v1 non-EGU inventory at varying assumed potential to emit (APTE) levels. For each APTE level, units with 2016v1 emissions greater than or equal to 50% of the APTE level were included. APTE estimates were developed to attempt to estimate potential to emit (PTE) using actual emissions as a surrogate; however, these APTE estimates do not follow the strict definition of a facility’s PTE that is typically included in stationary source permit assessment or determined for SIP purposes. APTE levels evaluated in this analysis for each ozone NAA and statewide outside of those nonattainment areas are listed below.

1) Sources with APTE greater than 100 tons per year (tpy) of NOx,
2) Sources with APTE greater than 50 tpy of NOx,
3) Sources with APTE greater than 25 tpy of NOx, and
4) Sources with APTE greater than 10 tpy of NOx

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[5] US Environmental Protection Agency (EPA) 2016v1 modeling platform. Available at https://www.epa.gov/air-emissions-modeling/2016v1-platform, accessed in June 2021.

2.0 CEMENT KILNS

2.1 Summary

This section focuses on emissions reductions for cement kilns. Cement kilns are classified as either dry process or wet process and may make use of preheaters or precalciners. Cement kilns may be fired by coal, natural gas, scrap tires or other fuels to convert raw materials into clinker, a critical component of Portland Cement. Table 2-1 summarizes key information for cement kiln control measures evaluated herein. Applicable emissions, emission reductions, and cost-effectiveness are presented in Table 2-1 on a LADCO region-wide basis. State- and NAA-level emissions, emission reductions, and cost-effectiveness are presented in subsections below. Emission reductions across all control measures (i.e., including control measures not selected for evaluation in this white paper) are provided in Appendix A.

Table 2-1. Control measure summary for cement kilns.[6]

2016 Emissions Estimates		
2016 Emissions [a]	NOx:	11,408 tons/year
Control Measure Summary, Including 2016 Emission Reduction Estimates		
		All APTE [b] Levels [c]
Selective Catalytic Reduction (High Stringency Scenario)	NOx Reduction:	10,087 tons/year
	Cost-effectiveness:	*$6,155 or $7,202/ton [d]*
	Applicable States:	*IL, MI, OH*
	Applicable NAAs:	*None [e]*
Selective Non-Catalytic Reduction (Medium Stringency Scenario)	NOx Reduction:	2,335 tons/year
	Cost-effectiveness:	*$1,525/ton*
	Applicable States:	*IL, MI, OH*
	Applicable NAAs:	*None [e]*
Selective Non-Catalytic Reduction - Ammonia (Medium Stringency Scenario)	NOx Reduction:	3,147 tons/year
	Cost-effectiveness:	*$1,683/ton*
	Applicable States:	*IL, MI*
	Applicable NAAs:	*None [e]*
Biosolid Injection Technology (Low Stringency Scenario)	NOx Reduction:	474 tons/year
	Cost-effectiveness:	*$523/ton*
	Applicable States:	*MI*
	Applicable NAAs:	*None [e]*
Low NOx Burner (Low Stringency Scenario)	NOx Reduction:	2,403 tons/year
	Cost-effectiveness:	*$710/ton*
	Applicable States:	*IL, MI, OH*
	Applicable NAAs:	*None [e]*

[a] Source: US Environmental Protection Agency (EPA) 2016v1 modeling platform. Available at https://www.epa.gov/air-emissions-modeling/2016v1-platform, accessed in June 2021.
[b] Assumed potential to emit
[c] Emission reductions and cost-effectiveness are equivalent across APTE levels for cement kilns.
[d] The cost-effectiveness is $6,155/ton for Selective Catalytic Reduction – Cement Manufacturing (Wet). The cost-effectiveness is $7,202/ton for Selective Catalytic Reduction – Cement Manufacturing (Dry).
[e] There were no cement kiln emissions in any LADCO NAA.

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[6] Excludes Indiana emissions except for in Chicago, Indiana nonattainment area counties (Lake County and Porter County).

2.2 Source Description

Portland cement manufacturing is an energy-intensive process in which raw materials are processed to make cement. Cement kilns are the main energy and fuel consuming process at cement plants.

A cement kiln is a large, rotating steel cylindrical furnace lined with refractory material such as firebrick (US Environmental Protection Agency (EPA), 2019a). The kiln slopes slightly, and the raw material, or meal, enters the kiln from the upper end (known as the "cold" or "back" end). The slope and rotation of the kiln causes the material to gradually move through the furnace. At the lower end (known as the "hot" end), the combustion of a primary fuel (e.g., coal, petroleum coke, natural gas, scrap tires) takes place to produce a high temperature. The material that leaves the hot end is called clinker, which is transferred to the clinker cooler. After cooling, clinker is further ground and mixed with gypsum to form Portland cement.

There are two methods of preparation of the raw material, wet or dry process. In the dry process, raw meal is dry-ground to a fine, flour-like powder before entering the kiln. In the wet process, raw materials are wet-ground with water to form a slurry. The wet process requires greater heat energy to evaporate the water from the slurry.

There is a single configuration that is typical of wet process kilns. Wet kilns generally have only one combustion zone and all of the pyroprocessing activity occurs in the rotating kiln.

There are three configurations for dry process kilns: long-dry, preheater, and preheater/precalciner. Long dry kilns are similar to wet kilns, but are fed low moisture rather than wet materials. Similar to wet kilns, long-dry kilns generally have only one combustion zone and all pyroprocessing activity occurs in the rotating kiln. For preheater and preheater/precalciner kilns, certain manufacturing processes (heating and calcination of the raw materials) happen in sections outside the rotary kiln (EPA 2007). In preheater kilns, raw material is heated before entering the kiln. Pre-heating allows for a shorter kiln and reduces combustion fuel use. A typical preheater/precalciner kiln consists of a vertical tower with a series of cyclone-type vessels and interconnecting ducts. After the preheater, the material enters the precalciner where carbon dioxide (CO_2) is calcined from the material. The raw meal is added at the top of the tower, and hot kiln exhaust flue gases from the kiln operation are used to preheat the material prior to its entrance into the kiln. Preheating and precalcining have the advantage of lowering fuel consumption.

NOx is generated during fuel combustion in both the burning zone of the kiln and, if included, in the burning zone of the precalcining vessel (EPA, 1995). Fuel combustion NOx results from both oxidation of chemically-bound nitrogen in the fuel and thermal fixation of nitrogen in the combustion air. Higher flame temperature and higher fuel nitrogen content result in higher NOx formation.

Table 2-2 lists the applicable source category classifications (SCCs) for cement kilns in the LADCO stationary point source inventory.

Table 2-2. Applicable SCCs for cement kilns.

Description One	Description Two	Description Three	Description Four	SCC
Industrial Processes	Mineral Products	Cement Manufacturing (Dry Process)	Kiln	30500606
			Preheater Kiln	30500622
			Preheater/Precalciner Kiln	30500623
		Cement Manufacturing (Wet Process)	Kiln	30500706

2.3 Selected Control Measures Description

For cement kilns, differing control measures were considered for each stringency level. The selected control measures and their estimated control efficiency is shown in Table 2-3. Descriptions of each control measure are included in the subsections below.

Table 2-3. Applicable control technology and associated control efficiency by stringency level.

Stringency Level	Control Measure	Control Efficiency (%)
High	Selective Catalytic Reduction	90
Medium	Selective Non-Catalytic Reduction	50
	Selective Non-Catalytic Reduction - Ammonia	50
Low	Biosolid Injection Technology	23
	Low NOx Burner	27

2.3.1 Selective Catalytic Reduction

Selective catalytic reduction (SCR) is a post-combustion control technology. An SCR emission control system uses a catalyst, typically ammonia or urea, to selectively reduce NOx emissions from exhaust gases (EPA, 2007). NOx is chemically reduced into molecular nitrogen (N_2) and water vapor (H_2O). The catalyst is not consumed but allows the reactions to occur at a lower temperature. This control can be applied to wet or dry-process cement manufacturing, regardless of whether it has a preheater/precalciner.

SCR can be installed at a cement kiln at two possible locations:

- After the particulate matter control device – a "low-dust" system.
- After the last cyclone without ducting – a "high-dust" system.

Low-dust systems allow for longer catalyst life and decreased danger of blockage. However, low-dust systems typically have higher energy costs due to additional heat required to bring cooled exhaust to the catalyst reaction temperature. In high-dust systems exhaust gas temperature is typically about equal to the temperature required for SCR; therefore, additional heating is not required.

2.3.2 Selective Non-Catalytic Reduction and Selective Non-Catalytic Reduction - Ammonia

Selective non-catalytic reduction (SNCR) is a post-combustion control technology in which NOx is chemically reduced into molecular N_2 and water vapor in the presence of ammonia. Typically, ammonia is injected as ammonia water or urea in the flue-gas at a temperature suitable for inducing substantial NOx emission reductions (EPA, 2007). Aqueous ammonia is a common SNCR reagent for cement kilns. Other potential reagents include anhydrous ammonia (injected as a gas), urea solutions, and ammonium sulfate solutions. Though the reagent can react with several flue gas components, the NOx reduction reaction is favored over other chemical reactions for a specific temperature range and in the presence of oxygen; therefore, SNCR is considered a selective chemical process (EPA, 2019b).

Unlike an SCR, no catalyst is used to increase the reaction rate in an SNCR. SNCR temperature range is critical to achieving optimal NOx reduction (EPA, 2007). At temperatures that are too high, competing reactions for the direct oxidation of ammonia lower NOx reduction efficiency.

At temperatures that are too low, NOx reduction reactions are too slow which results in excess ammonia slip.

SNCR installation is typically relatively simple for preheater/precalciner kilns as SNCR injection ports can be installed in the calciner combustion zone, the upper air inlet oxidation zone (before the deflection chamber), or in the area before the inlet to the bottom cyclone and after the mixing chamber (EPA, 2019b). For wet and long dry kilns, the middle of the kiln typically has the required temperature range. Rotary valves are typically installed at the end of a wet or long dry rotary kiln to inject ammonia or urea.

2.3.3 Low NOx Burner

A Low-NOx burner (LNB) is a combustion modification control technology that reduces NOx emissions by reducing flame turbulence, delaying fuel/air mixing, and establishing fuel-rich zones for initial combustion (EPA, 2007). Staged combustion is used to lower flame temperatures and reduce thermal NOx formation. Cement kilns in which less than 10% of the total combustion air is primary air are considered indirect-fired kilns. A greater proportion of recycled clinker cooler air is available for use as secondary combustion air in indirect-fired kilns; LNB can only be applied to indirect-fired kilns.

LNB kilns have two combustion zones; the first stage is the primary combustion zone and the second stage is the secondary combustion zone. In the primary combustion zone, flame turbulence and air and fuel mixing are suppressed, reducing the amount of primary air and delaying fuel combustion. Typically, flue gas is recycled into the primary combustion zone to reduce oxygen content and create a fuel-rich atmosphere. Thermal NOx formation is suppressed in the primary combustion zone because less oxygen is available. In the secondary combustion zone, cooler, oxygen-rich air is mixed into the secondary combustion zone, lowering temperature and thereby reducing NOx formation.

2.3.4 Biosolid Injection Technology

Biosolid injection technology utilizes dewatered biosolids from wastewater treatment plants to reduce NOx emissions (EPA, 2006). Ammonia in the biosolids acts as a reagent, similar to ammonia injection in an SNCR system, as described in Section 2.3.3. Biosolids are injected into the mixing chamber where the temperature is between 1600°F and 1700°F (typically where exhaust gases leave the kiln). The addition of biosolids at the exhaust gas outlet also reduces the gas temperature and thus makes it less favorable for NOx formation. Biosolid injection technology is applicable for preheater and precalciner kilns because the required temperature range typically occurs at the location (i.e., exhaust gas outlet) where it is feasible to inject biosolids. For other kiln types, the required temperature range typically occurs in the rotary kiln, where it is typically not feasible to inject biosolids.

2.4 NOx Emission Reductions

Table 2-4 shows the control measures that were implemented for each SCC and stringency level. Existing (as of 2016) NOx controls were accounted for in the analysis; potential emission reductions were calculated as incremental reductions from the existing controls. Existing NOx controls were identified based on "Control ID" in the 2016v1 modeling platform files. If the existing control efficiency was higher than the selected control measure for a unit, no emission reduction or cost was calculated. If the existing control efficiency was lower than the selected control measure, the surplus emission reduction and associated cost are calculated.

Estimated emission reductions are uncertain because 1) information on existing controls is unlikely to be comprehensive and 2) feasibility and emission reduction potential depends on site-specific conditions such as raw materials and fuels used and existing equipment configurations. Emission reductions can be more accurately estimated based on individual facility specific feasibility and emission control analysis. This analysis is a source category-level evaluation; therefore, facility specific analysis is not included.

Table 2-4. Cement kiln control measure applied to each SCC.

SCC	SCC Description	Stringency Level [a]		
		High	Medium	Low
30500606	Industrial Processes; Mineral Products; Cement Manufacturing (Dry Process); Kiln	Selective Catalytic Reduction; Cement Manufacturing - Dry	Selective Non-Catalytic Reduction - Ammonia; Cement Manufacturing - Dry	Low NOx Burner; Cement Manufacturing - Wet or Dry
30500622	Industrial Processes; Mineral Products; Cement Manufacturing (Dry Process); Preheater Kiln	Selective Catalytic Reduction; Cement Manufacturing - Dry	Selective Non-Catalytic Reduction; Cement Manufacturing - Dry	Low NOx Burner; Cement Manufacturing - Wet or Dry
30500706	Industrial Processes; Mineral Products; Cement Manufacturing (Wet Process); Kiln	Selective Catalytic Reduction; Cement Manufacturing - Wet	Selective Non-Catalytic Reduction; Cement Manufacturing - Wet	Low NOx Burner; Cement Manufacturing - Wet or Dry
30500623	Industrial Processes; Mineral Products; Cement Manufacturing (Dry Process); Preheater/Precalciner Kiln	Selective Catalytic Reduction; Cement Manufacturing - Dry	Selective Non-Catalytic Reduction; Cement Manufacturing - Dry	Biosolid Injection Technology; Cement Kilns

[a] Control measure assignments for each SCC were based on EPA's Menu of Control Measures[7] and EPA's Control Strategy Tool (CoST), version 3.7[8].

Cement kiln NOx emissions and emission reductions by LADCO state are presented in Table 2-5 and by LADCO NAA in Table 2-6. The number of units with 2016 NOx emissions is available in Appendix B. There are no cement kilns located in the NAAs (according to EPA's 2016v1 emission inventory) and therefore no NOx emission reductions in the NAAs. State-level emission reductions are equivalent under each APTE level, indicating that all potentially controlled sources have NOx APTE greater than 100 tpy. 2016 NOx emissions from cement kilns are from Michigan (60%), Illinois (27%), and Ohio

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[7] Menu of Control Measures for NAAQS Implementation. https://www.epa.gov/air-quality-implementation-plans/menu-control-measures-naaqs-implementation, Accessed January 2021.

[8] Control Strategy Tool. https://www.epa.gov/economic-and-cost-analysis-air-pollution-regulations/cost-analysis-modelstools-air-pollution#control%20strategy%20tool, Accessed January 2021.

(13%); NOx emission reductions are distributed similarly across stringency scenarios and APTE levels. Consistent with control efficiency estimates (see Table 2-3), medium stringency emission reductions are approximately twice the low stringency scenario estimates, and high stringency emission reductions are approximately twice the medium stringency scenario estimates.

Table 2-5. Statewide 2016 NOx emission reductions from cement kilns.[6] [9]

State	2016 NOx Emissions (tons/year)	2016 NOx Emission Reductions (tons/year)											
		APTE = 10 tons/year			APTE = 25 tons/year			APTE = 50 tons/year			APTE = 100 tons/year		
		Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
IL	3,066	828	1,533	2,760	828	1,533	2,760	828	1,533	2,760	828	1,533	2,760
MI	6,882	1,775	3,441	6,193	1,775	3,441	6,193	1,775	3,441	6,193	1,775	3,441	6,193
MN[10]	-	-	-	-	-	-	-	-	-	-	-	-	-
OH	1,460	274	508	1,134	274	508	1,134	274	508	1,134	274	508	1,134
WI	-	-	-	-	-	-	-	-	-	-	-	-	-

Table 2-6. NOx emission reductions from cement kilns by NAA.[6] [9]

Non-Attainment Area	2016 NOx Emissions (tons/year)	2016 NOx Emission Reductions (tons/year)											
		APTE = 10 tons/year			APTE = 25 tons/year			APTE = 50 tons/year			APTE = 100 tons/year		
		Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
Allegan, MI	-	-	-	-	-	-	-	-	-	-	-	-	-
Berrien, MI	-	-	-	-	-	-	-	-	-	-	-	-	-
Chicago, IL	-	-	-	-	-	-	-	-	-	-	-	-	-
Chicago, IN	-	[a]	[a]	[a]	[a]	[a]	[a]	-	-	-	-	-	-
Chicago, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
Cincinnati, OH	-	-	-	-	-	-	-	-	-	-	-	-	-
Cleveland, OH	-	-	-	-	-	-	-	-	-	-	-	-	-
Columbus, OH	-	-	-	-	-	-	-	-	-	-	-	-	-
Detroit, MI	-	-	-	-	-	-	-	-	-	-	-	-	-
Door, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
Manitowoc County, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
Muskegon, MI	-	-	-	-	-	-	-	-	-	-	-	-	-
Northern Milwaukee/Ozaukee, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
Sheboygan, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
St. Louis, IL	-	-	-	-	-	-	-	-	-	-	-	-	-

[a] APTE values of 10 tons/year and 25 tons/year are not applicable to Chicago, IN

[9] Cells populated with "-" indicate zero NOx emissions in the inventory and thus no emission reductions.

[10] Minnesota

2.5 Cost-effectiveness

Table 2-7 summarizes typical cost-effectiveness estimates for each control measure considered. Facility specific costs will vary based on raw material, fuel characteristics, equipment configuration, and other source specific factors.

Table 2-7. Typical cost-effectiveness for each control measure.

Stringency Level	Control Measure	Cost-effectiveness (2020$/ton)	Reference
High	Selective Catalytic Reduction	6,155 or 7,202 [a]	EPA CoST[8]
Medium	Selective Non-Catalytic Reduction	1,525	EPA CoST[8]
	Selective Non-Catalytic Reduction - Ammonia	1,683	EPA CoST[8]
Low	Biosolid Injection Technology	523	EPA Menu of Control Measures[7]
	Low NOx Burner	710	EPA CoST[8]

[a] The cost-effectiveness is $6,155/ton for Selective Catalytic Reduction – Cement Manufacturing (Wet). The cost-effectiveness is $7,202/ton for Selective Catalytic Reduction – Cement Manufacturing (Dry).

Table 2-8. Statewide total cost of cement kilns emissions reduction.[6] [11]

State	Total Cost (thousands of 2020$)											
	APTE = 10 tons/year			APTE = 25 tons/year			APTE = 50 tons/year			APTE = 100 tons/year		
	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
IL	587	2,454	19,875	587	2,454	19,875	587	2,454	19,875	587	2,454	19,875
MI	1,171	5,628	44,604	1,171	5,628	44,604	1,171	5,628	44,604	1,171	5,628	44,604
MN	-	-	-	-	-	-	-	-	-	-	-	-
OH	195	775	7,212	195	775	7,212	195	775	7,212	195	775	7,212
WI	-	-	-	-	-	-	-	-	-	-	-	-

Table 2-9. Statewide cost-effectiveness of cement kilns emissions reduction. [6] [11]

State	Cost-effectiveness (2020$/ton)											
	APTE = 10 tons/year			APTE = 25 tons/year			APTE = 50 tons/year			APTE = 100 tons/year		
	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
IL	710	1,601	7,202	710	1,601	7,202	710	1,601	7,202	710	1,601	7,202
MI	660	1,636	7,202	660	1,636	7,202	660	1,636	7,202	660	1,636	7,202
MN	-	-	-	-	-	-	-	-	-	-	-	-
OH	710	1,525	6,358	710	1,525	6,358	710	1,525	6,358	710	1,525	6,358
WI	-	-	-	-	-	-	-	-	-	-	-	-

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[11] Cells populated with "-" indicate zero NOx emissions in the inventory and thus no associated cost or cost-effectiveness.

2.6 Geographic Applicability

NOx emission reductions for cement kilns can only be achieved in the counties and states in which cement kilns are located. According to EPA's 2016v1 emission inventory, cement kiln emissions were limited to Illinois, Indiana, Michigan, and Ohio; there were no cement kiln emissions in Minnesota or Wisconsin or any LADCO NAA considered in this analysis.

2.7 Responsible Agency

The state air agency is responsible for enforcing SIP-approved and other air permitting rules. Each cement kiln emission source in the LADCO area has NOx APTE emissions in EPA's 2016v1 emission inventory of over 100 tons/year and therefore are expected to be subject Title V permit requirements.

2.8 Implementation Schedule

After a new rule is promulgated, facilities are typically given time to comply with the new rule for planning, analysis, and infrastructure changes necessary to comply. The timeline for existing sources to comply with Maximum Achievable Control Technology (MACT) standards is typically 3-years, but timelines for compliance typically vary from 1-4 years. Assuming that rules to limit cement kiln emissions are adopted in late-2023, and assuming a 2-year period from rule promulgation to controls installation, emission reduction would be achieved by 2026. Depending on regulatory requirements, a more aggressive or less aggressive timeline may be required in rulemakings.

2.9 Implementation Feasibility

There are several regulatory programs which limit cement kiln emission controls (several examples are listed below). Emission requirements may be expressed in mass of NOx emitted per mass of clinker produced or prescribe achievement of specific minimum emission reductions.

- New Source Performance Standard for Portland Cement Plants (NSPS Subpart F)[12]
- Texas Commission on Environmental Quality: 30 TAC Chapter 117, Subchapter E, Division 2[13]
- Air Pollution Control District of Jefferson County (Kentucky): Regulation 6.50 NOx Requirements for Portland Cement Kilns[14]
- Bay Area Air Quality Management District: Regulation 9 Inorganic Gaseous Pollutants Rule 13 Nitrogen Oxides, Particulate Matter, and Toxic Air Contaminants From Portland Cement Manufacturing[15]
- Knox County Department of Air Quality Management (Tennessee): Regulation 51.0 Standards for Cement Kilns[16]

To develop an emission control regulation for cement kilns, a facility-level assessment will likely be necessary as facility specific conditions (raw materials, fuels, and existing equipment configurations) will determine the feasibility and cost of controls.

2.10 Public Acceptance

Cement kilns can produce substantial emissions of NOx and other pollutants. Cement kiln control measures evaluated herein are very cost-effective and therefore can be shown to be a good regional

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[12] https://www.epa.gov/stationary-sources-air-pollution/portland-cement-plants-new-source-performance-standards-nsps, accessed in January, 2022

[13] https://www.tceq.texas.gov/airquality/stationary-rules/nox/cement-kilns, accessed in January, 2022

[14] https://louisvilleky.gov/document/apcd-regulation-650pdf, accessed in January, 2022

[15] https://www.baaqmd.gov/~/media/dotgov/files/rules/reg-9-rule-13--nitrogen-oxides-particulate-matter-and-toxic-air-contaminants-from-portland-cement-ma/documents/rg0913_101916-pdf.pdf?la=en, accessed in January, 2022

[16] https://knoxcounty.org/airquality/pdfs/regulations/regulation51.pdf, accessed in January, 2022

emission reductions strategy. Cement kiln operators may object to any further regulation of their operations, especially for the more costly control measures. Grant funding can be used to facilitate implementation of control measures.

2.11 All Controls Results

Analysis in the sections above includes the controls considered under low, medium, and high stringency scenarios, as indicated in Table 2-4 (i.e., those controls not highlighted in grey on Table 2-4). Emission reduction estimates across the full suite of stringency scenario and control combinations are presented in Appendix A, Tables A1 to A2.

3.0 COAL NON-EGU

3.1 Summary

This section focuses on emissions reductions for coal-fired boilers, excluding coal-fired electrical generating units (EGUs). Boilers are combustion devices that produce steam or heat water. Coal-fired boilers are widely used in a variety of industries. The most common type of coal used in boilers is bituminous coal and subbituminous coal. Table 3-1 summarizes key information for coal non-EGU control measures evaluated herein. Applicable emissions, emission reductions, and cost-effectiveness are presented in Table 3-1 on a LADCO region-wide basis. State- and NAA-level emissions, emission reductions, and cost-effectiveness are presented in subsections below. Emission reductions across all control measures (i.e., including control measures not selected for evaluation in this white paper) are provided in Appendix A.

Table 3-1. Control measure summary for coal non-EGU.[17]

2016 Emissions Estimates					
2016 Emissions [a]	NOx:	12,413 tons/year			
Control Measure Summary, Including 2016 Emission Reduction Estimates					
		APTE = 10	**APTE = 25 tons/year**	**APTE = 50 tons/year**	**APTE = 100 tons/year**
Selective Catalytic Reduction (High Stringency Scenario)	NOx Reduction:	6,997 tons/year	6,953 tons/year	6,940 tons/year	6,733 tons/year
	Cost-effectiveness:	*$7,553/ton*			
	Applicable States:	*IL, MI, MN, OH, WI*			
	Applicable NAAs:	*Cleveland, OH*			
Regenerative Selective Catalytic Reduction (Medium Stringency Scenario)	NOx Reduction:	5,536 tons/year	5,500 tons/year	5,489 tons/year	5,319 tons/year
	Cost-effectiveness:	*$3,876/ton*			
	Applicable States:	*IL, MI, MN, OH, WI*			
	Applicable NAAs:	*Cleveland, OH*			
Selective Non-Catalytic Reduction (Medium Stringency Scenario)	NOx Reduction:	145 tons/year [c]			
	Cost-effectiveness:	*$7,623/ton*			
	Applicable States:	*IL*			
	Applicable NAAs:	*None [b]*			
Selective Non-	NOx Reduction:	5,096 tons/year	5,068 tons/year	5,046 tons/year	4,923 tons/year
	Cost-effectiveness:	*$7,623/ton*			

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[17] Excludes Indiana emissions except for in Chicago, Indiana nonattainment area counties (Lake County and Porter County).

2016 Emissions Estimates		
2016 Emissions [a]	NOx:	12,413 tons/year
Control Measure Summary, Including 2016 Emission Reduction Estimates		
Catalytic Reduction (Low Stringency Scenario)	*Applicable States:*	*IL, MI, MN, OH, WI*
	Applicable NAAs:	*Cincinnati, OH; Cleveland, OH*

[a] Source: US Environmental Protection Agency (EPA) 2016v1 modeling platform. Available at https://www.epa.gov/air-emissions-modeling/2016v1-platform, accessed in June 2021.
[b] There were no coal non-EGU emissions for this control measure in any LADCO NAA.
[c] Emission reductions are the same across all APTE levels.

3.2 Source Description

Coal-fired boilers can generally be categorized by type and fuel. Specifically, the types of boilers can be defined as follows (EPA, 1995):

- Heat transfer method (watertube, firetube, or cast iron),
- Arrangement of the heat transfer surfaces (horizontal or vertical, straight or bent tube), and
- Firing configuration (suspension, stoker, or fluidized bed).

The watertube method is the most common heat transfer method for coal-fired boilers and is used for pulverized coal, cyclone, stoker, fluidized bed, and handfed units. Using the watertube method, coal is burned to create hot combustion gases which boils water in the steam-generating tubes. In pulverized coal-fired boilers, coal is pulverized to the level of talcum powder (i.e., at least 70 percent of the particles will pass through a 200-mesh sieve). Pulverized coal-fired boilers can be further categorized as dry bottom or wet bottom based on the condition of the ash. Coals with high fusion temperatures result in dry ash in dry bottom furnaces, while coals with low fusion temperatures result in molten ash in wet bottom furnaces. Pulverized coal-fired boilers can also be classified as wall or tangential depending on the type and location of the burners and the direction of coal injection into the furnace. For wall-fired boilers, burners can be mounted only on one wall or two opposing walls. For tangential boilers, burners are placed in the corners of the furnace.

The most common fuels are bituminous coals and subbituminous coals. Bituminous coals have lower moisture and volatile matter but higher sulfur content than subbituminous coals. In general, the heat values of bituminous coals range between 10,500 and 14,000 British thermal units per pound (Btu/lb) on a wet, mineral-matter-free basis; while subbituminous coals have heating values of 8,300 to 11,500 Btu/lb.

The primary NOx emissions from coal combustion are nitric oxide (NO), with nitrogen dioxide (NO_2) and nitrous oxide (N_2O) in very low volume percent. Generally, the weight percentage of nitrogen in bituminous and subbituminous coals ranges from 0.5 to 2 percent. Usually, 20 to 60 percent of the fuel nitrogen is oxidated to NOx; fuel nitrogen can account for up to 80 percent of combustion NOx.

Table 3-2 lists the applicable SCCs for coal non-EGU in the LADCO stationary point source inventory.

Table 3-2. Applicable SCCs for Coal Non-EGU.

Description One	Description Two	Description Three	Description Four	SCC
External Combustion	Industrial: Boilers	Bituminous/ Subbituminous Coal	Bituminous Coal: Pulverized Coal: Wet Bottom	10200201
			Bituminous Coal: Pulverized Coal: Dry Bottom	10200202
			Bituminous Coal: Cyclone Furnace	10200203
			Bituminous Coal: Spreader Stoker	10200204
			Bituminous Coal: Overfeed Stoker	10200205
			Bituminous Coal: Pulverized Coal: Dry Bottom (Tangential)	10200212
			Bituminous Coal: Atmospheric Fluidized Bed Combustion: Bubbling Bed	10200217
			Subbituminous Coal: Pulverized Coal: Dry Bottom	10200222
			Subbituminous Coal: Spreader Stoker	10200224
			Subbituminous Coal: Cogeneration	10200229
		Petroleum Coke [a]	All Boiler Sizes	10200802
		Wood/Bark Waste [a]	Bark-fired Boiler	10200901
			Wood/Bark-fired Boiler	10200902
			Wood-fired Boiler - Wet Wood (>=20% moisture)	10200903

[a] Non-coal fuels were included for this category at the request of LADCO

3.3 Selected Control Measures Description

For coal non-EGU sources, specific control measures were considered for each stringency level. The selected control measures and their estimated control efficiency are shown in Table 3-3. Descriptions of each control measure are included in the subsections below.

Table 3-3. Applicable control technology and associated control efficiency by stringency level.

Stringency Level	Control Measure	Control Efficiency (%)
High	Selective Catalytic Reduction	9 85
Medium	Regenerative Selective Catalytic Reduction	70
	Selective Non-Catalytic Reduction	45
Low	Selective Non-Catalytic Reduction	45

3.3.1 Selective Catalytic Reduction

SCR is a post-combustion control technology. An SCR emission control system uses a catalyst, typically ammonia or urea, to selectively reduce NOx emissions from exhaust gases (EPA, 2007). NOx is chemically reduced into molecular N_2 and water vapor. The catalyst is not consumed but allows the reactions to occur at a lower temperature.

The SCR system can be installed at different locations including upstream of an air heater and particulate control device, or downstream of the air heater, particulate control device, and flue gas desulfurization systems.

3.3.2 Selective Non-Catalytic Reduction

SNCR is a post-combustion control technology in which NOx is chemically reduced into molecular N_2 and water vapor in the presence of ammonia. Typically, ammonia is injected as ammonia water or urea in the flue-gas at a temperature suitable for inducing substantial NOx emission reductions (EPA, 2007). Aqueous ammonia is a common SNCR reagent. Other potential reagents include anhydrous ammonia (injected as a gas), urea solutions, and ammonium sulfate solutions. Though the reagent can react with several flue gas components, the NOx reduction reaction is favored over other chemical reactions for a specific temperature range and in the presence of oxygen; therefore, SNCR is considered a selective chemical process (EPA, 2019b).

Unlike an SCR, no catalyst is used to increase the reaction rate in an SNCR. SNCR temperature range is critical to achieving optimal NOx reduction (EPA, 2007). At temperatures that are too high, competing reactions for the direct oxidation of ammonia lower NOx reduction efficiency. At temperatures that are too low, NOx reduction reactions are too slow which results in excess ammonia slip.

The injection nozzle can be installed in the upper area of the furnace, i.e. in the post-combustion area (EPA, 2019b). The reagent and the flue gas mix and the heat of the boilers supply the energy for the reduction reaction. Single and multi-level injection systems are commonly used.

3.3.3 Regenerative Selective Catalytic Reduction

Regenerative selective catalytic reduction (RSCR) is a post-combustion control technology that combines a regenerative thermal oxidizer (RTO), for example, retention chamber burner, with conventional SCR technology.[18] Typically, an RSCR system can be used to reduce NOx emissions by installing controls at the tail-end of the gas stream for low-temperature applications where the flue gas is about 300-400°F.

3.4 NOx Emission Reductions

Table 3-4 shows the control measures that were implemented for each SCC and stringency level. Existing (as of 2016) NOx controls were accounted for in the analysis; potential emission reductions were calculated as incremental reductions from the existing controls. Existing NOx controls were identified based on “Control ID” in the 2016v1 modeling platform files. If the existing control efficiency was higher than the selected control measure for a unit, no emission reduction or cost was calculated. If the existing control efficiency was lower than the selected control measure, the surplus emission reduction and associated cost are calculated.

Estimated emission reductions are uncertain because 1) information on existing controls is unlikely to be comprehensive and 2) feasibility and emission reduction potential depends on site-specific conditions such as raw materials and fuels used and existing equipment configurations. Emission reductions can be more accurately estimated based on individual facility specific feasibility and

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[18] Menu of Control Measures for NAAQS Implementation. https://www.epa.gov/air-quality-implementation-plans/menu-control-measures-naaqs-implementation, Accessed January 2021.

emission control analysis. This analysis is a source category-level evaluation; therefore, facility specific analysis is not included.

Table 3-4. Coal Non-EGU control measure applied to each SCC.[19]

SCC	SCC Description	Stringency Level (Control technologies highlighted in grey were assessed in prior tasks but are not evaluated in this white paper) [a]		
		High	Medium	Low
10200201	External Combustion; Industrial: Boilers; Bituminous/Subbituminous Coal; Bituminous Coal: Pulverized Coal: Wet Bottom	Ultra Low NOx Burner and Selective Catalytic Reduction	Low NOx Burner and Selective Non-Catalytic Reduction	Selective Non-Catalytic Reduction
10200202	External Combustion; Industrial: Boilers; Bituminous/Subbituminous Coal; Bituminous Coal: Pulverized Coal: Dry Bottom	Ultra Low NOx Burner and Selective Catalytic Reduction	Low NOx Burner and Selective Non-Catalytic Reduction	Selective Non-Catalytic Reduction
10200203	External Combustion; Industrial: Boilers; Bituminous/Subbituminous Coal; Bituminous Coal: Cyclone Furnace	Selective Catalytic Reduction	Regenerative Selective Catalytic Reduction	Selective Non-Catalytic Reduction
10200204	External Combustion; Industrial: Boilers; Bituminous/Subbituminous Coal; Bituminous Coal: Spreader Stoker	Selective Catalytic Reduction	Regenerative Selective Catalytic Reduction	Selective Non-Catalytic Reduction
10200205	External Combustion; Industrial: Boilers; Bituminous/Subbituminous Coal; Bituminous Coal: Overfeed Stoker	Selective Catalytic Reduction	Regenerative Selective Catalytic Reduction	Selective Non-Catalytic Reduction
10200212	External Combustion; Industrial: Boilers; Bituminous/Subbituminous Coal; Bituminous Coal: Pulverized Coal: Dry Bottom (Tangential)	Ultra Low NOx Burner and Selective Catalytic Reduction	Low NOx Burner and Selective Non-Catalytic Reduction	Selective Non-Catalytic Reduction

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[19] Cells populated with "-" indicate no control technology is assigned.

SCC	SCC Description	Stringency Level (Control technologies highlighted in grey were assessed in prior tasks but are not evaluated in this white paper) [a]		
		High	Medium	Low
10200217	External Combustion; Industrial: Boilers; Bituminous/Subbituminous Coal; Bituminous Coal: Atmospheric Fluidized Bed Combustion: Bubbling Bed	Selective Catalytic Reduction	Selective Non-Catalytic Reduction	Selective Non-Catalytic Reduction
10200222	External Combustion; Industrial: Boilers; Bituminous/Subbituminous Coal; Subbituminous Coal: Pulverized Coal: Dry Bottom	Ultra Low NOx Burner and Selective Catalytic Reduction	Low NOx Burner and Selective Non-Catalytic Reduction	Selective Non-Catalytic Reduction
10200224	External Combustion; Industrial: Boilers; Bituminous/Subbituminous Coal; Subbituminous Coal: Spreader Stoker	Selective Catalytic Reduction	Regenerative Selective Catalytic Reduction	Selective Non-Catalytic Reduction
10200229	External Combustion; Industrial: Boilers; Bituminous/Subbituminous Coal; Subbituminous Coal: Cogeneration	Ultra Low NOx Burner and Selective Catalytic Reduction	Low NOx Burner and Selective Non-Catalytic Reduction	Selective Non-Catalytic Reduction
10200802	External Combustion; Industrial: Boilers; Petroleum Coke; All Boiler Sizes	c	c	c
10200901	External Combustion; Industrial: Boilers; Wood/Bark Waste; Bark-fired Boiler	b	b	b
10200902	External Combustion; Industrial: Boilers; Wood/Bark Waste; Wood/Bark-fired Boiler	b	b	b
10200903	External Combustion; Industrial: Boilers; Wood/Bark Waste; Wood-fired Boiler - Wet Wood (>=20% moisture)	b	b	b

[a] Control measure assignments for each SCC were based on EPA's Control Strategy Tool (CoST), version 3.7[20], and LADCO Four Factor Analysis[21].

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[20] Control Strategy Tool. https://www.epa.gov/economic-and-cost-analysis-air-pollution-regulations/cost-analysis-modelstools-air-pollution#control%20strategy%20tool, Accessed January 2021.

[21] Four Factor Analysis of Sources for Regional Haze in the LADCO Class I Areas (2015). https://www.ladco.org/technical/projects/regional-haze-progress/, Accessed July 2021.

[b] NOx control options are not feasible for wood-fired boilers at this time due to technical limitations or economic infeasibility[22].

[c] There was no readily available information on applicable NOx control measures for SCC 10200802.

Coal non-EGU NOx emissions and emission reductions by LADCO state are presented in Table 3-5 and by LADCO NAA in Table 3-6. The number of units with 2016 NOx emissions is available in Appendix B.

Illinois and Minnesota state-level emission reductions are equivalent under each APTE level indicating that all potentially controlled sources have NOx APTE greater than 100 tpy. For Michigan, Ohio, and Wisconsin, state-level emission reductions vary by APTE level. 2016 NOx emissions from coal non-EGU are from Wisconsin (53%), Minnesota (22%), Ohio (16%), Illinois (6%), and Michigan (3%); NOx emission reductions are distributed similarly across stringency scenarios and APTE levels.

There are NOx emission reductions in two NAAs, Cincinnati, OH and Cleveland, OH. Cincinnati, OH NOx emission reductions are only included under the low stringency scenario; Cleveland, OH has the same NOx emission reductions for all APTE levels.

3.5 Cost-effectiveness

Table 3-7 summarizes typical cost-effectiveness estimates for each control measure considered. Facility specific costs will vary based on raw material, fuel characteristics, equipment configuration, and other source specific factors.

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[22] https://www.nescaum.org/documents/controlling_emissions_from_wood_boilers.pdf/

Table 3-5. Statewide 2016 NOx emission reductions from coal non-EGU.[17]

State	2016 NOx Emissions (tons/year)	2016 NOx Emission Reductions (tons/year)											
		APTE = 10 tons/year			APTE = 25 tons/year			APTE = 50 tons/year			APTE = 100 tons/year		
		Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
IL	757	340	224	370	340	224	370	340	224	370	340	224	370
MI	360	159	225	274	159	225	274	159	225	274	119	185	225
MN	2,714	1,221	1,179	1,431	1,221	1,179	1,431	1,221	1,179	1,431	1,221	1,179	1,431
OH	1,960	857	135	164	844	122	148	829	122	148	773	36	43
WI	6,623	2,519	3,918	4,758	2,504	3,895	4,729	2,497	3,884	4,716	2,469	3,841	4,664

Table 3-6. NOx emission reductions from coal non-EGU by NAA.[17][17] [23]

Non-Attainment Area	2016 NOx Emissions (tons/year)	2016 NOx Emission Reductions (tons/year)											
		APTE = 10 tons/year			APTE = 25 tons/year			APTE = 50 tons/year			APTE = 100 tons/year		
		Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
Allegan, MI	-	-	-	-	-	-	-	-	-	-	-	-	-
Berrien, MI	-	-	-	-	-	-	-	-	-	-	-	-	-
Chicago, IL	-	-	-	-	-	-	-	-	-	-	-	-	-
Chicago, IN	-	a	a	a	a	a	a	-	-	-	-	-	-
Chicago, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
Cincinnati, OH	414	185	-	-	180	-	-	165	-	-	165	-	-
Cleveland, OH	103	23	36	43	23	36	43	23	36	43	23	36	43
Columbus, OH	-	-	-	-	-	-	-	-	-	-	-	-	-
Detroit, MI	-	-	-	-	-	-	-	-	-	-	-	-	-
Door, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
Manitowoc County, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
Muskegon, MI	-	-	-	-	-	-	-	-	-	-	-	-	-
Northern Milwaukee/Ozaukee, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
Sheboygan, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
St. Louis, IL	-	-	-	-	-	-	-	-	-	-	-	-	-

[a] APTE values of 10 tons/year and 25 tons/year are not applicable to Chicago, IN

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[23] Cells populated with "-" indicate zero NOx emissions in the inventory and thus no emission reductions.

Table 3-7. Typical cost-effectiveness for each control measure.

Stringency Level	Control Measure	Cost-effectiveness (2020$/ton)	Reference
High	Selective Catalytic Reduction	7,553	EPA CoST[20]
Medium	Regenerative Selective Catalytic Reduction	3,876	LADCO 4FA[21]
	Selective Non-Catalytic Reduction	7,623	EPA CoST[20]
Low	Selective Non-Catalytic Reduction	7,623	EPA CoST[20]

Table 3-8. Statewide total cost of coal non-EGU emissions reduction.[17]

State	Total Cost (thousands of 2020$)											
	APTE = 10 tons/year			APTE = 25 tons/year			APTE = 50 tons/year			APTE = 100 tons/year		
	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
IL	2,595	1,413	2,796	2,595	1,413	2,796	2,595	1,413	2,796	2,595	1,413	2,796
MI	1,211	872	2,070	1,211	872	2,070	1,211	872	2,070	908	718	1,699
MN	9,309	4,569	10,809	9,309	4,569	10,809	9,309	4,569	10,809	9,309	4,569	10,809
OH	6,529	523	1,237	6,432	474	1,121	6,319	474	1,121	5,896	139	328
WI	19,202	15,190	35,937	19,086	15,098	35,719	19,031	15,054	35,617	18,820	14,888	35,223

Table 3-9. Statewide cost-effectiveness of coal non-EGU emissions reduction.[17]

State	Cost-effectiveness (2020$/ton)											
	APTE = 10 tons/year			APTE = 25 tons/year			APTE = 50 tons/year			APTE = 100 tons/year		
	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
IL	7,623	6,298	7,553	7,623	6,298	7,553	7,623	6,298	7,553	7,623	6,298	7,553
MI	7,623	3,876	7,553	7,623	3,876	7,553	7,623	3,876	7,553	7,623	3,876	7,553
MN	7,623	3,876	7,553	7,623	3,876	7,553	7,623	3,876	7,553	7,623	3,876	7,553
OH	7,623	3,876	7,553	7,623	3,876	7,553	7,623	3,876	7,553	7,623	3,876	7,553
WI	7,623	3,876	7,553	7,623	3,876	7,553	7,623	3,876	7,553	7,623	3,876	7,553

Table 3-10. Cost of coal non-EGU emissions reduction by NAA.[1717] [24]

Non-Attainment Area	Total Cost (thousands of 2020$)											
	APTE = 10 tons/year			APTE = 25 tons/year			APTE = 50 tons/year			APTE = 100 tons/year		
	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
Allegan, MI	-	-	-	-	-	-	-	-	-	-	-	-
Berrien, MI	-	-	-	-	-	-	-	-	-	-	-	-
Chicago, IL	-	-	-	-	-	-	-	-	-	-	-	-
Chicago, IN	[a]	[a]	[a]	[a]	[a]	[a]	-	-	-	-	-	-
Chicago, WI	-	-	-	-	-	-	-	-	-	-	-	-
Cincinnati, OH	1,408	-	-	1,373	-	-	1,261	-	-	1,261	-	-
Cleveland, OH	175	139	328	175	139	328	175	139	328	175	139	328
Columbus, OH	-	-	-	-	-	-	-	-	-	-	-	-
Detroit, MI	-	-	-	-	-	-	-	-	-	-	-	-
Door, WI	-	-	-	-	-	-	-	-	-	-	-	-
Manitowoc County, WI	-	-	-	-	-	-	-	-	-	-	-	-
Muskegon, MI	-	-	-	-	-	-	-	-	-	-	-	-
Northern Milwaukee/Ozaukee, WI	-	-	-	-	-	-	-	-	-	-	-	-
Sheboygan, WI	-	-	-	-	-	-	-	-	-	-	-	-
St. Louis, IL	-	-	-	-	-	-	-	-	-	-	-	-

[a] APTE values of 10 tons/year and 25 tons/year are not applicable to Chicago, IN

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[24] Cells populated with "-" indicate zero NOx emissions in the inventory and thus no associated cost or cost-effectiveness.

Table 3-11. Cost-effectiveness of coal non-EGU emissions reduction by NAA.[17] [24]

Non-Attainment Area	Cost-effectiveness (2020$/ton)											
	APTE = 10 tons/year			APTE = 25 tons/year			APTE = 50 tons/year			APTE = 100 tons/year		
	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
Allegan, MI	-	-	-	-	-	-	-	-	-	-	-	-
Berrien, MI	-	-	-	-	-	-	-	-	-	-	-	-
Chicago, IL	-	-	-	-	-	-	-	-	-	-	-	-
Chicago, IN	a	a	a	a	a	a	-	-	-	-	-	-
Chicago, WI	-	-	-	-	-	-	-	-	-	-	-	-
Cincinnati, OH	7,623	-	-	7,623	-	-	7,623	-	-	7,623	-	-
Cleveland, OH	7,623	3,876	7,553	7,623	3,876	7,553	7,623	3,876	7,553	7,623	3,876	7,553
Columbus, OH	-	-	-	-	-	-	-	-	-	-	-	-
Detroit, MI	-	-	-	-	-	-	-	-	-	-	-	-
Door, WI	-	-	-	-	-	-	-	-	-	-	-	-
Manitowoc County, WI	-	-	-	-	-	-	-	-	-	-	-	-
Muskegon, MI	-	-	-	-	-	-	-	-	-	-	-	-
Northern Milwaukee/Ozaukee, WI	-	-	-	-	-	-	-	-	-	-	-	-
Sheboygan, WI	-	-	-	-	-	-	-	-	-	-	-	-
St. Louis, IL	-	-	-	-	-	-	-	-	-	-	-	-

[a] APTE values of 10 tons/year and 25 tons/year are not applicable to Chicago, IN

3.6 Geographic Applicability

NOx emission reductions for coal non-EGU sources can only be achieved in the counties and states in which they are located. According to EPA's 2016v1 emission inventory, coal non-EGU statewide emissions were limited to Illinois, Michigan, Minnesota, Ohio, and Wisconsin including Cincinnati, Ohio and Cleveland, Ohio NAAs. With the exception of Ohio, non-EGU emissions are limited to areas outside of NAAs.

3.7 Responsible Agency

The state air agency is responsible for enforcing SIP-approved and other air permitting rules. A vast majority of coal-fired external combustion non-EGU emissions in the LADCO area are from sources in EPA's 2016v1 emission inventory with APTE over 100 tons/year and therefore are expected to be subject Title V permit requirements; sources not subject to Title V thresholds may be permitted under state permit requirements.

3.8 Implementation Schedule

After a new rule is promulgated, facilities are typically given time to comply with the new rule for planning, analysis, and infrastructure changes necessary to comply. The timeline for existing sources to comply with MACT standards is typically 3-years, but timelines for compliance typically vary from 1-4 years. Assuming that rules to limit coal non-EGU emissions are adopted in late-2023, and assuming a 2-year period from rule promulgation to controls installation, emission reduction would be achieved by 2026. Depending on regulatory requirements, a more aggressive or less aggressive timeline may be required in rulemakings.

3.9 Implementation Feasibility

There are regulatory programs which limit coal non-EGU emissions, for example the New Source Performance Standard for Industrial-Commercial-Institutional Steam Generating Units[25]. Emission requirements are typically expressed in units of mass of NOx emitted per unit of energy input. To develop an emission control regulation for coal non-EGUs, a facility-level assessment will likely be necessary as facility specific conditions (boiler type, fuels, and existing equipment configurations) will determine the feasibility and cost of controls.

3.10 Public Acceptance

Coal non-EGUs can produce substantial emissions of NOx and other pollutants. Coal non-EGU control measures evaluated herein are generally cost-effective and therefore can be shown to be a good regional emission reductions strategy. Coal non-EGU operators may object to any further regulation of their operations, especially for the more costly control measures. Grant funding can be used to facilitate implementation of control measures.

3.11 All Controls Results

Analysis in the sections above includes the controls considered under low, medium, and high stringency scenarios, as indicated in Table 3-4 (i.e., those controls not highlighted in grey on Table 3-4). Emission reduction estimates across the full suite of stringency scenario and control combinations are presented in Appendix A, Tables A1 to A2.

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[25] https://www.epa.gov/stationary-sources-air-pollution/industrial-commercial-institutional-steam-generating-units-new, accessed in January, 2022

4.0 COKE

4.1 Summary

This section focuses on emissions reductions for coke manufacturing stationary sources. Coke manufacturing involves the use of furnaces in which raw materials are converted into coke as part of the steel manufacturing process. The furnaces used in coke manufacturing are a substantial sources of NOx emissions. Table 4-1 summarizes key information for coke control measures evaluated herein. Applicable emissions, emission reductions, and cost-effectiveness are presented in Table 4-1 on a LADCO region-wide basis. State- and NAA-level emissions, emission reductions, and cost-effectiveness are presented in subsections below. Emission reductions across all control measures (i.e., including control measures not selected for evaluation in this white paper) are provided in Appendix A.

Table 4-1. Control measure summary for coke.[26]

2016 Emissions Estimates					
2016 Emissions [a]	NOx:	5,522 tons/year			
Control Measure Summary, Including 2016 Emission Reduction Estimates					
		APTE = 10 tons/year	**APTE = 25 tons/year**	**APTE = 50 tons/year**	**APTE = 100 tons/year**
Selective Non-Catalytic Reduction (High/Medium/Low Stringency Scenario)	NOx Reduction:	1,147 tons/year	1,141 tons/year	3,302 tons/year	
	Cost-effectiveness:	*$3,248/ton*			
	Applicable States:	*IL, MI, OH*			
	Applicable NAAs:	*Cincinnati, OH; Detroit, MI; St. Louis, IL*		*Chicago, IN; Cincinnati, OH; Detroit, MI; St. Louis, IL*	

[a] Source: US Environmental Protection Agency (EPA) 2016v1 modeling platform. Available at https://www.epa.gov/air-emissions-modeling/2016v1-platform, accessed in June 2021.

4.2 Source Description

Coke is created from the heating of coal in an oxygen-free atmosphere to a distilled form in which volatile components are removed (EPA, 1995). Coke plants often operate in conjunction with iron and steel production facilities and demand for coke usually correlates to the demand for iron and steel since coke is typically used in steel manufacturing.

To create coke, coal is pulverized, blended, and cooked in a hot oven until a pure, carbon form is created. During the process, gases, tar, ammonium sulfate, and other compounds are generated (the by-products). Most coke in the US is produced using a "by-product" process, but it can also be produced using a "non-recovery" process. In the "non-recovery" process, the chemical by-products produced during the coke creation process are burned instead of being recovered as chemical by-products. According to the LADCO emission inventory, coke produced in the LADCO region uses the "by-product" process, during which the compounds generated are collected and repurposed.

Gases produced during the baking of coal are collected by large exhausters and shock-cooled so that the tar precipitates out and the vapors are condensed. The mixture is then further refined to extract tar. Materials such as water, benzene, and naphthalene are removed from the gas in a condenser or

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[26] Excludes Indiana emissions except for in Chicago, Indiana nonattainment area counties (Lake County and Porter County).

cooler, and the gas is sent through an oil scrubber where light oil is removed. The light oil is then packaged to be sold or reused in the process. Ammonia is collected either in its aqueous form or as ammonium sulfate salt, which can be dried and sold. In the US, tar-bottom coolers, wash-oil coolers, and cooling systems are used instead of direct gas coolers. Emissions from coke ovens include particulate matter (PM), sulfur dioxide (SO_2), NO_x, volatile organic compounds (VOC), and other pollutants.

Table 4-2 lists the applicable SCCs for coke in the LADCO stationary point source inventory.

Table 4-2. Applicable SCCs for coke.

Description One	Description Two	Description Three	Description Four	SCC
Industrial Processes	Primary Metal Production	Metallurgical Coke Manufacturing	By-product Process: Topside Leaks, Lid Leaks	30300314
			By-product Process: Combustion Stack: Coke Oven Gas (COG)	30300317
			By-product Process: Combustion Stack: Blast Furnace Gas (BFG)	30300318

4.3 Selected Control Measures Description

For coke sources, only one control measure was considered for all stringency levels. The selected control measure and its estimated control efficiency are shown in Table 4-3. A description of the control measure are included in the subsections below.

Table 4-3. Applicable control technology and associated control efficiency by stringency level.

Stringency Level	Control Measure	Control Efficiency (%)
Low, Medium, High	Selective Non-Catalytic Reduction	60

4.3.1 Selective Non-Catalytic Reduction

SNCR is a post-combustion control technology in which NOx is chemically reduced into molecular N_2 and water vapor in the presence of ammonia. Typically, ammonia is injected as ammonia water or urea in the flue-gas at a temperature suitable for inducing substantial NOx emission reductions (EPA, 2007). Aqueous ammonia is a common SNCR reagent. Other potential reagents include anhydrous ammonia (injected as a gas), urea solutions, and ammonium sulfate solutions. Though the reagent can react with several flue gas components, the NOx reduction reaction is favored over other chemical reactions for a specific temperature range and in the presence of oxygen; therefore, SNCR is considered a selective chemical process (EPA, 2019b).

Unlike an SCR, no catalyst is used to increase the reaction rate in an SNCR. SNCR temperature range is critical to achieving optimal NOx reduction (EPA, 2007). At temperatures that are too high, competing reactions for the direct oxidation of ammonia lower NOx reduction efficiency. At temperatures that are too low, NOx reduction reactions are too slow which results in excess ammonia slip.

SNCR is potentially applicable to facilities with gas stream temperatures that are suitable for the efficient SNCR operation.

4.4 NOx Emission Reductions

Table 4-4 shows the control measures that were implemented for each SCC and stringency level. Existing (as of 2016) NOx controls were accounted for in the analysis; potential emission reductions were calculated as incremental reductions from the existing controls. Existing NOx controls were identified based on "Control ID" in the 2016v1 modeling platform files. If the existing control efficiency was higher than the selected control measure for a unit, no emission reduction or cost was calculated. If the existing control efficiency was lower than the selected control measure, the surplus emission reduction and associated cost are calculated.

Estimated emission reductions are uncertain because 1) information on existing controls is unlikely to be comprehensive and 2) feasibility and emission reduction potential depends on site-specific conditions such as raw materials and fuels used and existing equipment configurations. Emission reductions can be more accurately estimated based on individual facility specific feasibility and emission control analysis. This analysis is a source category-level evaluation; therefore, facility specific analysis is not included.

Table 4-4. Coke control measure applied to each SCC.

SCC	SCC Description	Stringency Level [a]		
		High	Medium	Low
30300314	Industrial Processes; Primary Metal Production; Metallurgical Coke Manufacturing; By-product Process: Topside Leaks, Lid Leaks	Selective Non-Catalytic Reduction		
30300317	Industrial Processes; Primary Metal Production; Metallurgical Coke Manufacturing; By-product Process: Combustion Stack: Coke Oven Gas (COG)	Selective Non-Catalytic Reduction		
30300318	Industrial Processes; Primary Metal Production; Metallurgical Coke Manufacturing; By-product Process: Combustion Stack: Blast Furnace Gas (BFG)	Selective Non-Catalytic Reduction		

[a] Control measure assignments for each SCC were based on EPA's Control Strategy Tool (CoST), version 3.7[27].

Coke NOx emissions and emission reductions by LADCO state are presented in Table 4-5 and by LADCO NAA in Table 4-6. The number of units with 2016 NOx emissions is available in Appendix B.

State-level emission reductions are equivalent under each APTE level indicating that all potentially controlled sources have NOx APTE greater than 100 tpy. Emissions are also the same across stringency scenarios because SNCR is the control that is applied across all scenarios. 2016 NOx emissions from coke are from Chicago, IN (65%), Ohio (19%), Minnesota (9%), Illinois (7%); NOx emission reductions are distributed similarly across stringency scenarios and APTE levels.

There are NOx emission reductions in four NAAs, namely, Chicago, IN; Cincinnati, OH; Detroit, MI; and St. Louis, IL.

4.5 Cost-effectiveness

Table 4-7 summarizes typical cost-effectiveness estimates for each control measure considered. Facility specific costs will vary based on raw material, fuel characteristics, equipment configuration, and other source specific factors. Table 4-8 and Table 4-9 show statewide cost and cost-effectiveness estimates, respectively. Table 4-10 and Table 4-11 show cost and cost-effectiveness estimates, respectively, by NAA.

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[27] Control Strategy Tool. https://www.epa.gov/economic-and-cost-analysis-air-pollution-regulations/cost-analysis-modelstools-air-pollution#control%20strategy%20tool, Accessed January 2021.

Table 4-5. Statewide 2016 NOx emission reductions from coke.[26] [28]

State	2016 NOx Emissions (tons/year)	2016 NOx Emission Reductions (tons/year)											
		APTE = 10 tons/year			APTE = 25 tons/year			APTE = 50 tons/year			APTE = 100 tons/year		
		Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
IL	376	220	220	220	215	215	215	215	215	215	215	215	215
MI	521	313	313	313	313	313	313	313	313	313	313	313	313
MN	-	-	-	-	-	-	-	-	-	-	-	-	-
OH	1,023	613	613	613	613	613	613	613	613	613	613	613	613
WI	-	-	-	-	-	-	-	-	-	-	-	-	-

Table 4-6. NOx emission reductions from coke by NAA.[26] [28]

Non-Attainment Area	2016 NOx Emissions (tons/year)	2016 NOx Emission Reductions (tons/year)											
		APTE = 10 tons/year			APTE = 25 tons/year			APTE = 50 tons/year			APTE = 100 tons/year		
		Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
Allegan, MI	-	-	-	-	-	-	-	-	-	-	-	-	-
Berrien, MI	-	-	-	-	-	-	-	-	-	-	-	-	-
Chicago, IL	-	-	-	-	-	-	-	-	-	-	-	-	-
Chicago, IN	3,602	[a]	[a]	[a]	[a]	[a]	[a]	2,161	2,161	2,161	2,161	2,161	2,161
Chicago, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
Cincinnati, OH	280	168	168	168	168	168	168	168	168	168	168	168	168
Cleveland, OH	-	-	-	-	-	-	-	-	-	-	-	-	-
Columbus, OH	-	-	-	-	-	-	-	-	-	-	-	-	-
Detroit, MI	521	313	313	313	313	313	313	313	313	313	313	313	313
Door, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
Manitowoc County, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
Muskegon, MI	-	-	-	-	-	-	-	-	-	-	-	-	-
Northern Milwaukee/Ozaukee, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
Sheboygan, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
St. Louis, IL	376	220	220	220	215	215	215	215	215	215	215	215	215

[a] APTE values of 10 tons/year and 25 tons/year are not applicable to Chicago, IN

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[28] Cells populated with "-" indicate zero NOx emissions in the inventory and thus no emission reductions.

Table 4-7. Typical cost-effectiveness for each control measure.

Stringency Level	Control Measure	Cost-effectiveness (2020$/ton)	Reference
High, Medium, Low	Selective Non-Catalytic Reduction	3,248	EPA CoST[27]

Table 4-8. Statewide total cost of coke emissions reduction.[26] [29]

State	Total Cost (thousands of 2020$)											
	APTE = 10 tons/year			APTE = 25 tons/year			APTE = 50 tons/year			APTE = 100 tons/year		
	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
IL	716	716	716	697	697	697	697	697	697	697	697	697
MI	1,015	1,015	1,015	1,015	1,015	1,015	1,015	1,015	1,015	1,015	1,015	1,015
MN	-	-	-	-	-	-	-	-	-	-	-	-
OH	1,992	1,992	1,992	1,992	1,992	1,992	1,992	1,992	1,992	1,992	1,992	1,992
WI	-	-	-	-	-	-	-	-	-	-	-	-

Table 4-9. Statewide cost-effectiveness of coke emissions reduction.[26] [29]

State	Cost-effectiveness (2020$/ton)											
	APTE = 10 tons/year			APTE = 25 tons/year			APTE = 50 tons/year			APTE = 100 tons/year		
	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
IL	3,248	3,248	3,248	3,248	3,248	3,248	3,248	3,248	3,248	3,248	3,248	3,248
MI	3,248	3,248	3,248	3,248	3,248	3,248	3,248	3,248	3,248	3,248	3,248	3,248
MN	-	-	-	-	-	-	-	-	-	-	-	-
OH	3,248	3,248	3,248	3,248	3,248	3,248	3,248	3,248	3,248	3,248	3,248	3,248
WI	-	-	-	-	-	-	-	-	-	-	-	-

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[29] Cells populated with "-" indicate zero NOx emissions in the inventory and thus no associated cost or cost-effectiveness.

Table 4-10. Cost of coke emissions reduction by NAA.[26] [29]

Non-Attainment Area	Total Cost (thousands of 2020$)											
	APTE = 10 tons/year			APTE = 25 tons/year			APTE = 50 tons/year			APTE = 100 tons/year		
	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
Allegan, MI	-	-	-	-	-	-	-	-	-	-	-	-
Berrien, MI	-	-	-	-	-	-	-	-	-	-	-	-
Chicago, IL	-	-	-	-	-	-	-	-	-	-	-	-
Chicago, IN	[a]	[a]	[a]	[a]	[a]	[a]	7,018	7,018	7,018	7,018	7,018	7,018
Chicago, WI	-	-	-	-	-	-	-	-	-	-	-	-
Cincinnati, OH	546	546	546	546	546	546	546	546	546	546	546	546
Cleveland, OH	-	-	-	-	-	-	-	-	-	-	-	-
Columbus, OH	-	-	-	-	-	-	-	-	-	-	-	-
Detroit, MI	1,015	1,015	1,015	1,015	1,015	1,015	1,015	1,015	1,015	1,015	1,015	1,015
Door, WI	-	-	-	-	-	-	-	-	-	-	-	-
Manitowoc County, WI	-	-	-	-	-	-	-	-	-	-	-	-
Muskegon, MI	-	-	-	-	-	-	-	-	-	-	-	-
Northern Milwaukee/Ozaukee, WI	-	-	-	-	-	-	-	-	-	-	-	-
Sheboygan, WI	-	-	-	-	-	-	-	-	-	-	-	-
St. Louis, IL	716	716	716	697	697	697	697	697	697	697	697	697

[a] APTE values of 10 tons/year and 25 tons/year are not applicable to Chicago, IN

Table 4-11. Cost-effectiveness of coke emissions reduction by NAA.[26] [29]

Non-Attainment Area	Cost-effectiveness (2020$/ton)											
	APTE = 10 tons/year			APTE = 25 tons/year			APTE = 50 tons/year			APTE = 100 tons/year		
	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
Allegan, MI	-	-	-	-	-	-	-	-	-	-	-	-
Berrien, MI	-	-	-	-	-	-	-	-	-	-	-	-
Chicago, IL	-	-	-	-	-	-	-	-	-	-	-	-
Chicago, IN	[a]	[a]	[a]	[a]	[a]	[a]	3,248	3,248	3,248	3,248	3,248	3,248
Chicago, WI	-	-	-	-	-	-	-	-	-	-	-	-
Cincinnati, OH	3,248	3,248	3,248	3,248	3,248	3,248	3,248	3,248	3,248	3,248	3,248	3,248
Cleveland, OH	-	-	-	-	-	-	-	-	-	-	-	-
Columbus, OH	-	-	-	-	-	-	-	-	-	-	-	-
Detroit, MI	3,248	3,248	3,248	3,248	3,248	3,248	3,248	3,248	3,248	3,248	3,248	3,248
Door, WI	-	-	-	-	-	-	-	-	-	-	-	-
Manitowoc County, WI	-	-	-	-	-	-	-	-	-	-	-	-
Muskegon, MI	-	-	-	-	-	-	-	-	-	-	-	-
Northern Milwaukee/Ozaukee, WI	-	-	-	-	-	-	-	-	-	-	-	-
Sheboygan, WI	-	-	-	-	-	-	-	-	-	-	-	-
St. Louis, IL	3,248	3,248	3,248	3,248	3,248	3,248	3,248	3,248	3,248	3,248	3,248	3,248

[a] APTE values of 10 tons/year and 25 tons/year are not applicable to Chicago, IN

4.6 Geographic Applicability

NOx emission reductions for coke manufacturing can only be achieved in the counties and states in which coke manufacturing facilities are located. According to EPA's 2016v1 emission inventory, coke manufacturing 1) statewide emissions were limited to Illinois, Michigan, and Ohio; there were no statewide coke manufacturing emissions in Minnesota or Wisconsin and 2) NAA emissions were limited to Chicago, IN; Cincinnati, OH; Detroit, MI; and St. Louis, IL.

4.7 Responsible Agency

The state air agency is responsible for enforcing SIP-approved and other air permitting rules. Each applicable coke manufacturing emission source in the LADCO area has NOx APTE in EPA's 2016v1 emission inventory of over 100 tons/year and therefore are expected to be subject Title V permit requirements.

4.8 Implementation Schedule

After a new rule is promulgated, facilities are typically given time to comply with the new rule for planning, analysis, and infrastructure changes necessary to comply. The timeline for existing sources to comply with MACT standards is typically 3-years, but timelines for compliance typically vary from 1-4 years. Assuming that rules to limit coke manufacturing source emissions are adopted in late-2023, and assuming a 2-year period from rule promulgation to controls installation, emission reduction would be achieved by 2026. Depending on regulatory requirements, a more aggressive or less aggressive timeline may be required in rulemakings.

4.9 Implementation Feasibility

There are regulatory programs which limit coke emissions; however, NOx emission limits have generally not been explicitly prescribed. At the Federal level, Coke Oven By-Product Recovery Plants are regulated under National Emissions Standards for Hazardous Air Pollutants (NESHAP)[30]. The Bay Area Air Quality Management District Regulation 9 Rule 14: Petroleum Coke Calcining Operations [31] addresses SO_2 emissions; however, the regulation text notes that the regulation may be amended to include NOx emission limits. To develop an emission control regulation for coke manufacturing, a facility-level assessment will likely be necessary as facility specific conditions (raw materials, fuels, and existing equipment configurations) will determine the feasibility and cost of controls.

4.10 Public Acceptance

Coke manufacturing facilities can produce substantial emissions of NOx and other pollutants. The coke manufacturing emission control measure evaluated herein is cost-effective and therefore can be shown to be a good regional emission reductions strategy. Coke manufacturing facility operators may object to any further regulation of their operations. Grant funding can be used to facilitate implementation of control measures.

4.11 All Controls Results

Analysis in the sections above includes the controls considered under low, medium, and high stringency scenarios, as indicated in Table 4-4 (i.e., those controls not highlighted in grey on Table 4-4). Emission reduction estimates across the full suite of stringency scenario and control combinations are presented in Appendix A, Tables A1 to A2.

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[30] https://www.epa.gov/stationary-sources-air-pollution/coke-oven-product-recovery-plants-national-emissions-standards, accessed in February, 2022

[31] https://www.baaqmd.gov/~/media/dotgov/files/rules/regulation-9-rule-14--petroleum-coke-calcining-operations/documents/rg0914-pdf.pdf?la=en&rev=dffbc95d7de040c0b1ee51c01ca9bab6, accessed in February, 2022

5.0 GAS-FIRED EXTERNAL COMBUSTION SOURCES

5.1 Summary

This section focuses on emissions reductions for natural gas-fired external combustion sources. Natural gas-fueled external combustion sources (typically boilers and heaters) are widely used in a variety of industrial, commercial, and residential settings and may be used for electricity or heat generation. Table 5-1 summarizes key information for gas-fired external combustion sources control measures evaluated herein. Applicable emissions, emission reductions, and cost-effectiveness are presented in Table 5-1 on a LADCO region-wide basis. State- and NAA-level emissions, emission reductions, and cost-effectiveness are presented in subsections below. Emission reductions across all control measures (i.e., including control measures not selected for evaluation in this white paper) are provided in Appendix A.

Table 5-1. Control measure summary for gas-fired external combustion sources.[32]

2016 Emissions Estimates					
2016 Emissions [a]	NOx:	32,318 tons/year			
Control Measure Summary, Including 2016 Emission Reduction Estimates					
		APTE = 10 tons/year	**APTE = 25 tons/year**	**APTE = 50 tons/year**	**APTE = 100 tons/year**
Selective Catalytic Reduction (High Stringency Scenario)	NOx Reduction:	1,313 tons/year	958 tons/year	1,958 tons/year	1,644 tons/year
	Cost-effectiveness:	*$1,657 or $10,957/ton* [b]			
	Applicable States:	*IL, MI, MN, OH, WI*			*MI, MN, WI*
	Applicable NAAs:	*Chicago, IL; Chicago, WI; Cleveland, OH; Columbus, OH; Detroit, MI; Manitowoc County, WI; Northern Milwaukee/Ozaukee, WI; St. Louis, IL*	*Cleveland, OH; Columbus, OH; Detroit, MI; Northern Milwaukee/Ozaukee, WI*	*Chicago, IN; Columbus, OH; Detroit, MI*	*Chicago, IN; Detroit, MI*
Low NOx Burner and Flue Gas Recirculation (Medium Stringency Scenario)	NOx Reduction:	1,074 tons/year	916 tons/year	1,862 tons/year	1,697 tons/year
	Cost-effectiveness:	*$7,532, $14,163 or $26,449/ton* [c]*; or $5,069/ton* [d]			*$7,532 or $14,163/ton* [c]*; or $5,069/ton* [d]
	Applicable States:	*IL, MI, MN, OH, WI*	*IL, MI, OH, WI*		*IL, MI, OH*
	Applicable NAAs:	*Chicago, IL; Cincinnati, OH; Cleveland, OH; Columbus, OH; Detroit, MI; Manitowoc County, WI; Northern Milwaukee/Ozaukee, WI; St. Louis, IL*	*Chicago, IL; Cincinnati, OH; Cleveland, OH; Detroit, MI*	*Chicago, IL; Chicago, IN; Cincinnati, OH; Detroit, MI*	*Chicago, IL; Chicago, IN; Detroit, MI*
Low NOx Burner and Selective Non-	NOx Reduction:	11,449 tons/year	8,526 tons/year	7,665 tons/year	5,584 tons/year
	Cost-effectiveness:	*$6,918, $12,366 or $22,403/ton* [e]			*$6,918 or $12,366/ton* [e]

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[32] Excludes Indiana emissions except for in Chicago, Indiana nonattainment area counties (Lake County and Porter County).

2016 Emissions Estimates					
2016 Emissions [a]	NOx:	32,318 tons/year			
Control Measure Summary, Including 2016 Emission Reduction Estimates					
Catalytic Reduction (Medium Stringency Scenario)	*Applicable States:*	*IL, MI, MN, OH, WI*			
	Applicable NAAs:	*Allegan, MI; Berrien, MI; Chicago, IL; Chicago, WI; Cincinnati, OH; Cleveland, OH; Columbus, OH; Detroit, MI; Muskegon, MI; Northern Milwaukee/Ozaukee, WI; Sheboygan, WI; St. Louis, IL*	*Allegan, MI; Chicago, IL; Cincinnati, OH; Cleveland, OH; Columbus, OH; Detroit, MI; Muskegon, MI; Northern Milwaukee/Ozaukee, WI; St. Louis, IL*	*Chicago, IL; Chicago, IN; Cincinnati, OH; Cleveland, OH; Columbus, OH; Detroit, MI; Northern Milwaukee/Ozaukee, WI; St. Louis, IL*	*Chicago, IL; Chicago, IN; Cincinnati, OH; Detroit, MI; Northern Milwaukee/Ozaukee, WI*
Flue Gas Recirculation (Low Stringency Scenario)	NOx Reduction:	6,817 tons/year	5,189 tons/year	5,393 tons/year	4,187 tons/year
	Cost-effectiveness:	*$6,776, $12,752 or $23,906/ton* [f]			*$6,776 or $12,752/ton* [f]
	Applicable States:	*IL, MI, MN, OH, WI*			
	Applicable NAAs:	*Allegan, MI; Berrien, MI; Chicago, IL; Chicago, WI; Cincinnati, OH; Cleveland, OH; Columbus, OH; Detroit, MI; Muskegon, MI; Northern Milwaukee/Ozaukee, WI; Sheboygan, WI; St. Louis, IL*	*Allegan, MI; Chicago, IL; Cincinnati, OH; Cleveland, OH; Columbus, OH; Detroit, MI; Muskegon, MI; Northern Milwaukee/Ozaukee, WI; St. Louis, IL*	*Chicago, IL; Chicago, IN; Cincinnati, OH; Cleveland, OH; Columbus, OH; Detroit, MI; Northern Milwaukee/Ozaukee, WI*	*Chicago, IL; Chicago, IN; Cincinnati, OH; Detroit, MI; Northern Milwaukee/Ozaukee, WI*

2016 Emissions Estimates					
2016 Emissions [a]	NOx:	32,318 tons/year			
Control Measure Summary, Including 2016 Emission Reduction Estimates					
Selective Non-Catalytic Reduction (Low Stringency Scenario)	NOx Reduction:	180 tons/year	92 tons/year	64 tons/year	24 tons/year
	Cost-effectiveness:	*$10,239/ton*			
	Applicable States:	*IL, MI, OH, WI*		*IL, MI, WI*	*MI*
	Applicable NAAs:	*Chicago, IL; Cleveland, OH; Columbus, OH; Detroit, MI; Manitowoc County, WI; Northern Milwaukee/Ozaukee, WI; St. Louis, IL*	*Cleveland, OH; Detroit, MI*	*Detroit, MI*	*Detroit, MI*

[a] Source: US Environmental Protection Agency (EPA) 2016v1 modeling platform. Available at https://www.epa.gov/air-emissions-modeling/2016v1-platform, accessed in June 2021.

[b] The cost-effectiveness is $1,657/ton for Selective Catalytic Reduction - Utility Boiler - Oil-Gas/Tangential. The cost-effectiveness is $10,957/ton for Selective Catalytic Reduction - ICI Boilers - Gas.

[c] The cost-effectiveness is $26,449/ton for sources with an emission rate less than 50 tons/year; $14,163 for sources with an emission rate between 50 and 100 tons/year; $7,532 for sources with an emission rate higher than 100 tons/year for Low NOx Burner and Flue Gas Recirculation - ICI Boilers - Process Gas.

[d] The cost-effectiveness is $5,069/ton for Low NOx Burner and Flue Gas Recirculation - Space Heaters - Natural Gas.

[e] The cost-effectiveness is $22,403/ton for sources with an emission rate less than 50 tons/year; $12,366 for sources with an emission rate between 50 and 100 tons/year; $6,918 for sources with an emission rate higher than 100 tons/year.

[f] The cost-effectiveness is $23,906/ton for sources with an emission rate less than 50 tons/year; $12,752 for sources with an emission rate between 50 and 100 tons/year; $6,776 for sources with an emission rate higher than 100 tons/year.

5.2 Source Description

Natural gas is composed of over 85% methane with smaller amounts of ethane, propane, butane, and other compounds and is used widely in external and internal combustion applications throughout the United States (EPA, 1994).

Gas-fired boilers can be classified into three types: watertube, firetube, and cast iron. In watertube boilers, water passes through tubes heated by the combustion of gases. It is used in a variety of processes including the heating of hot water and the generation of high pressure steam for the production of electricity. In firetube boilers, hot gases flow through tubes, heating the water outside the tubes. These boilers can be used to generate process steam and run space heating systems. Cast iron boilers work the same way as firetubes except that instead steel construction, the units are constructed of cast iron. Cast iron boilers can be used to produce low-pressure steam and hot water.

Emissions created from gas-fired external combustion are mainly composed of NO_x, CO, CO_2, CH_4, N_2O, VOCs, PM, and SO_2.

Table 5-2 lists the applicable SCCs for gas-fired external combustion sources in the LADCO stationary point source inventory. Several EGU SCCs appear in this list because large non-EGU facilities can have their own onsite power generation. These EGU boilers are typically included in the non-EGU inventory along with other sources.

Table 5-2. Applicable SCCs for gas-fired external combustion sources.

Description One	Description Two	Description Three	Description Four	SCC
External Combustion	Electric Generation: Boilers	Natural Gas	Boiler, >= 100 Million BTU/hr	10100601
			Boiler < 100 Million BTU, except tangential	10100602
			Boiler, Tangential-fired	10100604
		Process Gas	Boiler, >= 100 Million BTU/hr	10100701
			Boiler < 100 Million Btu/hr	10100702
	Industrial: Boilers	Natural Gas	> 100 Million BTU/hr	10200601
			10-100 Million BTU/hr	10200602
			< 10 Million BTU/hr	10200603
		Process Gas	Blast Furnace Gas	10200704
			Coke Oven Gas	10200707
			Other: Specify in Comments	10200799
	Commercial/Institutional: Boilers	Natural Gas	> 100 Million BTU/hr	10300601
			10-100 Million BTU/hr	10300602
			< 10 Million BTU/hr	10300603
	Space Heaters	Industrial	Natural Gas	10500106

5.3 Selected Control Measures Description

For gas-fired external combustion sources, specific control measures were considered for each stringency level. The selected control measures and their estimated control efficiency are shown in Table 5-3. Descriptions of each control measure are included in the subsections below.

Table 5-3. Applicable control technology and associated control efficiency by stringency level.

Stringency Level	Control Measure	Control Efficiency (%)
High	Selective Catalytic Reduction	80 or 85 [a]
Medium	Low NOx Burner and Flue Gas Recirculation	60 or 61 [b]
	Low NOx Burner and Selective Non-Catalytic Reduction	69.5
Low	Flue Gas Recirculation	40
	Selective Non-Catalytic Reduction	45

[a] The control efficiency is 80% for Selective Catalytic Reduction - Utility Boiler - Oil-Gas/Tangential. The control efficiency is 85% for Selective Catalytic Reduction - ICI Boilers - Gas.
[b] The control efficiency is 60% for Low NOx Burner and Flue Gas Recirculation - ICI Boilers - Process Gas. The control efficiency is 61% for Low NOx Burner and Flue Gas Recirculation - Space Heaters - Natural Gas.

5.3.1 Selective Catalytic Reduction

SCR is a post-combustion control technology. An SCR emission control system uses a catalyst, typically ammonia or urea, to selectively reduce NOx emissions from exhaust gases (EPA, 2007). NOx is chemically reduced into molecular N_2 and water vapor. The catalyst is not consumed but allows the reactions to occur at a lower temperature.

The SCR system can be installed at different locations including upstream of an air heater and particulate control device, or downstream of the air heater, particulate control device, and flue gas desulfurization systems.

5.3.2 Flue Gas Recirculation

Flue gas recirculation is a control in which combustion is moderated by diluting combustion air with flue gas from the stack. Flue gas is recycled from the stack to the burner windbox (the windbox is the area behind the burner throats that supplies combustion air to the burners). Recirculated gas is mixed with combustion air prior to being fed to the burner. Combustion products in the flue gas are inert during combustion, reducing NOx emissions by reducing combustion temperatures thereby reducing thermal NOx formation and, to a lesser extent, reducing oxygen concentration in the primary flame zone thereby reducing NOx formation. Correct tuning of the amount of flue gas recirculation is the key parameter for achieving optimal NOx reductions from flue gas recirculation. Flue gas recirculation is less common as a retrofit because of the required hardware modifications such as ductwork, recirculation fan, and air mixing controls (EPA, 1994).

5.3.3 Low NOx Burner and Flue Gas Recirculation

Low NOx burners spread combustion over multiple stages allowing for control of both stoichiometric and temperature profiles during combustion (EPA, 1994). Emission reductions are achieved by one or more of the following:

- Reducing oxygen content in the combustion zone, limiting fuel NOx formation;
- Reducing flame temperature, limiting thermal NOx formation;
- Reducing residence time at peak temperature, limiting thermal NOx formation;

Low NOx burners may be designed to delay the combustion process resulting in a cooler flame thereby suppressing thermal NOx or to create stratified fuel-rich and fuel-lean regions in or near the burner. In fuel-rich regions, fuel NOx formation is reduced; in fuel-lean regions, thermal NOx formation is reduced. Low NOx burners are often used in conjunction with flue gas recirculation to sustain a lower, stable flame temperature with increased recirculation gas flow.

5.3.4 Selective Non-Catalytic Reduction

SNCR is a post-combustion control technology in which NOx is chemically reduced into molecular N_2 and water vapor in the presence of ammonia. Typically, ammonia is injected as ammonia water or urea in the flue-gas at a temperature suitable for inducing substantial NOx emission reductions (EPA, 2007). Aqueous ammonia is a common SNCR reagent. Other potential reagents include anhydrous ammonia (injected as a gas), urea solutions, and ammonium sulfate solutions. Though the reagent can react with several flue gas components, the NOx reduction reaction is favored over other chemical reactions for a specific temperature range and in the presence of oxygen; therefore, SNCR is considered a selective chemical process (EPA, 2019b).

Unlike an SCR, no catalyst is used to increase the reaction rate in an SNCR. SNCR temperature range is critical to achieving optimal NOx reduction (EPA, 2007). At temperatures that are too high, competing reactions for the direct oxidation of ammonia lower NOx reduction efficiency. At temperatures that are too low, NOx reduction reactions are too slow which results in excess ammonia slip.

SNCR is potentially applicable to facilities with gas stream temperatures that are suitable for the efficient SNCR operation.

5.3.5 Low NOx Burner and Selective Non-Catalytic Reduction

Low NOx burners can be used in conjunction with SNCR to lower NOx emissions. When used together, low NOx burners are used to set gas stream temperatures to the range suitable for optimizing SNCR emission reductions.

5.4 NOx Emission Reductions

Table 5-4 shows the control measures that were implemented for each SCC and stringency level. Existing (as of 2016) NOx controls were accounted for in the analysis; potential emission reductions were calculated as incremental reductions from the existing controls. Existing NOx controls were identified based on “Control ID” in the 2016v1 modeling platform files. If the existing control efficiency was higher than the selected control measure for a unit, no emission reduction or cost was calculated. If the existing control efficiency was lower than the selected control measure, the surplus emission reduction and associated cost are calculated.

Estimated emission reductions are uncertain because 1) information on existing controls is unlikely to be comprehensive and 2) feasibility and emission reduction potential depends on site-specific conditions such as raw materials and fuels used and existing equipment configurations. Emission reductions can be more accurately estimated based on individual facility specific feasibility and emission control analysis. This analysis is a source category-level evaluation; therefore, facility specific analysis is not included.

Table 5-4. Gas-fired external combustion sources control measure applied to each SCC.

SCC [b]	SCC Description [b]	Stringency Level (Control technologies highlighted in grey were assessed in prior tasks but are not evaluated in this white paper) [a]		
		High	Medium	Low
10100601	External Combustion; Electric Generation: Boilers; Natural Gas; Boiler, >= 100 Million BTU/hr	Selective Catalytic Reduction	Low NOx Burner, Over-fired Air and Selective Non-Catalytic Reduction	Low NOx Coal-and-Air Nozzles with separated Over-fired Air
10100602	External Combustion; Electric Generation: Boilers; Natural Gas; Boiler < 100 Million BTU, except tangential	Selective Catalytic Reduction	Low NOx Burner, Over-fired Air and Selective Non-Catalytic Reduction	Low NOx Coal-and-Air Nozzles with cross-Coupled Over-fired Air
10100604	External Combustion; Electric Generation: Boilers; Natural Gas; Boiler, Tangential-fired	Selective Catalytic Reduction	Natural Gas Reburn	Low NOx Coal-and-Air Nozzles with cross-Coupled Over-fired Air
10100701	External Combustion; Electric Generation: Boilers; Process Gas; Boiler, >= 100 Million BTU/hr	Selective Catalytic Reduction	Selective Catalytic Reduction	Selective Catalytic Reduction
10100702	External Combustion; Electric Generation: Boilers; Process Gas; Boiler < 100 Million Btu/hr	Selective Catalytic Reduction	Selective Catalytic Reduction	Selective Catalytic Reduction
10200601	External Combustion; Industrial: Boilers; Natural Gas; > 100 Million BTU/hr	Ultra Low NOx Burner and Selective Catalytic Reduction	Low NOx Burner and Selective Non-Catalytic Reduction	Flue Gas Recirculation
10200602	External Combustion; Industrial: Boilers; Natural Gas; 10-100 Million BTU/hr	Ultra Low NOx Burner and Selective Catalytic Reduction	Low NOx Burner and Selective Non-Catalytic Reduction	Flue Gas Recirculation

SCC [b]	SCC Description [b]	Stringency Level (Control technologies highlighted in grey were assessed in prior tasks but are not evaluated in this white paper) [a]		
		High	Medium	Low
10200603	External Combustion; Industrial: Boilers; Natural Gas; < 10 Million BTU/hr	Ultra Low NOx Burner and Selective Catalytic Reduction	Low NOx Burner and Selective Non-Catalytic Reduction	Flue Gas Recirculation
10200704	External Combustion; Industrial: Boilers; Process Gas; Blast Furnace Gas	Ultra Low NOx Burner and Selective Catalytic Reduction	Low NOx Burner and Flue Gas Recirculation	Flue Gas Recirculation
10200707	External Combustion; Industrial: Boilers; Process Gas; Coke Oven Gas	Ultra Low NOx Burner and Selective Catalytic Reduction	Low NOx Burner and Flue Gas Recirculation	Flue Gas Recirculation
10200799	External Combustion; Industrial: Boilers; Process Gas; Other: Specify in Comments	Ultra Low NOx Burner	Low NOx Burner and Flue Gas Recirculation	Flue Gas Recirculation
10300601	External Combustion; Commercial/Institutional: Boilers; Natural Gas; > 100 Million BTU/hr	Ultra Low NOx Burner and Selective Catalytic Reduction	Low NOx Burner and Selective Non-Catalytic Reduction	Flue Gas Recirculation
10300602	External Combustion; Commercial/Institutional: Boilers; Natural Gas; 10-100 Million BTU/hr	Ultra Low NOx Burner and Selective Catalytic Reduction	Low NOx Burner and Selective Non-Catalytic Reduction	Flue Gas Recirculation
10300603	External Combustion; Commercial/Institutional: Boilers; Natural Gas; < 10 Million BTU/hr	Ultra Low NOx Burner and Selective Catalytic Reduction	Low NOx Burner and Selective Non-Catalytic Reduction	Flue Gas Recirculation
10500106	External Combustion; Space Heaters; Industrial; Natural Gas	Selective Catalytic Reduction	Low NOx Burner and Flue Gas Recirculation	Selective Non-Catalytic Reduction

[a] Control measure assignments for each SCC were based on EPA's Control Strategy Tool (CoST), version 3.7[33].

[b] Several EGU SCCs are included because large non-EGU facilities can have their own onsite power generation. These EGU boilers are typically included in the non-EGU inventory along with other sources.

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[33] Control Strategy Tool. https://www.epa.gov/economic-and-cost-analysis-air-pollution-regulations/cost-analysis-modelstools-air-pollution#control%20strategy%20tool, Accessed January 2021.

Gas-fired external combustion sources NOx emissions and emission reductions by LADCO state are presented in Table 5-5 and by LADCO NAA in Table 5-6. The number of units with 2016 NOx emissions is available in Appendix B.

State-level emission reductions differ under each APTE level indicating that potentially controlled sources have a range of NOx APTE from 10 tons/year to greater than 100 tons/year. 2016 NOx emissions from gas-fired external combustion sources are from Ohio (21%), Illinois (18%), Chicago, IN (18%), Wisconsin (15%), Michigan (15%), and Minnesota (14%); NOx emission reductions are generally distributed similarly across stringency scenarios and APTE levels. There are NOx emission reductions in all LADCO region NAAs except Door, WI.

Table 5-5. Statewide 2016 NOx emission reductions from gas-fired external combustion sources.[26] [34]

State	2016 NOx Emissions (tons/year)	2016 NOx Emission Reductions (tons/year)											
		APTE = 10 tons/year			APTE = 25 tons/year			APTE = 50 tons/year			APTE = 100 tons/year		
		Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
IL	5,800	1,405	2,552	70	878	1,597	37	609	1,107	26	424	733	-
MI	4,751	1,183	2,320	236	915	1,836	118	612	1,252	67	454	942	45
MN	4,466	1,055	1,928	260	755	1,361	229	549	987	185	296	537	135
OH	6,633	2,135	3,616	190	1,844	3,113	178	1,531	2,580	135	1,309	2,197	-
WI	4,776	1,219	2,106	557	887	1,536	396	689	1,192	324	447	776	243

Table 5-6. NOx emission reductions from gas-fired external combustion sources by NAA.[26] [28]

Non-Attainment Area	2016 NOx Emissions (tons/year)	2016 NOx Emission Reductions (tons/year)											
		APTE = 10 tons/year			APTE = 25 tons/year			APTE = 50 tons/year			APTE = 100 tons/year		
		Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
Allegan, MI	64	11	20	-	5	10	-	-	-	-	-	-	-
Berrien, MI	21	6	10	-	-	-	-	-	-	-	-	-	-
Chicago, IL	2,694	557	1,015	24	301	553	-	191	355	-	108	184	-
Chicago, IN	5,892	[a]	[a]	[a]	[a]	[a]	[a]	1,467	2,410	1,221	1,281	2,096	1,221
Chicago, WI	38	5	9	10	-	-	-	-	-	-	-	-	-
Cincinnati, OH	2,229	830	1,430	-	761	1,312	-	674	1,168	-	597	1,037	-
Cleveland, OH	593	152	254	22	95	158	16	36	62	-	-	-	-
Columbus, OH	302	57	105	27	32	61	21	22	39	21	-	-	-
Detroit, MI	1,700	476	800	167	336	562	82	155	257	45	107	175	45
Door, WI	1	-	-	-	-	-	-	-	-	-	-	-	-
Manitowoc County, WI	21	3	4	5	-	-	-	-	-	-	-	-	-
Muskegon, MI	53	10	17	-	6	10	-	-	-	-	-	-	-
Northern Milwaukee/Ozaukee, WI	726	170	294	44	140	243	25	140	243	-	140	243	-
Sheboygan, WI	36	6	11	-	-	-	-	-	-	-	-	-	-
St. Louis, IL	247	46	99	9	23	61	-	-	13	-	-	-	-

[a] APTE values of 10 tons/year and 25 tons/year are not applicable to Chicago, IN

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[34] Cells populated with "-" indicate zero NOx emissions in the inventory and thus no emission reductions.

5.5 Cost-effectiveness

Table 5-7 summarizes typical cost-effectiveness estimates for each control measure considered. Facility specific costs will vary based on raw material, fuel characteristics, equipment configuration, and other source specific factors. Table 5-8 and Table 5-9 show statewide cost and cost-effectiveness estimates, respectively. Table 5-10 and Table 5-11 show cost and cost-effectiveness estimates, respectively, by NAA.

Table 5-7. Typical cost-effectiveness for each control measure.

Stringency Level	Control Measure	Cost-effectiveness (2020$/ton)	Reference
High	Selective Catalytic Reduction	1,657 or 10,957 [a]	EPA CoST[27]
Medium	Low NOx Burner and Flue Gas Recirculation	7,532, 14,163 or 26,449 [b]; or 5,069 [c]	EPA CoST[27]
	Low NOx Burner and Selective Non-Catalytic Reduction	6,918, 12,366 or 22,403 [d]	EPA CoST[27]
Low	Flue Gas Recirculation	6,776, 12,752 or 23,906 [e]	EPA CoST[27]
	Selective Non-Catalytic Reduction	10,239	EPA CoST[27]

[a] The cost-effectiveness is $1,657/ton for Selective Catalytic Reduction - Utility Boiler - Oil-Gas/Tangential. The cost-effectiveness is $10,957/ton for Selective Catalytic Reduction - ICI Boilers - Gas.

[b] The cost-effectiveness is $26,449/ton for sources with an emission rate less than 50 tons/year; $14,163 for sources with an emission rate between 50 and 100 tons/year; $7,532 for sources with an emission rate higher than 100 tons/year for Low NOx Burner and Flue Gas Recirculation - ICI Boilers - Process Gas.

[c] The cost-effectiveness is $5,069/ton for Low NOx Burner and Flue Gas Recirculation - Space Heaters - Natural Gas.

[d] The cost-effectiveness is $22,403/ton for sources with an emission rate less than 50 tons/year; $12,366 for sources with an emission rate between 50 and 100 tons/year; $6,918 for sources with an emission rate higher than 100 tons/year.

[e] The cost-effectiveness is $23,906/ton for sources with an emission rate less than 50 tons/year; $12,752 for sources with an emission rate between 50 and 100 tons/year; $6,776 for sources with an emission rate higher than 100 tons/year.

Table 5-8. Statewide total cost of gas-fired external combustion sources emissions reduction.[26] [35]

State	Total Cost (thousands of 2020$)											
	APTE = 10 tons/year			APTE = 25 tons/year			APTE = 50 tons/year			APTE = 100 tons/year		
	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
IL	27,698	47,839	562	15,261	26,696	303	8,834	15,716	285	4,599	7,832	-
MI	20,428	36,897	2,382	14,831	27,401	1,166	7,836	14,467	738	4,341	8,336	495
MN	21,170	36,538	431	14,015	23,807	379	9,072	15,431	307	3,042	5,350	223
OH	29,230	48,872	519	22,315	37,528	443	14,945	25,414	223	9,645	16,767	-
WI	22,662	36,981	1,437	14,935	24,547	910	10,195	16,828	791	4,593	7,850	402

Table 5-9. Statewide cost-effectiveness of gas-fired external combustion sources emissions reduction.[26] [29]

State	Cost-effectiveness (2020$/ton)											
	APTE = 10 tons/year			APTE = 25 tons/year			APTE = 50 tons/year			APTE = 100 tons/year		
	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
IL	19,712	18,742	8,021	17,377	16,719	8,232	14,497	14,202	10,957	10,837	10,686	-

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[35] Cells populated with "-" indicate zero NOx emissions in the inventory and thus no associated cost or cost-effectiveness.

MI	17,273	15,907	10,114	16,203	14,926	9,893	12,815	11,552	10,957	9,568	8,845	10,957
MN	20,072	18,949	1,657	18,554	17,497	1,657	16,536	15,639	1,657	10,263	9,968	1,657
OH	13,690	13,516	2,727	12,100	12,055	2,491	9,761	9,851	1,657	7,366	7,631	-
WI	18,589	17,557	2,580	16,829	15,980	2,299	14,793	14,122	2,442	10,285	10,117	1,657

Table 5-10. Cost of gas-fired external combustion sources emissions reduction by NAA.[26] [29]

Non-Attainment Area	Total Cost (thousands of 2020$)											
	APTE = 10 tons/year			APTE = 25 tons/year			APTE = 50 tons/year			APTE = 100 tons/year		
	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
Allegan, MI	274	445	-	131	214	-	-	-	-	-	-	-
Berrien, MI	132	216	-	-	-	-	-	-	-	-	-	-
Chicago, IL	12,017	20,799	158	5,984	10,601	-	3,350	6,165	-	1,383	2,332	-
Chicago, IN	[a]	[a]	[a]	[a]	[a]	[a]	13,864	23,715	2,023	9,400	16,377	2,023
Chicago, WI	129	210	16	-	-	-	-	-	-	-	-	-
Cincinnati, OH	9,833	16,667	-	8,182	13,964	-	6,103	10,534	-	4,270	7,532	-
Cleveland, OH	3,520	5,693	185	2,166	3,471	175	854	1,391	-	-	-	-
Columbus, OH	1,310	2,300	99	774	1,374	34	538	876	34	-	-	-
Detroit, MI	9,315	14,922	1,755	6,505	10,531	901	2,457	3,840	495	1,298	1,937	495
Door, WI	-	-	-	-	-	-	-	-	-	-	-	-
Manitowoc County, WI	27	18	55	-	-	-	-	-	-	-	-	-
Muskegon, MI	230	374	-	137	222	-	-	-	-	-	-	-
Northern Milwaukee/Ozaukee, WI	1,627	2,764	115	948	1,682	42	948	1,682	-	948	1,682	-
Sheboygan, WI	151	246	-	-	-	-	-	-	-	-	-	-
St. Louis, IL	1,023	2,107	101	545	1,376	-	-	284	-	-	-	-

[a] APTE values of 10 tons/year and 25 tons/year are not applicable to Chicago, IN

Table 5-11. Cost-effectiveness of gas-fired external combustion sources emissions reduction by NAA.[26] [29]

Non-Attainment Area	Cost-effectiveness (2020$/ton)											
	APTE = 10 tons/year			APTE = 25 tons/year			APTE = 50 tons/year			APTE = 100 tons/year		
	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
Allegan, MI	23,906	22,403	-	23,906	22,403	-	-	-	-	-	-	-
Berrien, MI	23,906	22,403	-	-	-	-	-	-	-	-	-	-
Chicago, IL	21,569	20,485	6,575	19,886	19,163	-	17,564	17,357	-	12,752	12,667	-
Chicago, IN	[a]	[a]	[a]	[a]	[a]	[a]	9,447	9,842	1,657	7,340	7,814	1,657
Chicago, WI	23,906	22,403	1,657	-	-	-	-	-	-	-	-	-
Cincinnati, OH	11,851	11,654	-	10,756	10,641	-	9,059	9,018	-	7,152	7,260	-
Cleveland, OH	23,146	22,406	8,316	22,695	21,961	10,957	23,906	22,403	-	-	-	-
Columbus, OH	23,149	21,893	3,723	23,906	22,403	1,657	23,906	22,403	1,657	-	-	-
Detroit, MI	19,555	18,656	10,519	19,387	18,742	10,957	15,852	14,937	10,957	12,188	11,041	10,957
Door, WI	-	-	-	-	-	-	-	-	-	-	-	-
Manitowoc County, WI	10,239	5,069	10,957	-	-	-	-	-	-	-	-	-
Muskegon, MI	23,906	22,403	-	23,906	22,403	-	-	-	-	-	-	-
Northern Milwaukee/Ozaukee, WI	9,590	9,406	2,593	6,776	6,918	1,657	6,776	6,918	-	6,776	6,918	-
Sheboygan, WI	23,906	22,403	-	-	-	-	-	-	-	-	-	-
St. Louis, IL	22,446	21,267	10,957	23,906	22,403	-	-	22,403	-	-	-	-

[a] APTE values of 10 tons/year and 25 tons/year are not applicable to Chicago, IN

5.6 Geographic Applicability

NOx emission reductions for gas-fired external combustion sources can only be achieved in the counties and states in which these sources are located. According to EPA's 2016v1 emission inventory, gas-fired external combustion source emissions are widespread, occurring in all LADCO states and NAAs.

5.7 Responsible Agency

The state air agency is responsible for enforcing SIP-approved and other air permitting rules. Applicable natural gas-fired external combustion emissions in the LADCO area are from sources in EPA's 2016v1 emission inventory with a wide range of APTE from 10 tons/year to greater than over 100 tons/year. Sources with APTE over 100 tons/year are expected to be subject to Title V permit requirements; sources not subject to Title V thresholds may be permitted under state permit requirements.

5.8 Implementation Schedule

After a new rule is promulgated, facilities are typically given time to comply with the new rule for planning, analysis, and infrastructure changes necessary to comply. The timeline for existing sources to comply with MACT standards is typically 3-years, but timelines for compliance typically vary from 1-4 years. Assuming that rules to limit natural gas-fire external combustion source emissions are adopted in late-2023, and assuming a 2-year period from rule promulgation to controls installation, emission reduction would be achieved by 2026. Depending on regulatory requirements, a more aggressive or less aggressive timeline may be required in rulemakings.

5.9 Implementation Feasibility

There are several regulatory programs which limit gas-fired external combustion source emissions. Emission requirements are typically expressed in units of mass of NOx emitted per unit of energy input, for example in the New Source Performance Standard for Industrial-Commercial-Institutional Steam Generating Units[36]. Several agencies have promulgated regulations to limit NOx emissions from boilers, for example, Texas Commission on Environmental Quality (30 TAC Chapter 117, Subchapter B)[37] and the South Coast Air Quality Management District (Rule 1146: Emissions of Oxides of Nitrogen from Industrial, Institutional and Commercial Boilers, Steam Generators, and Process Heaters)[38].

To develop an emission control regulation for gas-fired external combustion sources, an assessment facility-level assessment may be necessary as facility specific conditions (boiler type, fuels, and existing equipment configurations) will determine the feasibility and cost of controls.

5.10 Public Acceptance

Gas-fired external combustion sources can produce substantial emissions of NOx and other pollutants. Several gas-fired external combustion source control measures evaluated herein are very cost-effective, and therefore can be shown to be a good regional emission reductions strategy. Gas-fired external combustion source operators may object to any further regulation of their operations, especially for the more costly control measures. Grant funding can be used to facilitate implementation of control measures.

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[36] https://www.epa.gov/stationary-sources-air-pollution/portland-cement-plants-new-source-performance-standards-nsps, accessed in January, 2022

[37] http://texreg.sos.state.tx.us/public/readtac%24ext.ViewTAC?tac_view=5&ti=30&pt=1&ch=117&sch=B, accessed in January, 2022

[38] http://www.aqmd.gov/docs/default-source/rule-book/reg-xi/rule-1146.pdf?sfvrsn=4, accessed in January, 2022

5.11 All Controls Results

Analysis in the sections above includes the controls considered under low, medium, and high stringency scenarios, as indicated in Table 5-4 (i.e., those controls not highlighted in grey on Table 5-4). Emission reduction estimates across the full suite of stringency scenario and control combinations are presented in Appendix A, Tables A1 to A2.

6.0 GLASS SOURCES

6.1 Summary

This section focuses on emissions reductions for glass manufacturing sources. Melting furnaces are the main source of NOx emissions in the glass manufacturing process and are the subject of this section. Table 6-1 summarizes key information for glass sources control measures evaluated herein. Applicable emissions, emission reductions, and cost-effectiveness are presented in Table 6-1 on a LADCO region-wide basis. State- and NAA-level emissions, emission reductions, and cost-effectiveness are presented in subsections below. Emission reductions across all control measures (i.e., including control measures not selected for evaluation in this white paper) are provided in Appendix A.

Table 6-1. Control measure summary for glass sources.[39]

2016 Emissions Estimates					
2016 Emissions [a]	NOx:	10,312 tons/year			
Control Measure Summary, Including 2016 Emission Reduction Estimates					
		APTE = 10 tons/year	**APTE = 25 tons/year**	**APTE = 50 tons/year**	**APTE = 100 tons/year**
Selective Catalytic Reduction (High Stringency Scenario)	NOx Reduction:	2,256 tons/year	2,250 tons/year		2,152 tons/year
	Cost-effectiveness:	*$2,102 or $2,707/ton [b]; or $5,010/ton [c]*			
	Applicable States:	*IL, MN, OH*			
	Applicable NAAs:	*Chicago, IL; Columbus, OH*			
Oxygen Enriched Air Staging (Medium Stringency Scenario)	NOx Reduction:	5,699 tons/year	5,693 tons/year		5,572 tons/year
	Cost-effectiveness:	*$842/ton*			
	Applicable States:	*IL, MI, MN, OH, WI*			
	Applicable NAAs:	*Chicago, IL; Columbus, OH; Detroit, MI*			
Low NOx Burner (Low Stringency Scenario)	NOx Reduction:	1,203 tons/year	1,200 tons/year		1,148 tons/year
	Cost-effectiveness:	*$1,338 or $1,704/ton [d]; or $2,970/ton [e]*			
	Applicable States:	*IL, MN, OH*			
	Applicable NAAs:	*Chicago, IL; Columbus, OH*			

[a] Source: US Environmental Protection Agency (EPA) 2016v1 modeling platform. Available at https://www.epa.gov/air-emissions-modeling/2016v1-platform, accessed in June 2021.
[b] The cost-effectiveness is $2,707/ton for sources with an emission rate less than 365 tons/year; $2,102/ton for sources with an emission rate higher than 365 tons/year for Selective Catalytic Reduction - Glass Manufacturing – Container.
[c] The cost-effectiveness is $5,010/ton for Selective Catalytic Reduction - Glass Manufacturing - Pressed.
[d] The cost-effectiveness is $1,704/ton for sources with an emission rate less than 365 tons/year; $1,338/ton for sources with an emission rate higher than 365 tons/year for Low NOx Burner - Glass Manufacturing – Container.
[e] The cost-effectiveness is $2,970/ton for Low NOx Burner - Glass Manufacturing - Pressed.

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[39] Excludes Indiana emissions except for in Chicago, Indiana nonattainment area counties (Lake County and Porter County).

6.2 Source Description

Glass is produced when sand, limestone, and soda ash are crushed, mixed, and melted in a furnace (EPA, 1995). In a melting furnace, raw materials for glass production are fed into a furnace and heated. The furnace has either side or end ports that connect brick checkers to the inside of the melter. Checkers collect furnace exhaust gas heat. When the air flow is reversed, this heat is used to preheat the furnace combustion air. As the new material melts, it is passed through the throat of the burner into a refiner where the glass is heat conditioned to prepare it for the forming process. Container glass, flat glass, and pressed and blown glass are products of glass manufacturing. The difference between these products lies in the forming and finishing processes. Container glass is composed of 51% soda-lime and pressing and/or blowing are used to create the final product. Pressed and blown glass are created the same way, but the glass is composed of 25% soda-lime. Flat glass is formed by rolling, floating, or drawing the glass. Pressing and blowing involved the use of molds to form gobs of glass. Rolling involves moving the glass across rollers that are either flat or patterned. Drawing involved pulling glass up through rollers.

The main pollutants emitted in glass production are PM, SO_2, and NOx from combustion in the furnace. NOx can form in the high furnace temperatures, and SO_2 is formed from the decomposition of the sulfates in the batch and the sulfur in the fuel. PM results from the volatilization of the materials in the melt and the mixing of the materials in the melt with other gases. These pollutants are collected in the checker and gas passages.

Table 6-2 lists the applicable SCCs for glass sources in the LADCO stationary point source inventory.

Table 6-2. Applicable SCCs for glass sources.

Description One	Description Two	Description Three	Description Four	SCC
Industrial Processes	Mineral Products	Glass Manufacture	Container Glass: Melting Furnace	30501402
			Flat Glass: Melting Furnace	30501403
			Pressed and Blown Glass: Melting Furnace	30501404

6.3 Selected Control Measures Description

For glass sources, specific control measures were considered for each stringency level. The selected control measures and their estimated control efficiency are shown in Table 6-3. Descriptions of each control measure are included in the subsections below.

Table 6-3. Applicable control technology and associated control efficiency by stringency level.

Stringency Level	Control Measure	Control Efficiency (%)
High	Selective Catalytic Reduction	75
Medium	Oxygen Enriched Air Staging	65
Low	Low NOx Burner	40

6.3.1 Selective Catalytic Reduction

SCR is a post-combustion control technology. An SCR emission control system uses a catalyst, typically ammonia or urea, to selectively reduce NOx emissions from exhaust gases (EPA, 2007). NOx is chemically reduced into molecular N_2 and water vapor. The catalyst is not consumed but allows the reactions to occur at a lower temperature.

The SCR system can be installed at different locations including upstream of an air heater and particulate control device, or downstream of the air heater, particulate control device, and flue gas desulfurization systems.

6.3.2 Oxygen Enriched Air Staging

In glass furnaces that utilize atmospheric air combustion, inert nitrogen dilutes reactive oxygen and carries away energy in hot combusted gas exiting the furnace. Increasing oxygen in combustion air can reduce energy loss, increase heating efficiency and decrease NOx emissions (DOE, 2005). Oxygen enriched air staging can result in higher combustion temperatures, enhancing heat transfer from fuel to feedstock thereby allowing for increased furnace throughput. Oxygen enriched air staging has been shown to have economical applications and can be applied as a retrofit to existing glass furnaces.

6.3.3 Low NOx Burner

Low NOx burners spread combustion over multiple stages allowing for control of both stoichiometric and temperature profiles during combustion (EPA, 1994). Emission reductions are achieved by one or more of the following:

- Reducing oxygen content in the combustion zone, limiting fuel NOx formation;
- Reducing flame temperature, limiting thermal NOx formation;
- Reducing residence time at peak temperature, limiting thermal NOx formation;

Low NOx burners may be designed to delay the combustion process resulting in a cooler flame thereby suppressing thermal NOx or to create stratified fuel-rich and fuel-lean regions in or near the burner. In fuel-rich regions, fuel NOx formation is reduced; in fuel-lean regions, thermal NOx formation is reduced.

6.4 NOx Emission Reductions

Table 6-4 shows the control measures that were implemented for each SCC and stringency level. Existing (as of 2016) NOx controls were accounted for in the analysis; potential emission reductions were calculated as incremental reductions from the existing controls. Existing NOx controls were identified based on “Control ID” in the 2016v1 modeling platform files. If the existing control efficiency was higher than the selected control measure for a unit, no emission reduction or cost was calculated. If the existing control efficiency was lower than the selected control measure, the surplus emission reduction and associated cost are calculated.

Estimated emission reductions are uncertain because 1) information on existing controls is unlikely to be comprehensive and 2) feasibility and emission reduction potential depends on site-specific conditions such as raw materials and fuels used and existing equipment configurations. Emission reductions can be more accurately estimated based on individual facility specific feasibility and emission control analysis. This analysis is a source category-level evaluation; therefore, facility specific analysis is not included.

Table 6-4. Glass sources control measure applied to each SCC.

SCC	SCC Description	Stringency Level (Control technologies highlighted in grey were assessed in prior tasks but are not evaluated in this white paper) [a]		
		High	Medium	Low
30501402	Industrial Processes; Mineral Products; Glass Manufacture; Container Glass: Melting Furnace	Selective Catalytic Reduction	Oxygen Enriched Air Staging	Low NOx Burner
30501403	Industrial Processes; Mineral Products; Glass Manufacture; Flat Glass: Melting Furnace	Catalytic Ceramic Filter	Oxygen Enriched Air Staging	Electric Boost
30501404	Industrial Processes; Mineral Products; Glass Manufacture; Pressed and Blown Glass: Melting Furnace	Selective Catalytic Reduction	Oxygen Enriched Air Staging	Low NOx Burner

[a] Control measure assignments for each SCC were based on EPA's Control Strategy Tool (CoST), version 3.7[40].

Glass sources NOx emissions and emission reductions by LADCO state are presented in Table 6-5 and by LADCO NAA in Table 6-6. The number of units with 2016 NOx emissions is available in Appendix B.

Illinois, Minnesota, and Ohio state-level emission reductions are similar across APTE levels of indicating that most emission sources have greater than 100 tpy APTE. 2016 NOx emissions from glass sources are from Illinois (32%), Wisconsin (30%), Ohio (21%), Michigan (10%), and Minnesota (6%). There are no emission reductions for Michigan or Wisconsin under the low and high scenario. For Michigan, all facilities fall under SCC 30501403 and therefore were not evaluated under low and high scenarios (see Table 6-4). In Wisconsin, emissions under SCC 30501403 were not evaluated under low and high scenarios (see Table 6-4) and emissions under SCC 30501402 were not evaluated because these sources all indicated a higher control efficiency than the selected control technology. For states and stringency scenarios with NOx emission reductions, those NOx emission reductions are distributed similarly across stringency scenarios and APTE levels. There are NOx emission reductions in three NAAs, Chicago, IL; Columbus, OH; and Detroit, MI.

6.5 Cost-effectiveness

Table 6-7 summarizes typical cost-effectiveness estimates for each control measure considered. Facility specific costs will vary based on raw material, fuel characteristics, equipment configuration, and other source specific factors. Table 6-8 and Table 6-9 show statewide cost and cost-effectiveness estimates, respectively. Table 6-10 and Table 6-11 show cost and cost-effectiveness estimates, respectively, by NAA.

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[40] Control Strategy Tool. https://www.epa.gov/economic-and-cost-analysis-air-pollution-regulations/cost-analysis-modelstools-air-pollution#control%20strategy%20tool, Accessed January 2021.

Table 6-5. Statewide 2016 NOx emission reductions from glass sources.[26] [41]

State	2016 NOx Emissions (tons/year)	2016 NOx Emission Reductions (tons/year)											
		APTE = 10 tons/year			APTE = 25 tons/year			APTE = 50 tons/year			APTE = 100 tons/year		
		Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
IL	3,345	427	2,174	800	427	2,174	800	427	2,174	800	375	2,090	702
MI	1,005	-	419	-	-	419	-	-	419	-	-	382	-
MN	662	265	430	496	265	430	496	265	430	496	265	430	496
OH	2,195	512	1,426	960	508	1,421	953	508	1,421	953	508	1,421	953
WI	3,105	-	1,250	-	-	1,250	-	-	1,250	-	-	1,250	-

Table 6-6. NOx emission reductions from glass sources by NAA.[26] [28]

Non-Attainment Area	2016 NOx Emissions (tons/year)	2016 NOx Emission Reductions (tons/year)											
		APTE = 10 tons/year			APTE = 25 tons/year			APTE = 50 tons/year			APTE = 100 tons/year		
		Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
Allegan, MI	-	-	-	-	-	-	-	-	-	-	-	-	-
Berrien, MI	-	-	-	-	-	-	-	-	-	-	-	-	-
Chicago, IL	190	76	123	142	76	123	142	76	123	142	24	39	45
Chicago, IN	-	[a]	[a]	[a]	[a]	[a]	[a]	-	-	-	-	-	-
Chicago, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
Cincinnati, OH	<1	-	-	-	-	-	-	-	-	-	-	-	-
Cleveland, OH	-	-	-	-	-	-	-	-	-	-	-	-	-
Columbus, OH	542	217	352	406	217	352	406	217	352	406	217	352	406
Detroit, MI	1,005	-	419	-	-	419	-	-	419	-	-	382	-
Door, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
Manitowoc County, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
Muskegon, MI	-	-	-	-	-	-	-	-	-	-	-	-	-
Northern Milwaukee/Ozaukee, WI	106	-	-	-	-	-	-	-	-	-	-	-	-
Sheboygan, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
St. Louis, IL	-	-	-	-	-	-	-	-	-	-	-	-	-

[a] APTE values of 10 tons/year and 25 tons/year are not applicable to Chicago, IN

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[41] Cells populated with “-“ indicate zero NOx emissions in the inventory and thus no emission reductions.

Table 6-7. Typical cost-effectiveness for each control measure.

Stringency Level	Control Measure	Cost-effectiveness (2020$/ton)	Reference
High	Selective Catalytic Reduction	2,102 or 2,707 [a]; or 5,010 [b]	EPA CoST[27]
Medium	Oxygen Enriched Air Staging	842	EPA CoST[27]
Low	Low NOx Burner	1,338 or 1,704 [c]; or 2,970 [d]	EPA CoST[27]

[a] The cost-effectiveness is $2,707/ton for sources with an emission rate less than 365 tons/year; $2,102/ton for sources with an emission rate higher than 365 tons/year for Selective Catalytic Reduction - Glass Manufacturing – Container.
[b] The cost-effectiveness is $5,010/ton for Selective Catalytic Reduction - Glass Manufacturing - Pressed.
[c] The cost-effectiveness is $1,704/ton for sources with an emission rate less than 365 tons/year; $1,338/ton for sources with an emission rate higher than 365 tons/year for Low NOx Burner - Glass Manufacturing – Container.
[d] The cost-effectiveness is $2,970/ton for Low NOx Burner - Glass Manufacturing - Pressed.

Table 6-8. Statewide total cost of gas-fired external combustion sources emissions reduction.[26] [42]

State	Total Cost (thousands of 2020$)											
	APTE = 10 tons/year			APTE = 25 tons/year			APTE = 50 tons/year			APTE = 100 tons/year		
	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
IL	678	1,830	2,019	678	1,830	2,019	678	1,830	2,019	575	1,759	1,705
MI	-	352	-	-	352	-	-	352	-	-	322	-
MN	451	362	1,344	451	362	1,344	451	362	1,344	451	362	1,344
OH	1,361	1,201	4,264	1,350	1,196	4,230	1,350	1,196	4,230	1,350	1,196	4,230
WI	-	1,052	-	-	1,052	-	-	1,052	-	-	1,052	-

Table 6-9. Statewide cost-effectiveness of gas-fired external combustion sources emissions reduction.[26] [29]

State	Cost-effectiveness (2020$/ton)											
	APTE = 10 tons/year			APTE = 25 tons/year			APTE = 50 tons/year			APTE = 100 tons/year		
	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
IL	1,589	842	2,523	1,589	842	2,523	1,589	842	2,523	1,534	842	2,427
MI	-	842	-	-	842	-	-	842	-	-	842	-
MN	1,704	842	2,707	1,704	842	2,707	1,704	842	2,707	1,704	842	2,707
OH	2,658	842	4,442	2,656	842	4,438	2,656	842	4,438	2,656	842	4,438
WI	-	842	-	-	842	-	-	842	-	-	842	-

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[42] Cells populated with "-" indicate zero NOx emissions in the inventory and thus no associated cost or cost-effectiveness.

Table 6-10. Cost of gas-fired external combustion sources emissions reduction by NAA.[26] [29]

Non-Attainment Area	Total Cost (thousands of 2020$)											
	APTE = 10 tons/year			APTE = 25 tons/year			APTE = 50 tons/year			APTE = 100 tons/year		
	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
Allegan, MI	-	-	-	-	-	-	-	-	-	-	-	-
Berrien, MI	-	-	-	-	-	-	-	-	-	-	-	-
Chicago, IL	144	104	435	144	104	435	144	104	435	41	33	121
Chicago, IN	[a]	[a]	[a]	[a]	[a]	[a]	-	-	-	-	-	-
Chicago, WI	-	-	-	-	-	-	-	-	-	-	-	-
Cincinnati, OH	-	-	-	-	-	-	-	-	-	-	-	-
Cleveland, OH	-	-	-	-	-	-	-	-	-	-	-	-
Columbus, OH	644	296	2,035	644	296	2,035	644	296	2,035	644	296	2,035
Detroit, MI	-	352	-	-	352	-	-	352	-	-	322	-
Door, WI	-	-	-	-	-	-	-	-	-	-	-	-
Manitowoc County, WI	-	-	-	-	-	-	-	-	-	-	-	-
Muskegon, MI	-	-	-	-	-	-	-	-	-	-	-	-
Northern Milwaukee/Ozaukee, WI	-	-	-	-	-	-	-	-	-	-	-	-
Sheboygan, WI	-	-	-	-	-	-	-	-	-	-	-	-
St. Louis, IL	-	-	-	-	-	-	-	-	-	-	-	-

[a] APTE values of 10 tons/year and 25 tons/year are not applicable to Chicago, IN

Table 6-11. Cost-effectiveness of gas-fired external combustion sources emissions reduction by NAA.[26] [29]

Non-Attainment Area	Cost-effectiveness (2020$/ton)											
	APTE = 10 tons/year			APTE = 25 tons/year			APTE = 50 tons/year			APTE = 100 tons/year		
	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
Allegan, MI	-	-	-	-	-	-	-	-	-	-	-	-
Berrien, MI	-	-	-	-	-	-	-	-	-	-	-	-
Chicago, IL	1,895	842	3,056	1,895	842	3,056	1,895	842	3,056	1,704	842	2,707
Chicago, IN	[a]	[a]	[a]	[a]	[a]	[a]	-	-	-	-	-	-
Chicago, WI	-	-	-	-	-	-	-	-	-	-	-	-
Cincinnati, OH	-	-	-	-	-	-	-	-	-	-	-	-
Cleveland, OH	-	-	-	-	-	-	-	-	-	-	-	-
Columbus, OH	2,970	842	5,010	2,970	842	5,010	2,970	842	5,010	2,970	842	5,010
Detroit, MI	-	842	-	-	842	-	-	842	-	-	842	-
Door, WI	-	-	-	-	-	-	-	-	-	-	-	-
Manitowoc County, WI	-	-	-	-	-	-	-	-	-	-	-	-
Muskegon, MI	-	-	-	-	-	-	-	-	-	-	-	-
Northern Milwaukee/Ozaukee, WI	-	-	-	-	-	-	-	-	-	-	-	-
Sheboygan, WI	-	-	-	-	-	-	-	-	-	-	-	-
St. Louis, IL	-	-	-	-	-	-	-	-	-	-	-	-

[a] APTE values of 10 tons/year and 25 tons/year are not applicable to Chicago, IN

6.6 Geographic Applicability

NOx emission reductions for glass manufacturing can only be achieved in the counties and states in which glass manufacturing facilities are located. According to EPA's 2016v1 emission inventory, glass manufacturing emissions occurred in Illinois, Michigan, Minnesota, Ohio, and Wisconsin. NOx emission reductions were limited to Chicago, IL; Columbus, OH; and Detroit, MI; other NAAs that have glass manufacturing facilities either do not have NOx emissions greater than APTE thresholds and/or NOx emissions are from units for which existing controls have a higher control efficiency than the selected control measures.

6.7 Responsible Agency

The state air agency is responsible for enforcing SIP-approved and other air permitting rules. Applicable glass manufacturing emission sources in the LADCO area generally have APTE greater than 50 tons/year, and most emissions are from sources with APTE greater than 100 tons/year. Sources with APTE over 100 tons/year are expected to be subject to Title V permit requirements; sources not subject to Title V thresholds may be permitted under state permit requirements.

6.8 Implementation Schedule

After a new rule is promulgated, facilities are typically given time to comply with the new rule for planning, analysis, and infrastructure changes necessary to comply. The timeline for existing sources to comply with MACT standards is typically 3-years, but timelines for compliance typically vary from 1-4 years. Assuming that rules to limit glass manufacturing source emissions are adopted in late-2023, and assuming a 2-year period from rule promulgation to controls installation, emission reduction would be achieved by 2026. Depending on regulatory requirements, a more aggressive or less aggressive timeline may be required in rulemakings.

6.9 Implementation Feasibility

There are several regulatory programs which limit glass manufacturing emissions (examples are listed below). Emission requirements may be expressed in mass of NOx emitted per mass of product.

- New Source Performance Standard for Glass Manufacturing Plants (NSPS Subpart CC)[43]
- South Coast Air Quality Management District, Rule 1117: Emissions of Oxides of Nitrogen from Glass Melting Furnaces[44]
- Bay Area Air Quality Management District, Regulation 9 Rule 12: Nitrogen Oxides From Glass Melting Furnaces[45]

To develop an emission control regulation for glass manufacturing, a facility-level assessment will likely be necessary as facility specific conditions (raw materials, fuels, and existing equipment configurations) will determine the feasibility and cost of controls.

6.10 Public Acceptance

Glass manufacturing facilities can produce substantial emissions of NOx and other pollutants. Glass manufacturing source control measures evaluated herein are very cost-effective and therefore can be shown to be a good regional emission reductions strategy. Glass manufacturing facility operators may object to any further regulation of their operations. Grant funding can be used to facilitate implementation of control measures.

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[43] https://www.epa.gov/stationary-sources-air-pollution/glass-manufacturing-plants-new-source-performance-standards-nsps, accessed in January, 2022

[44] http://www.aqmd.gov/docs/default-source/rule-book/reg-xi/rule-1117.pdf?sfvrsn=4, accessed in January, 2022

[45] https://www.baaqmd.gov/~/media/dotgov/files/rules/reg-9-rule-12-nitrogen-oxides-from-glass-melting-furnaces/documents/rg0912.pdf?la=en&rev=29e7064c0e39439c9dee09b104af8dff, accessed in January, 2022

6.11 All Controls Results

Analysis in the sections above includes the controls considered under low, medium, and high stringency scenarios, as indicated in Table 6-4 (i.e., those controls not highlighted in grey on Table 6-4). Emission reduction estimates across the full suite of stringency scenario and control combinations are presented in Appendix A, Tables A1 to A2.

7.0 DIESEL-FIRED INTERNAL COMBUSTION ENGINES

7.1 Summary

This section focuses on emissions reductions for diesel-fired internal combustion engines (ICEs). Diesel-fired ICEs are used in stationary source applications, primarily to generate electricity. Table 7-1 summarizes key information for diesel-fired internal combustion engines control measures evaluated herein. Applicable emissions, emission reductions, and cost-effectiveness are presented in Table 7-1 on a LADCO region-wide basis. State- and NAA-level emissions, emission reductions, and cost-effectiveness are presented in subsections below. Emission reductions across all control measures (i.e., including control measures not selected for evaluation in this white paper) are provided in Appendix A.

Table 7-1. Control measure summary for diesel-fired internal combustion engines.[46]

2016 Emissions Estimates					
2016 Emissions [a]	NOx:	4,750 tons/year			
Control Measure Summary, Including 2016 Emission Reduction Estimates					
		APTE = 10 tons/year	**APTE = 25 tons/year**	**APTE = 50 tons/year**	**APTE = 100 tons/year**
Selective Catalytic Reduction (High Stringency Scenario)	NOx Reduction:	1,716 tons/year	1,232 tons/year	940 tons/year	602 tons/year
	Cost-effectiveness:	*$12,324 or $4,634/ton* [b]			
	Applicable States:	*IL, MI, MN, OH, WI*			*MI, MN, OH*
	Applicable NAAs:	*Chicago, IL; Cleveland, OH; Detroit, MI; Manitowoc County, WI; Muskegon, MI; Northern Milwaukee/Ozaukee, WI; St. Louis, IL*	*Chicago, IL; Cleveland, OH; Detroit, MI; Manitowoc County, WI; Muskegon, MI; Northern Milwaukee/Ozaukee, WI*	*Chicago, IL; Cleveland, OH; Detroit, MI; Manitowoc County, WI*	*Cleveland, OH*
Ignition Retard (Medium/Low Stringency Scenario)	NOx Reduction:	755 tons/year	590 tons/year	468 tons/year	375 tons/year
	Cost-effectiveness:	*$970 or $1,525/ton* [c]			
	Applicable States:	*IL, MI, MN, OH, WI*			*MI, MN, OH*
	Applicable NAAs:	*Berrien, MI; Chicago, IL; Cleveland, OH; Detroit, MI; Manitowoc County, WI; Muskegon, MI; Northern Milwaukee/Ozaukee, WI; St. Louis, IL*	*Chicago, IL; Cleveland, OH; Detroit, MI; Manitowoc County, WI; Muskegon, MI; Northern Milwaukee/Ozaukee, WI*	*Chicago, IL; Cleveland, OH; Detroit, MI; Manitowoc County, WI*	*Cleveland, OH; Detroit, MI*

[a] Source: US Environmental Protection Agency (EPA) 2016v1 modeling platform. Available at https://www.epa.gov/air-emissions-modeling/2016v1-platform, accessed in June 2021.

[b] The cost-effectiveness is $12,324/ton for Selective Catalytic Reduction - ICE - Diesel. The cost-effectiveness is $4,634/ton for Selective Catalytic Reduction - Internal Combustion Engines - Oil.

[c] The cost-effectiveness is $1,525/ton for sources with an emission rate less than 365 tons/year; $970 for sources with an emission rate higher than 365 tons/year.

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[46] Excludes Indiana emissions except for in Chicago, Indiana nonattainment area counties (Lake County and Porter County).

7.2 Source Description

Internal combustion (IC) engines can be fueled by diesel, gasoline, or natural gas. Diesel is the most versatile fuel, being usable for engines of all sizes (EPA, 1995). In a reciprocating IC engine, the fuel is compressed in a small volume and ignited, creating pressure that pushes pistons through its cylinder.

There are two types of ignition used for IC engines; compression ignition (CI) and spark ignition (SI). All diesel powered IC engines use CI. In CI, air is heated in the cylinder and diesel fuel is pumped into the heated cylinder, igniting spontaneously. The compression ratio, the ratio of cylinder volume at the bottom of its stroke to the full cylinder volume, is higher in CI engines because fuel is not introduced until after compression. As a result, there is no danger of premature autoignition.

Emissions from IC engines mostly come from the exhaust (NO_x, organic compounds (OC), CO, and PM) with some additional pollution coming from organic compounds released from the oil pan, and from the fuel tank and carburetor through evaporation. Since diesel fuels have low volatility, evaporative losses are minimal.

Table 7-2 lists the applicable SCCs for diesel-fired internal combustion sources in the LADCO stationary point source inventory.

Table 7-2. Applicable SCCs for Diesel-fired Internal Combustion Engines (ICE Diesel).

Description One	Description Two	Description Three	Description Four	SCC
Internal Combustion Engines	Electric Generation	Distillate Oil (Diesel)	Reciprocating	20100102
			Reciprocating: Exhaust	20100107
	Industrial		Reciprocating	20200102
			Turbine: Cogeneration	20200103
			Reciprocating: Cogeneration	20200104
		Other Fuels	Diesel: Large Bore Engine	20200401
			Dual Fuel (Oil/Gas): Large Bore Engine	20200402
	Commercial/Institutional	Distillate Oil (Diesel)	Reciprocating	20300101
	Engine Testing	Reciprocating Engine	Diesel/Kerosene	20400402
			Distillate Oil	20400403

7.3 Selected Control Measures Description

For diesel-fired internal combustion engines, specific control measures were considered for each stringency level. The selected control measures and their estimated control efficiency are shown in Table 7-3. Descriptions of each control measure are included in the subsections below.

Table 7-3. Applicable control technology and associated control efficiency by stringency level.

Stringency Level	Control Measure	Control Efficiency (%)
High	Selective Catalytic Reduction	90 or 80 [a]
Medium, Low	Ignition Retard	25

[a] The control efficiency is 90% for Selective Catalytic Reduction - ICE - Diesel. The control efficiency is 80% for Selective Catalytic Reduction - Internal Combustion Engines - Oil.

7.3.1 Selective Catalytic Reduction

SCR is a post-combustion control technology. An SCR emission control system uses a catalyst, typically ammonia or urea, to selectively reduce NOx emissions from exhaust gases (EPA, 2007). NOx is chemically reduced into molecular N_2 and water vapor. The catalyst is not consumed but allows the reactions to occur at a lower temperature.

The SCR system is typically installed downstream of the engine and particulate trap (if applicable).

7.3.2 Ignition Retard

For diesel engines, injection of fuel into the cylinder initiates the combustion process. Retarding ignition refers to initiation of the fuel combustion process when the piston is creating increased combustion chamber volume during the downward stroke. The increased volume decreases temperature and pressure in the combustion chamber thereby lowering NOx formation. Care must be taken such that ignition retarding timing reduces NOx to the extent feasible while not causing engine misfire, or other undesirable effects. Electronic injection is typically required.

7.4 NOx Emission Reductions

Table 7-4 shows the control measures that were implemented for each SCC and stringency level. Existing (as of 2016) NOx controls were accounted for in the analysis; potential emission reductions were calculated as incremental reductions from the existing controls. Existing NOx controls were identified based on “Control ID” in the 2016v1 modeling platform files. If the existing control efficiency was higher than the selected control measure for a unit, no emission reduction or cost was calculated. If the existing control efficiency was lower than the selected control measure, the surplus emission reduction and associated cost are calculated.

Estimated emission reductions are uncertain because 1) information on existing controls is unlikely to be comprehensive and 2) feasibility and emission reduction potential depends on site-specific conditions such as raw materials and fuels used and existing equipment configurations. Emission reductions can be more accurately estimated based on individual facility specific feasibility and emission control analysis. This analysis is a source category-level evaluation; therefore, facility specific analysis is not included.

Table 7-4. Diesel-fired internal combustion engines control measure applied to each SCC.

SCC	SCC Description	Stringency Level (Control technologies highlighted in grey were assessed in prior tasks but are not evaluated in this white paper) [a]		
		High	Medium	Low
20100102	Internal Combustion Engines; Electric Generation; Distillate Oil (Diesel); Reciprocating	Selective Catalytic Reduction	Ignition Retard	
20100107	Internal Combustion Engines; Electric Generation; Distillate Oil (Diesel); Reciprocating: Exhaust	Selective Catalytic Reduction	Ignition Retard	
20200102	Internal Combustion Engines; Industrial; Distillate Oil (Diesel); Reciprocating	Selective Catalytic Reduction	Ignition Retard	
20200103	Internal Combustion Engines; Industrial; Distillate Oil (Diesel); Turbine: Cogeneration	Selective Catalytic Reduction	Ignition Retard	
20200104	Internal Combustion Engines; Industrial; Distillate Oil (Diesel); Reciprocating: Cogeneration	Selective Catalytic Reduction	Ignition Retard	
20200401	Internal Combustion Engines; Industrial; Other Fuels; Diesel: Large Bore Engine	Layered Combustion	Ignition Retard	
20200402	Internal Combustion Engines; Industrial; Other Fuels; Dual Fuel (Oil/Gas): Large Bore Engine	Layered Combustion	Ignition Retard	
20300101	Internal Combustion Engines; Commercial/Institutional; Distillate Oil (Diesel); Reciprocating	Selective Catalytic Reduction	Ignition Retard	
20400402	Internal Combustion Engines; Engine Testing; Reciprocating Engine; Diesel/Kerosene	Selective Catalytic Reduction	Ignition Retard	
20400403	Internal Combustion Engines; Engine Testing; Reciprocating Engine; Distillate Oil	Selective Catalytic Reduction	Ignition Retard	

[a] Control measure assignments for each SCC were based on EPA's Control Strategy Tool (CoST), version 3.7[47].

Diesel-fired ICE NOx emissions and emission reductions by LADCO state are presented in Table 7-5 and by LADCO NAA in Table 7-6. The number of units with 2016 NOx emissions is available in Appendix B.

State-level emission reductions differ by APTE level indicating that potentially controlled sources generally have a range of NOx APTE from 10 tons/year to greater than 100 tons/year. Illinois and Wisconsin do not have facilities with over a 100 tons/year APTE and thus do not have emission reductions for the 100 tons/year APTE level. 2016 NOx emissions from diesel-fired internal combustion engines are from Michigan (37%), Minnesota (29%), Illinois (19%), Ohio (8%), Wisconsin (6%), and Chicago, IN (2%). There are NOx emission reductions in eight out of fifteen NAAs.

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[47] Control Strategy Tool. https://www.epa.gov/economic-and-cost-analysis-air-pollution-regulations/cost-analysis-modelstools-air-pollution#control%20strategy%20tool, Accessed January 2021.

7.5 Cost-effectiveness

Table 7-7 summarizes typical cost-effectiveness estimates for each control measure considered. Facility specific costs will vary based on raw material, fuel characteristics, equipment configuration, and other source specific factors. Table 7-8 and Table 7-9 show statewide cost and cost-effectiveness estimates, respectively.

Table 7-10 and Table 7-11 show cost and cost-effectiveness estimates, respectively, by NAA.

Table 7-5. Statewide 2016 NOx emission reductions from diesel-fired internal combustion engines.[26] [48]

State	2016 NOx Emissions (tons/year)	2016 NOx Emission Reductions (tons/year)											
		APTE = 10 tons/year			APTE = 25 tons/year			APTE = 50 tons/year			APTE = 100 tons/year		
		Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
IL	899	116	116	381	68	68	221	46	46	147	-	-	-
MI	1,740	337	337	516	305	305	421	288	288	376	288	288	355
MN	1,394	203	203	556	146	146	407	88	88	267	48	48	123
OH	375	58	58	186	43	43	137	39	39	125	39	39	125
WI	264	41	41	78	29	29	46	7	7	24	-	-	-

Table 7-6. NOx emission reductions from diesel-fired internal combustion engines by NAA.[26] [28]

Non-Attainment Area	2016 NOx Emissions (tons/year)	2016 NOx Emission Reductions (tons/year)											
		APTE = 10 tons/year			APTE = 25 tons/year			APTE = 50 tons/year			APTE = 100 tons/year		
		Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
Allegan, MI	<1	-	-	-	-	-	-	-	-	-	-	-	-
Berrien, MI	11	2	2	-	-	-	-	-	-	-	-	-	-
Chicago, IL	519	63	63	209	24	24	80	7	7	22	-	-	-
Chicago, IN	77	[a]	[a]	[a]	[a]	[a]	[a]	-	-	-	-	-	-
Chicago, WI	<1	-	-	-	-	-	-	-	-	-	-	-	-
Cincinnati, OH	6	-	-	-	-	-	-	-	-	-	-	-	-
Cleveland, OH	196	42	42	134	39	39	125	39	39	125	39	39	125
Columbus, OH	3	-	-	-	-	-	-	-	-	-	-	-	-
Detroit, MI	1,121	213	213	112	191	191	47	180	180	22	180	180	-
Door, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
Manitowoc County, WI	41	10	10	35	10	10	35	7	7	24	-	-	-
Muskegon, MI	31	6	6	19	6	6	19	-	-	-	-	-	-
Northern Milwaukee/Ozaukee, WI	74	11	11	19	7	7	10	-	-	-	-	-	-
Sheboygan, WI	<1	-	-	-	-	-	-	-	-	-	-	-	-
St. Louis, IL	23	3	3	10	-	-	-	-	-	-	-	-	-

[a] APTE values of 10 tons/year and 25 tons/year are not applicable to Chicago, IN

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[48] Cells populated with "-" indicate zero NOx emissions in the inventory and thus no emission reductions.

Table 7-7. Typical cost-effectiveness for each control measure.

Stringency Level	Control Measure	Cost-effectiveness (2020$/ton)	Reference
High	Selective Catalytic Reduction	12,324 or 4,634 [a]	EPA CoST[27]
Medium, Low	Ignition Retard	970 or 1,525 [b]	EPA CoST[27]

[a] The cost-effectiveness is $12,324/ton for Selective Catalytic Reduction - ICE - Diesel. The cost-effectiveness is $4,634/ton for Selective Catalytic Reduction - Internal Combustion Engines - Oil.

[b] The cost-effectiveness is $1,525/ton for sources with an emission rate less than 365 tons/year; $970 for sources with an emission rate higher than 365 tons/year.

Table 7-8. Statewide total cost of diesel-fired internal combustion engines emissions reduction.[26] [49]

State	Total Cost (thousands of 2020$)											
	APTE = 10 tons/year			APTE = 25 tons/year			APTE = 50 tons/year			APTE = 100 tons/year		
	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
IL	176	176	2,510	103	103	1,308	70	70	683	-	-	-
MI	414	414	3,364	365	365	2,688	339	339	2,481	339	339	2,381
MN	309	309	6,240	222	222	4,937	135	135	3,293	73	73	1,512
OH	88	88	898	65	65	636	60	60	579	60	60	579
WI	63	63	618	44	44	397	10	10	298	-	-	-

Table 7-9. Statewide cost-effectiveness of diesel-fired internal combustion engines emissions reduction.[26] [29]

State	Cost-effectiveness (2020$/ton)											
	APTE = 10 tons/year			APTE = 25 tons/year			APTE = 50 tons/year			APTE = 100 tons/year		
	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
IL	1,525	1,525	6,588	1,525	1,525	5,920	1,525	1,525	4,634	-	-	-
MI	1,229	1,229	6,522	1,197	1,197	6,384	1,178	1,178	6,591	1,178	1,178	6,711
MN	1,525	1,525	11,230	1,525	1,525	12,122	1,525	1,525	12,324	1,525	1,525	12,324
OH	1,525	1,525	4,836	1,525	1,525	4,634	1,525	1,525	4,634	1,525	1,525	4,634
WI	1,525	1,525	7,908	1,525	1,525	8,715	1,525	1,525	12,324	-	-	-

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[49] Cells populated with "-" indicate zero NOx emissions in the inventory and thus no associated cost or cost-effectiveness.

Table 7-10. Cost of diesel-fired internal combustion engines emissions reduction by NAA.[26] [29]

Non-Attainment Area	Total Cost (thousands of 2020$)											
	APTE = 10 tons/year			APTE = 25 tons/year			APTE = 50 tons/year			APTE = 100 tons/year		
	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
Allegan, MI	-	-	-	-	-	-	-	-	-	-	-	-
Berrien, MI	4	4	-	-	-	-	-	-	-	-	-	-
Chicago, IL	96	96	1,468	37	37	532	10	10	102	-	-	-
Chicago, IN	[a]	[a]	[a]	[a]	[a]	[a]	-	-	-	-	-	-
Chicago, WI	-	-	-	-	-	-	-	-	-	-	-	-
Cincinnati, OH	-	-	-	-	-	-	-	-	-	-	-	-
Cleveland, OH	64	64	622	60	60	579	60	60	579	60	60	579
Columbus, OH	-	-	-	-	-	-	-	-	-	-	-	-
Detroit, MI	224	224	567	192	192	219	175	175	100	175	175	-
Door, WI	-	-	-	-	-	-	-	-	-	-	-	-
Manitowoc County, WI	16	16	350	16	16	350	10	10	298	-	-	-
Muskegon, MI	9	9	88	9	9	88	-	-	-	-	-	-
Northern Milwaukee/Ozaukee, WI	17	17	88	10	10	47	-	-	-	-	-	-
Sheboygan, WI	-	-	-	-	-	-	-	-	-	-	-	-
St. Louis, IL	4	4	125	-	-	-	-	-	-	-	-	-

[a] APTE values of 10 tons/year and 25 tons/year are not applicable to Chicago, IN

Table 7-11. Cost-effectiveness of diesel-fired internal combustion engines emissions reduction by NAA.[26] [29]

Non-Attainment Area	Cost-effectiveness (2020$/ton)											
	APTE = 10 tons/year			APTE = 25 tons/year			APTE = 50 tons/year			APTE = 100 tons/year		
	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
Allegan, MI	-	-	-	-	-	-	-	-	-	-	-	-
Berrien, MI	1,525	1,525	-	-	-	-	-	-	-	-	-	-
Chicago, IL	1,525	1,525	7,009	1,525	1,525	6,669	1,525	1,525	4,634	-	-	-
Chicago, IN	[a]	[a]	[a]	[a]	[a]	[a]	-	-	-	-	-	-
Chicago, WI	-	-	-	-	-	-	-	-	-	-	-	-
Cincinnati, OH	-	-	-	-	-	-	-	-	-	-	-	-
Cleveland, OH	1,525	1,525	4,634	1,525	1,525	4,634	1,525	1,525	4,634	1,525	1,525	4,634
Columbus, OH	-	-	-	-	-	-	-	-	-	-	-	-
Detroit, MI	1,055	1,055	5,069	1,003	1,003	4,634	970	970	4,634	970	970	-
Door, WI	-	-	-	-	-	-	-	-	-	-	-	-
Manitowoc County, WI	1,525	1,525	9,884	1,525	1,525	9,884	1,525	1,525	12,324	-	-	-
Muskegon, MI	1,525	1,525	4,634	1,525	1,525	4,634	-	-	-	-	-	-
Northern Milwaukee/Ozaukee, WI	1,525	1,525	4,634	1,525	1,525	4,634	-	-	-	-	-	-
Sheboygan, WI	-	-	-	-	-	-	-	-	-	-	-	-
St. Louis, IL	1,525	1,525	12,324	-	-	-	-	-	-	-	-	-

[a] APTE values of 10 tons/year and 25 tons/year are not applicable to Chicago, IN

7.6 Geographic Applicability

NOx emission reductions for diesel-fired ICEs can only be achieved in the counties and states in which there are substantial emissions from these sources. According to EPA's 2016v1 emission inventory, diesel-fired ICE statewide emissions occur in Illinois, Michigan, Minnesota, Ohio, and Wisconsin. For NAAs, according to EPA's 2016v1 emission inventory, there are diesel-fired ICE emissions in all NAAs; however NAA emission reductions for diesel-fired ICEs are limited to Chicago, IL; Cleveland, OH; Detroit, MI; and Northern Milwaukee/Ozaukee, WI. Other NAAs that have diesel-fired ICE emissions either do not have NOx emissions greater than APTE thresholds and/or NOx emissions are from units for which existing controls have a higher control efficiency than the selected control measures.

7.7 Responsible Agency

The state air agency is responsible for enforcing SIP-approved and other air permitting rules. Applicable diesel-fired ICE emissions in the LADCO area are from sources in EPA's 2016v1 emission inventory with a wide range of APTE from 10 tons/year to greater than over 100 tons/year. Sources with APTE over 100 tons/year are expected to be subject to Title V permit requirements; sources not subject to Title V thresholds may be permitted under state permit requirements.

7.8 Implementation Schedule

After a new rule is promulgated, facilities are typically given time to comply with the new rule for planning, analysis, and infrastructure changes necessary to comply. The timeline for existing sources to comply with MACT standards is typically 3-years, but timelines for compliance typically vary from 1-4 years. Assuming that rules to limit diesel-fired ICEs emissions are adopted in late-2023, and assuming a 2-year period from rule promulgation to controls installation, emission reduction would be achieved by 2026. Depending on regulatory requirements, a more aggressive or less aggressive timeline may be required in rulemakings.

7.9 Implementation Feasibility

There are several regulatory programs which limit diesel-fired ICE emissions (examples are listed below). Emission requirements may be expressed in mass of NOx emitted per horsepower-hour.

- New Source Performance Standard for Stationary Compression Ignition Internal Combustion Engines (NSPS Subpart IIII)[50]
- Texas Commission on Environmental Quality: 30 TAC Chapter 117, Subchapter D, Division 2[51]

7.10 Public Acceptance

Diesel-fired ICEs can produce substantial emissions of NOx and other pollutants. Diesel-fired ICE control measures evaluated herein are cost-effective, and therefore can be shown to be a good regional emission reductions strategy. Diesel-fired ICE operators may object to any further regulation of their operations, especially for the more costly control measures. Grant funding can be used to facilitate implementation of control measures.

7.11 All Controls Results

Analysis in the sections above includes the controls considered under low, medium, and high stringency scenarios, as indicated in Table 7-4 (i.e., those controls not highlighted in grey on Table 7-4). Emission reduction estimates across the full suite of stringency scenario and control combinations are presented in Appendix A, Tables A1 to A2.

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[50] https://www.epa.gov/stationary-engines/new-source-performance-standards-stationary-compression-ignition-internal-0, accessed in January, 2022

[51] https://texreg.sos.state.tx.us/public/readtac$ext.TacPage?sl=R&app=9&p_dir=&p_rloc=&p_tloc=&p_ploc=&pg=1&p_tac=&ti=30&pt=1&ch=117&rl=2110, accessed in January, 2022

8.0 NATURAL GAS-FIRED INTERNAL COMBUSTION ENGINES

8.1 Summary

This section focuses on emissions reductions for natural gas-fired ICEs. Natural gas-fired engines are used in a variety of industries to generate electricity and do other work (such as compress natural gas). Table 8-1 summarizes key information for natural gas-fired internal combustion engines control measures evaluated herein. Applicable emissions, emission reductions, and cost-effectiveness are presented in Table 8-1 on a LADCO region-wide basis. State- and NAA-level emissions, emission reductions, and cost-effectiveness are presented in subsections below. Emission reductions across all control measures (i.e., including control measures not selected for evaluation in this white paper) are provided in Appendix A.

Table 8-1. Control measure summary for natural gas-fired internal combustion engines.[52]

2016 Emissions Estimates					
2016 Emissions [a]	NOx:	3,505 tons/year			
Control Measure Summary, Including 2016 Emission Reduction Estimates					
		APTE = 10 tons/year	**APTE = 25 tons/year**	**APTE = 50 tons/year**	**APTE = 100 tons/year**
EMx and Dry Low NOx Combustion (High Stringency Scenario)	NOx Reduction:	1,493 tons/year	1,356 tons/year	1,136 tons/year	849 tons/year
	Cost-effectiveness:	*$2,464/ton*			
	Applicable States:	*IL, MI, MN, OH, WI*	*IL, MI, MN, OH*		
	Applicable NAAs:	*Allegan, MI; Chicago, IL; Cincinnati, OH; Cleveland, OH; Detroit, MI*	*Allegan, MI; Chicago, IL; Cincinnati, OH; Detroit, MI*	*Allegan, MI; Chicago, IL; Detroit, MI*	*Chicago, IL; Detroit, MI*
Non-Selective Catalytic Reduction (High Stringency Scenario)	NOx Reduction:	31 tons/year	12 tons/year	*Not applicable* [c]	*Not applicable* [c]
	Cost-effectiveness:	*$656/ton*			
	Applicable States:	*OH*			
	Applicable NAAs:	*Cleveland, OH*	*None* [b]		
Adjust Air to Fuel Ratio (Medium Stringency Scenario)	NOx Reduction:	80 tons/year	48 tons/year	26 tons/year	10 tons/year
	Cost-effectiveness:	*$752 or $3,109/ton* [d]			
	Applicable States:	*IL, MI, MN, OH, WI*	*IL, MN, WI*	*WI*	
	Applicable NAAs:	*Chicago, IL; Cleveland, OH; Detroit, MI; Manitowoc County, WI; Northern Milwaukee/Ozaukee, WI*	*Chicago, IL; Manitowoc County, WI; Northern Milwaukee/Ozaukee, WI*	*Manitowoc County, WI; Northern Milwaukee/Ozaukee, WI*	*Manitowoc County, WI*

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[52] Excludes Indiana emissions except for in Chicago, Indiana nonattainment area counties (Lake County and Porter County).

2016 Emissions Estimates					
2016 Emissions [a]	NOx:	3,505 tons/year			
Control Measure Summary, Including 2016 Emission Reduction Estimates					
Low NOx Burner (Medium Stringency Scenario)	NOx Reduction:	277 tons/year	251 tons/year	176 tons/year	154 tons/year
	Cost-effectiveness:	*$970/ton*			
	Applicable States:	*IL, MN, OH, WI*	*IL, MN, WI*	*IL, WI*	
	Applicable NAAs:	*Chicago, IL; Cincinnati, OH; Northern Milwaukee/Ozaukee, WI*	*Chicago, IL; Northern Milwaukee/Ozaukee, WI*		*Northern Milwaukee/Ozaukee, WI*
Adjust Air to Fuel Ratio (Low Stringency Scenario)	NOx Reduction:	135 tons/year	90 tons/year	65 tons/year	43 tons/year
	Cost-effectiveness:	*$752 or $3,109/ton* [d]			
	Applicable States:	*IL, MI, MN, OH, WI*	*IL, MN, OH, WI*	*OH, WI*	
	Applicable NAAs:	*Chicago, IL; Cleveland, OH; Detroit, MI; Manitowoc County, WI; Muskegon, MI; Northern Milwaukee/Ozaukee, WI*	*Chicago, IL; Manitowoc County, WI; Northern Milwaukee/Ozaukee, WI*	*Manitowoc County, WI; Northern Milwaukee/Ozaukee, WI*	*Manitowoc County, WI*

2016 Emissions Estimates					
2016 Emissions [a]	NOx:	3,505 tons/year			
Control Measure Summary, Including 2016 Emission Reduction Estimates					
Water Injection (Low Stringency Scenario)	NOx Reduction:	1,248 tons/year	1,127 tons/year	928 tons/year	701 tons/year
	Cost-effectiveness:	*$1,553 or $2,781/ton* [e]			
	Applicable States:	*IL, MI, MN, OH, WI*			
	Applicable NAAs:	*Allegan, MI; Chicago, IL; Cincinnati, OH; Cleveland, OH; Detroit, MI; Northern Milwaukee/Ozaukee, WI*	*Allegan, MI; Chicago, IL; Cincinnati, OH; Detroit, MI; Northern Milwaukee/Ozaukee, WI*	*Allegan, MI; Chicago, IL; Detroit, MI; Northern Milwaukee/Ozaukee, WI*	*Chicago, IL; Detroit, MI; Northern Milwaukee/Ozaukee, WI*

[a] Source: US Environmental Protection Agency (EPA) 2016v1 modeling platform. Available at https://www.epa.gov/air-emissions-modeling/2016v1-platform, accessed in June 2021.

[b] There were no ICE Gas emissions in any LADCO NAA.

[c] There were no ICE Gas sources in the APTE level.

[d] The cost-effectiveness is $3,109/ton for sources with an emission rate less than 365 tons/year; $752/ton for sources with an emission rate higher than 365 tons/year.

[e] The cost-effectiveness is $2,781/ton for sources with an emission rate less than 365 tons/year; $1,553/ton for sources with an emission rate higher than 365 tons/year.

8.2 Source Description

ICEs can be fueled by diesel, gasoline, or natural gas (EPA, 1995). In a reciprocating ICE, the fuel is compressed in a small volume and ignited, creating pressure that pushes pistons through its cylinder. In a turbine engine, air flows through compressor blades to the combustor in which fuel is added to the air stream; the combustion generates a high-temperature gas which enters a turbine and drives the compressor. Reciprocating ICE use is widespread across many applications, turbine engines tend to be more specialized to specific applications such as aircraft, electrical generators, pumps, and gas compressors.

There are two types of ignition used for reciprocating ICEs; compression ignition (CI) and spark ignition (SI). All reciprocating natural gas-fueled engines are spark ignited in which combustion is started through an electric discharge. The compression ratio, the ratio of cylinder volume at the bottom of its stroke to when it's at the top, is higher in CI engines because fuel is not introduced until after compression. Since the thermal efficiency of engines increases with increased pressure ratio, which is directly correlated with compression ratio, SI engines are less efficient than CI engines. SI engines are able to respond faster to load changes but tend to have a lighter weight structure that cannot withstand higher pressures.

Emissions from ICEs mostly come from the exhaust (NO_x, OC, CO, and PM).

Table 8-2 lists the applicable SCCs for gas-fired internal combustion sources in the LADCO stationary point source inventory.

Table 8-2. Applicable SCCs for Gas-Fired Internal Combustion Engines (ICE Gas).

Description One	Description Two	Description Three	Description Four	SCC
Internal Combustion Engines	Electric Generation	Natural Gas	Turbine	20100201
			Reciprocating	20100202
	Industrial		Turbine	20200201
			Reciprocating	20200202
			Turbine: Cogeneration	20200203
			4-cycle Rich Burn	20200253
			4-cycle Lean Burn	20200254
	Commercial/Institutional		Reciprocating	20300201
			Turbine	20300202
			Turbine: Cogeneration	20300203
			Reciprocating: Cogeneration	20300204
		Digester Gas	Turbine	20300701
			Reciprocating: POTW Digester Gas	20300702
			Reciprocating: Exhaust	20300707
	Engine Testing	Turbine	Natural Gas	20400301
		Reciprocating Engine	Gasoline	20400401

8.3 Selected Control Measures Description

For natural gas-fired ICEs, specific control measures were considered for each stringency level. The selected control measures and their estimated control efficiency are shown in Table 8-3. Descriptions of each control measure are included in the subsections below.

Table 8-3. Applicable control technology and associated control efficiency by stringency level.

Stringency Level	Control Measure	Control Efficiency (%)
High	EMx and Dry Low NOx Combustion	99
	Non-Selective Catalytic Reduction	90
Medium	Low NOx Burner	84
Medium, Low	Adjust Air to Fuel Ratio	20
Low	Water Injection	72

8.3.1 EMx and Dry Low NOx Combustion

EMx is a catalytic absorption system that was developed by EmeraChem LLC. It is a post-combustion multi-pollutant control technology that uses a single catalyst to remove NOx, CO, and VOC from turbine exhaust (EPA, 2015). NOx is removed by oxidizing NO to NO_2, then adsorbing NO_2 onto the catalytic surface. The catalyst is refreshed as necessary with hydrogen gas. EMx may be used in combination with dry low NOx combustion. Dry low NOx combustion is an advanced combustor design which suppresses NOx formation. Thermal NOx formation is decreased by 1) lowering combustor temperature by using lean mixtures of air and/or fuel staging, and/or 2) decreasing residence time in the combustor (EPA, 1995).

8.3.2 Non-Selective Catalytic Reduction

Non-selective catalytic reduction (NSCR) is an emission control measure by which NOx is converted to N_2 in the presence of a catalyst applicable to reciprocating ICEs. NSCR application is limited to engines with normal exhaust oxygen levels of 4% or less (i.e., 4-stroke rich burn engines). Air and fuel mixture must be tightly controlled to maintain high NOx emission reduction efficiency while not causing high hydrocarbon emissions. NSCR can be applied to most rich-burn engines as a retrofit technology. NSCR is typically not able to be applied to lean burn engines.

8.3.3 Low NOx Burner

Low NOx burners apply to gas turbines and reduce emissions by lowering the temperature of one combustion zone and reducing the amount of oxygen available in another (EPA, 1993). Emission reductions are achieved by one or more of the following:

- Reducing oxygen content in the combustion zone, limiting fuel NOx formation;
- Reducing flame temperature, limiting thermal NOx formation;
- Reducing residence time at peak temperature, limiting thermal NOx formation;

Low NOx burners may be designed to delay the combustion process resulting in a cooler flame thereby suppressing thermal NOx or to create stratified fuel-rich and fuel-lean regions in or near the combustor. In fuel-rich regions, fuel NOx formation is reduced; in fuel-lean regions, thermal NOx formation is reduced. This control applies to natural gas fired turbines with uncontrolled NOx emissions greater than 10 tons per year.

8.3.4 Adjust Air to Fuel Ratio

This control measure utilizes air to fuel ratio adjustment to reduce NOx emissions from turbines. By adjusting the air to fuel ratio to a lean mixture, excess air acts as a heat sink to lower combustion temperatures and thereby lower thermal NOx formation. This control applies to gas turbines with uncontrolled NOx emissions greater than 10 tons per year (EPA, 2019b).

8.3.5 Water Injection

Water injection is a control measure by which turbine combustion temperatures are reduced through water injection in the flame zone and thereby limit thermal NOx formation. Water injection typically decreases engine efficiency by 2 to 3 percent and increases power output by 5 to 6 percent (EPA 1993). Water injection may increase maintenance requirements as well as CO and hydrocarbon emissions. Water purity is important to prevent erosion or deposit formation in turbines. A water injection system typically includes water treatment, pumps, water metering, turbine mounted injection models and piping and can be added as a retrofit to most gas turbines. The water fuel ratio is a critical parameter for determining achievable NOx reductions for a given turbine.

8.4 NOx Emission Reductions

Table 8-4 shows the control measures that were implemented for each SCC and stringency level. Existing (as of 2016) NOx controls were accounted for in the analysis; potential emission reductions were calculated as incremental reductions from the existing controls. Existing NOx controls were identified based on "Control ID" in the 2016v1 modeling platform files. If the existing control efficiency was higher than the selected control measure for a unit, no emission reduction or cost was calculated. If the existing control efficiency was lower than the selected control measure, the surplus emission reduction and associated cost are calculated.

Estimated emission reductions are uncertain because 1) information on existing controls is unlikely to be comprehensive and 2) feasibility and emission reduction potential depends on site-specific conditions such as raw materials and fuels used and existing equipment configurations. Emission reductions can be more accurately estimated based on individual facility specific feasibility and emission control analysis. This analysis is a source category-level evaluation; therefore, facility specific analysis is not included.

Table 8-4. Natural gas-fired internal combustion engines control measure applied to each SCC.

SCC	SCC Description	Stringency Level (Control technologies highlighted in grey were assessed in prior tasks but are not evaluated in this white paper) [a]		
		High	Medium	Low
20100201	Internal Combustion Engines; Electric Generation; Natural Gas; Turbine	Selective Catalytic Reduction and Steam Injection	Low NOx Burner	Water Injection
20100202	Internal Combustion Engines; Electric Generation; Natural Gas; Reciprocating	Adjust Air to Fuel Ratio and Ignition Retard	Adjust Air to Fuel Ratio	Adjust Air to Fuel Ratio
20200201	Internal Combustion Engines; Industrial; Natural Gas; Turbine	EMx and Dry Low NOx Combustion	Dry Low NOx Combustion	Water Injection

SCC	SCC Description	Stringency Level (Control technologies highlighted in grey were assessed in prior tasks but are not evaluated in this white paper) [a]		
		High	Medium	Low
20200202	Internal Combustion Engines; Industrial; Natural Gas; Reciprocating	Non-Selective Catalytic Reduction or Layered Combustion	Non-Selective Catalytic Reduction or Adjust Air Fuel Ratio and Ignition Retard	Adjust Air to Fuel Ratio
20200203	Internal Combustion Engines; Industrial; Natural Gas; Turbine: Cogeneration	EMx and Dry Low NOx Combustion	Dry Low NOx Combustion	Water Injection
20200253	Internal Combustion Engines; Industrial; Natural Gas; 4-cycle Rich Burn	Non-Selective Catalytic Reduction	Adjust Air to Fuel Ratio and Ignition Retard	Adjust Air to Fuel Ratio
20200254	Internal Combustion Engines; Industrial; Natural Gas; 4-cycle Lean Burn	Layered Combustion	Low Emission Combustion	Adjust Air to Fuel Ratio
20300201	Internal Combustion Engines; Commercial/Institutional; Natural Gas; Reciprocating	Adjust Air to Fuel Ratio and Ignition Retard	Adjust Air to Fuel Ratio	Adjust Air to Fuel Ratio
20300202	Internal Combustion Engines; Commercial/Institutional; Natural Gas; Turbine	EMx and Dry Low NOx Combustion	Dry Low NOx Combustion	Water Injection
20300203	Internal Combustion Engines; Commercial/Institutional; Natural Gas; Turbine: Cogeneration	EMx and Dry Low NOx Combustion	Dry Low NOx Combustion	Water Injection
20300204	Internal Combustion Engines; Commercial/Institutional; Natural Gas; Reciprocating: Cogeneration	Adjust Air to Fuel Ratio and Ignition Retard	Adjust Air to Fuel Ratio	Adjust Air to Fuel Ratio
20300701	Internal Combustion Engines; Commercial/Institutional; Digester Gas; Turbine	EMx and Dry Low NOx Combustion	Dry Low NOx Combustion	Water Injection
20300702	Internal Combustion Engines; Commercial/Institutional; Digester Gas; Reciprocating: POTW Digester Gas	Adjust Air to Fuel Ratio and Ignition Retard	Adjust Air to Fuel Ratio	Adjust Air to Fuel Ratio

SCC	SCC Description	Stringency Level (Control technologies highlighted in grey were assessed in prior tasks but are not evaluated in this white paper) [a]		
		High	Medium	Low
20300707	Internal Combustion Engines; Commercial/Institutional; Digester Gas; Reciprocating: Exhaust	Adjust Air to Fuel Ratio and Ignition Retard	Adjust Air to Fuel Ratio	Adjust Air to Fuel Ratio
20400301	Internal Combustion Engines; Engine Testing; Turbine; Natural Gas	EMx and Dry Low NOx Combustion	Dry Low NOx Combustion	Water Injection
20400401	Internal Combustion Engines; Engine Testing; Reciprocating Engine; Gasoline	Ignition Retard	Ignition Retard	Ignition Retard

[a] Control measure assignments for each SCC were based on EPA's Control Strategy Tool (CoST), version 3.7[53].

Natural gas-fired ICE NOx emissions and emission reductions by LADCO state are presented in Table 8-5 and by LADCO NAA in Table 8-6. The number of units with 2016 NOx emissions is available in Appendix B.

State-level emission reductions differ under each APTE level indicating that potentially controlled sources have a range of NOx APTE from 10 tons/year to greater than 100 tons/year. 2016 NOx emissions from natural gas-fired internal combustion engines are from Illinois (34%), Michigan (23%), Ohio (22%), Wisconsin (14%), Minnesota (6%), and Chicago, IN (<1%). There are NOx emission reductions in eight out of fifteen NAAs.

8.5 Cost-effectiveness

Table 8-7 summarizes typical cost-effectiveness estimates for each control measure considered. Facility specific costs will vary based on raw material, fuel characteristics, equipment configuration, and other source specific factors. Table 8-8 and Table 8-9 show statewide cost and cost-effectiveness estimates, respectively. Table 8-10 and Table 8-11 show cost and cost-effectiveness estimates, respectively, by NAA.

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[53] Control Strategy Tool. https://www.epa.gov/economic-and-cost-analysis-air-pollution-regulations/cost-analysis-modelstools-air-pollution#control%20strategy%20tool, Accessed January 2021.

Table 8-5. Statewide 2016 NOx emission reductions from natural gas-fired internal combustion engines.[26] [54]

State	2016 NOx Emissions (tons/year)	2016 NOx Emission Reductions (tons/year)											
		APTE = 10 tons/year			APTE = 25 tons/year			APTE = 50 tons/year			APTE = 100 tons/year		
		Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
IL	1,204	513	166	592	468	145	558	332	71	439	279	50	392
MI	817	291	2	406	279	-	400	242	-	333	68	-	94
MN	215	84	20	89	68	18	72	52	-	72	52	-	72
OH	770	337	8	421	280	-	339	251	-	291	245	-	291
WI	486	158	161	16	122	137	-	116	131	-	100	115	-

Table 8-6. NOx emission reductions from natural gas-fired internal combustion engines by NAA.[26] [28]

Non-Attainment Area	2016 NOx Emissions (tons/year)	2016 NOx Emission Reductions (tons/year)											
		APTE = 10 tons/year			APTE = 25 tons/year			APTE = 50 tons/year			APTE = 100 tons/year		
		Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
Allegan, MI	77	55	-	76	55	-	76	55	-	76	-	-	-
Berrien, MI	<1	-	-	-	-	-	-	-	-	-	-	-	-
Chicago, IL	450	190	29	310	170	29	285	91	21	167	38	-	120
Chicago, IN	13	[a]	[a]	[a]	[a]	[a]	[a]	-	-	-	-	-	-
Chicago, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
Cincinnati, OH	83	48	5	61	15	-	21	-	-	-	-	-	-
Cleveland, OH	64	22	3	33	-	-	-	-	-	-	-	-	-
Columbus, OH	-	-	-	-	-	-	-	-	-	-	-	-	-
Detroit, MI	563	162	2	221	156	-	214	144	-	197	68	-	94
Door, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
Manitowoc County, WI	51	10	10	-	10	10	-	10	10	-	10	10	-
Muskegon, MI	29	5	-	-	-	-	-	-	-	-	-	-	-
Northern Milwaukee/Ozaukee, WI	278	114	129	-	101	116	-	98	113	-	90	105	-
Sheboygan, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
St. Louis, IL	<1	-	-	-	-	-	-	-	-	-	-	-	-

[a] APTE values of 10 tons/year and 25 tons/year are not applicable to Chicago, IN

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[54] Cells populated with "-" indicate zero NOx emissions in the inventory and thus no emission reductions.

Table 8-7. Typical cost-effectiveness for each control measure.

Stringency Level	Control Measure	Cost-effectiveness (2020$/ton)	Reference
High	EMx and Dry Low NOx Combustion	2,464	EPA CoST[27]
	Non-Selective Catalytic Reduction	656	EPA CoST[27]
Medium	Low NOx Burner	970	EPA CoST[27]
Medium, Low	Adjust Air to Fuel Ratio	752 or 3,109 [a]	EPA CoST[27]
Low	Water Injection	1,553 or 2,781 [b]	EPA CoST[27]

[a] The cost-effectiveness is $3,109/ton for sources with an emission rate less than 365 tons/year; $752/ton for sources with an emission rate higher than 365 tons/year.

[b] The cost-effectiveness is $2,781/ton for sources with an emission rate less than 365 tons/year; $1,553/ton for sources with an emission rate higher than 365 tons/year.

Table 8-8. Statewide total cost of natural gas-fired internal combustion engines emissions reduction.[26] [55]

State	Total Cost (thousands of 2020$)											
	APTE = 10 tons/year			APTE = 25 tons/year			APTE = 50 tons/year			APTE = 100 tons/year		
	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
IL	1,432	187	1,458	1,305	166	1,374	922	69	1,082	775	48	966
MI	810	5	1,001	777	-	985	674	-	822	190	-	232
MN	237	33	219	191	25	177	146	-	177	146	-	177
OH	954	15	982	793	-	814	711	-	717	692	-	717
WI	458	278	39	349	201	-	330	182	-	282	133	-

Table 8-9. Statewide cost-effectiveness of natural gas-fired internal combustion engines emissions reduction.[26] [29]

State	Cost-effectiveness (2020$/ton)											
	APTE = 10 tons/year			APTE = 25 tons/year			APTE = 50 tons/year			APTE = 100 tons/year		
	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
IL	2,790	1,125	2,464	2,789	1,148	2,464	2,781	970	2,464	2,781	970	2,464
MI	2,788	3,109	2,464	2,781	-	2,464	2,781	-	2,464	2,781	-	2,464
MN	2,810	1,620	2,464	2,799	1,423	2,464	2,781	-	2,464	2,781	-	2,464
OH	2,829	1,869	2,333	2,830	-	2,399	2,832	-	2,464	2,825	-	2,464
WI	2,898	1,721	2,464	2,867	1,468	-	2,854	1,394	-	2,814	1,160	-

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[55] Cells populated with "-" indicate zero NOx emissions in the inventory and thus no associated cost or cost-effectiveness.

Table 8-10. Cost of natural gas-fired internal combustion engines emissions reduction by NAA.[26] [29]

Non-Attainment Area	Total Cost (thousands of 2020$)											
	APTE = 10 tons/year			APTE = 25 tons/year			APTE = 50 tons/year			APTE = 100 tons/year		
	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
Allegan, MI	154	-	188	154	-	188	154	-	188	-	-	-
Berrien, MI	-	-	-	-	-	-	-	-	-	-	-	-
Chicago, IL	531	46	763	476	46	703	253	21	411	106	-	295
Chicago, IN	[a]	[a]	[a]	[a]	[a]	[a]	-	-	-	-	-	-
Chicago, WI	-	-	-	-	-	-	-	-	-	-	-	-
Cincinnati, OH	134	4	150	42	-	51	-	-	-	-	-	-
Cleveland, OH	63	10	63	-	-	-	-	-	-	-	-	-
Columbus, OH	-	-	-	-	-	-	-	-	-	-	-	-
Detroit, MI	451	5	543	433	-	527	399	-	486	190	-	232
Door, WI	-	-	-	-	-	-	-	-	-	-	-	-
Manitowoc County, WI	32	32	-	32	32	-	32	32	-	32	32	-
Muskegon, MI	16	-	-	-	-	-	-	-	-	-	-	-
Northern Milwaukee/Ozaukee, WI	326	178	-	284	136	-	275	127	-	250	102	-
Sheboygan, WI	-	-	-	-	-	-	-	-	-	-	-	-
St. Louis, IL	-	-	-	-	-	-	-	-	-	-	-	-

[a] APTE values of 10 tons/year and 25 tons/year are not applicable to Chicago, IN

Table 8-11. Cost-effectiveness of natural gas-fired internal combustion engines emissions reduction by NAA.[26] [29]

Non-Attainment Area	Cost-effectiveness (2020$/ton)											
	APTE = 10 tons/year			APTE = 25 tons/year			APTE = 50 tons/year			APTE = 100 tons/year		
	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
Allegan, MI	2,781	-	2,464	2,781	-	2,464	2,781	-	2,464	-	-	-
Berrien, MI	-	-	-	-	-	-	-	-	-	-	-	-
Chicago, IL	2,797	1,549	2,464	2,796	1,549	2,464	2,781	970	2,464	2,781	-	2,464
Chicago, IN	[a]	[a]	[a]	[a]	[a]	[a]	-	-	-	-	-	-
Chicago, WI	-	-	-	-	-	-	-	-	-	-	-	-
Cincinnati, OH	2,781	970	2,464	2,781	-	2,464	-	-	-	-	-	-
Cleveland, OH	2,862	3,109	1,915	-	-	-	-	-	-	-	-	-
Columbus, OH	-	-	-	-	-	-	-	-	-	-	-	-
Detroit, MI	2,784	3,109	2,464	2,781	-	2,464	2,781	-	2,464	2,781	-	2,464
Door, WI	-	-	-	-	-	-	-	-	-	-	-	-
Manitowoc County, WI	3,109	3,109	-	3,109	3,109	-	3,109	3,109	-	3,109	3,109	-
Muskegon, MI	3,109	-	-	-	-	-	-	-	-	-	-	-
Northern Milwaukee/Ozaukee, WI	2,851	1,375	-	2,817	1,176	-	2,808	1,124	-	2,781	970	-
Sheboygan, WI	-	-	-	-	-	-	-	-	-	-	-	-
St. Louis, IL	-	-	-	-	-	-	-	-	-	-	-	-

[a] APTE values of 10 tons/year and 25 tons/year are not applicable to Chicago, IN

8.6 Geographic Applicability

NOx emission reductions for natural gas-fired ICEs can only be achieved in the counties and states in which there are substantial emissions from these sources. According to EPA's 2016v1 emission inventory, natural gas-fired ICE statewide emissions occur in Illinois, Michigan, Minnesota, Ohio, and Wisconsin. For NAAs, according to EPA's 2016v1 emission inventory, there are diesel-fired ICE emissions in most NAAs; however NAA's with emission reductions are limited to Allegan, WI; Chicago, IL; Cincinnati, OH; Cleveland, OH; Detroit, MI; Manitowoc County, WI; and Northern Milwaukee/Ozaukee, WI. Other NAAs that have natural gas-fired ICE emissions either do not have NOx emissions greater than APTE thresholds and/or NOx emissions are from units for which existing controls have a higher control efficiency than the selected control measures

8.7 Responsible Agency

The state air agency is responsible for enforcing SIP-approved and other air permitting rules. Applicable natural gas-fired ICE emissions in the LADCO area are from sources in EPA's 2016v1 emission inventory with a wide range of APTE, from 10 tons/year to greater than over 100 tons/year. Sources with APTE over 100 tons/year are expected to be subject to Title V permit requirements; sources not subject to Title V thresholds may be permitted under state permit requirements.

8.8 Implementation Schedule

After a new rule is promulgated, facilities are typically given time to comply with the new rule for planning, analysis, and infrastructure changes necessary to comply. The timeline for existing sources to comply with MACT standards is typically 3-years, but timelines for compliance typically vary from 1-4 years. Assuming that rules to limit natural gas-fired ICE emissions are adopted in late-2023, and assuming a 2-year period from rule promulgation to controls installation, emission reduction would be achieved by 2026. Depending on regulatory requirements, a more aggressive or less aggressive timeline may be required in rulemakings.

8.9 Implementation Feasibility

There are several regulatory programs which limit natural gas ICE emissions (examples are listed below). Emission requirements may be expressed in mass of NOx emitted per horsepower-hour.

- New Source Performance Standard for Stationary Spark Ignition Internal Combustion Engines (NSPS Subpart JJJJ)[56]
- Texas Commission on Environmental Quality: 30 TAC Chapter 117, Subchapter E, Division 4[57]
- South Coast Air Quality Management District, Rule 1110.2: Emissions from Gaseous- and Liquid-Fueled Engines[58]

8.10 Public Acceptance

Natural gas-fired ICEs can produce substantial emissions of NOx and other pollutants. Natural gas-fired ICE control measures evaluated herein are very cost-effective and therefore can be shown to be a good regional emission reductions strategy. Natural gas-fired ICE operators may object to any further regulation of their operations, especially for the more costly control measures. Grant funding can be used to facilitate implementation of control measures.

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[56] https://www.epa.gov/stationary-engines/new-source-performance-standards-stationary-spark-ignition-internal-combustion-0, accessed in January, 2022

[57] https://www.tceq.texas.gov/airquality/stationary-rules/nox/etx-engine, accessed in January, 2022

[58] https://www.aqmd.gov/docs/default-source/rule-book/reg-xi/rule-1110-2.pdf?sfvrsn=4, accessed in January, 2022

8.11 All Controls Results

Analysis in the sections above includes the controls considered under low, medium, and high stringency scenarios, as indicated in Table 8-4 (i.e., those controls not highlighted in grey on Table 8-4). Emission reduction estimates across the full suite of stringency scenario and control combinations are presented in Appendix A, Tables A1 to A2.

9.0 IRON & STEEL SOURCES

9.1 Summary

This section focuses on emissions reductions for iron and steel manufacturing sources (excluding coke manufacturing which is addressed in Chapter 4.0). Controllable NOx emissions for iron and steel manufacturing are mainly related to furnace and sintering sources. Table 9-1 summarizes key information for iron and steel sources control measures evaluated herein. Applicable emissions, emission reductions, and cost-effectiveness are presented in Table 9-1 on a LADCO region-wide basis. State- and NAA-level emissions, emission reductions, and cost-effectiveness are presented in subsections below. Emission reductions across all control measures (i.e., including control measures not selected for evaluation in this white paper) are provided in Appendix A.

Table 9-1. Control measure summary for iron and steel sources.[59]

2016 Emissions Estimates					
2016 Emissions [a]	NOx:	4,148 tons/year			
Control Measure Summary, Including 2016 Emission Reduction Estimates					
		APTE = 10 tons/year	**APTE = 25 tons/year**	**APTE = 50 tons/year**	**APTE = 100 tons/year**
Selective Catalytic Reduction (High Stringency Scenario)	NOx Reduction:	631 tons/year	611 tons/year	1,605 tons/year	1,112 tons/year
	Cost-effectiveness:	*$4,702/ton*			
	Applicable States:	*IL, MI, OH*		*IL, OH*	*IL*
	Applicable NAAs:	*Chicago, IL; Cleveland, OH; Detroit, MI; St. Louis, IL*	*Cleveland, OH; Detroit, MI; St. Louis, IL*	*Chicago, IN; Cleveland, OH; St. Louis, IL*	*Chicago, IN*
Low NOx Burner and Flue Gas Recirculation (High Stringency Scenario)	NOx Reduction:	262 tons/year	189 tons/year	568 tons/year	509 tons/year
	Cost-effectiveness:	*$1,149 or $752/ton* [b]			
	Applicable States:	*IL, MI, OH*	*IL, OH*		
	Applicable NAAs:	*Cleveland, OH; Detroit, MI; St. Louis, IL*	*Cleveland, OH*	*Chicago, IN*	
Low NOx Burner and Flue Gas Recirculation (Medium Stringency Scenario)	NOx Reduction:	183 tons/year	121 tons/year	94 tons/year	47 tons/year
	Cost-effectiveness:	*$1,485/ton*			
	Applicable States:	*OH*			
	Applicable NAAs:	*Cincinnati, OH; Cleveland, OH*			*None* [c]

[a] Source: US Environmental Protection Agency (EPA) 2016v1 modeling platform. Available at https://www.epa.gov/air-emissions-modeling/2016v1-platform, accessed in June 2021.
[b] The cost-effectiveness is $1,149/ton for Low NOx Burner and Flue Gas Recirculation - Iron & Steel Mills - Galvanizing. The cost-effectiveness is $752/ton for Low NOx Burner and Flue Gas Recirculation - Iron and Steel Production; Blast Heating or Reheating.
[c] There were no iron and steel emissions in any LADCO NAA.

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[59] Excludes Indiana emissions except for in Chicago, Indiana nonattainment area counties (Lake County and Porter County).

9.2 Source Description

In an integrated iron and steel plant, steel is produced through a series of nine processes (EPA, 1995):

1. Coke production
2. Sinter production
3. Iron production
4. Iron preparation
5. Steel production
6. Semifinished product preparation
7. Finished product preparation
8. Heat and electricity supply
9. Transport and handling of raw, intermediate, and waste materials

Coke production is discussed in Section 4.2 above. Sinter production takes raw materials such as iron ore, limestone, flue dust, coke breeze, and other materials, heat them, cools them, and runs them through furnaces. Iron is produced when hot gas is applied to materials containing iron such as iron ore, pellets, and sinter. In steel production, iron and other materials are heated and refined. In the semifinished product, molten metal is poured into ingots and formed in molds. The processes involved in iron and steel production require energy as heat or electricity, the transport and handling of raw materials as well as the disposal of waste materials. There are three types of furnaces in which the raw materials are refined; blast furnaces, basic oxygen furnaces, and electric arc furnaces.

In a blast furnace, ores (iron), coke (as fuel), and flux (limestone, dolomite, and sinter) are continuously supplied through the top of the furnace. The hot blast air is blown into the lower section of the furnace so that chemical reactions happen throughout the furnace as the material descends. Blast air reacts with coke and fluxes to form molten reduced iron, CO, and slag.

High-purity oxygen is lanced (or injected) into the basic oxygen furnace which contains molten iron from a blast furnace and iron scrap. As the oxygen reacts with carbon and other impurities such as silicon and phosphorus, they are removed from the metal.

Electric arc furnaces use high-current electric arcs to melt steel scrap and produce carbon and alloy steels. Electric arc furnaces are equipped with carbon electrodes that can create electric current and generate heat between the electrodes and through the scrap.

Throughout the production process and from the handling of raw materials, NOx and other pollutants are emitted. In sinter production, the primary source of emissions is from the windbox exhaust. Blast furnaces and other types of furnaces, where the sinter is sent to be charged after being cooled, generate NOx as a by-product of combustion.

Table 9-2 lists the applicable SCCs for iron and steel sources in the LADCO stationary point source inventory.

Table 9-2. Applicable SCCs for Iron & Steel sources.

Description One	Description Two	Description Three	Description Four	SCC
Industrial Processes	Primary Metal Production	Integrated Iron and Steel Manufacturing	Sintering: Windbox	30301503
			Blast Furnace: Charging	30301511
			Blast Furnace: Casting/Tapping: Casthouse Roof Monitor	30301512
			Blast Furnace: Casting/Tapping: Local Evacuation	30301513
			Basic Oxygen Furnace (BOF): Top Blown Furnace: Primary	30301522
			Basic Oxygen Furnace (BOF): Open Hood Stack	30301526
			Electric Arc Furnace (EAF): Specialty Steel	30301532
			Electric Arc Furnace (EAF): Carbon Steel	30301544
			Coating: Tin, Zinc, etc.	30301575
			Heat Treating Furnace: Annealing	30301587
			Other Not Classified	30301599

9.3 Selected Control Measures Description

For iron and steel sources, specific control measures were considered for high and medium stringency levels. Low stringency levels were not selected for evaluation in this section (see Table 9-4 below). The selected control measures and their estimated control efficiency are shown in Table 9-3. Descriptions of each control measure are included in the subsections below.

Table 9-3. Applicable control technology and associated control efficiency by stringency level.

Stringency Level	Control Measure	Control Efficiency (%)
High	Selective Catalytic Reduction	90
	Low NOx Burner and Flue Gas Recirculation	60 or 77 [a]
Medium	Low NOx Burner and Flue Gas Recirculation	60

[a] The control efficiency is 60% for Low NOx Burner and Flue Gas Recirculation - Iron & Steel Mills - Galvanizing. The control efficiency is 77% for Low NOx Burner and Flue Gas Recirculation - Iron and Steel Production; Blast Heating or Reheating.

9.3.1 Low NOx Burner and Flue Gas Recirculation

Low NOx burners spread combustion over multiple stages allowing for control of both stoichiometric and temperature profiles during combustion (EPA, 1994). Emission reductions are achieved by one or more of the following:

- Reducing oxygen content in the combustion zone, limiting fuel NOx formation;
- Reducing flame temperature, limiting thermal NOx formation;
- Reducing residence time at peak temperature, limiting thermal NOx formation;

Low NOx burners may be designed to delay the combustion process resulting in a cooler flame thereby suppressing thermal NOx or to create stratified fuel-rich and fuel-lean regions in or near the burner. In fuel-rich regions, fuel NOx formation is reduced; in fuel-lean regions, thermal NOx formation is reduced. Low NOx burners are often used in conjunction with flue gas recirculation to sustain a lower, stable flame temperature with increased recirculation gas flow.

9.3.2 Selective Catalytic Reduction

SCR is a post-combustion control technology. An SCR emission control system uses a catalyst, typically ammonia or urea, to selectively reduce NOx emissions from exhaust gases (EPA, 2007). NOx is chemically reduced into molecular N_2 and water vapor. The catalyst is not consumed but allows the reactions to occur at a lower temperature.

The SCR system can be installed at different locations including upstream of an air heater and particulate control device, or downstream of the air heater, particulate control device, and flue gas desulfurization systems.

9.4 NOx Emission Reductions

Table 9-4 shows the control measures that were implemented for each SCC and stringency level. Existing (as of 2016) NOx controls were accounted for in the analysis; potential emission reductions were calculated as incremental reductions from the existing controls. Existing NOx controls were identified based on "Control ID" in the 2016v1 modeling platform files. If the existing control efficiency was higher than the selected control measure for a unit, no emission reduction or cost was calculated. If the existing control efficiency was lower than the selected control measure, the surplus emission reduction and associated cost are calculated.

Estimated emission reductions are uncertain because 1) information on existing controls is unlikely to be comprehensive and 2) feasibility and emission reduction potential depends on site-specific conditions such as raw materials and fuels used and existing equipment configurations. Emission reductions can be more accurately estimated based on individual facility specific feasibility and emission control analysis. This analysis is a source category-level evaluation; therefore, facility specific analysis is not included.

Table 9-4. Iron and steel sources control measure applied to each SCC.

SCC	SCC Description	Stringency Level (Control technologies highlighted in grey were assessed in prior tasks but are not evaluated in this white paper) [a]		
		High	Medium	Low
30301503	Industrial Processes; Primary Metal Production; Integrated Iron and Steel Manufacturing; Sintering: Windbox	Selective Catalytic Reduction	Low NOx Burner, Over-fired Air and Gas Reburn	Low NOx Burner
30301512	Industrial Processes; Primary Metal Production; Integrated Iron and Steel Manufacturing; Blast Furnace: Casting/Tapping: Casthouse Roof Monitor	Selective Catalytic Reduction	Low NOx Burner, Over-fired Air and Gas Reburn	Low NOx Burner
30301513	Industrial Processes; Primary Metal Production; Integrated Iron and Steel Manufacturing; Blast Furnace: Casting/Tapping: Local Evacuation	Selective Catalytic Reduction	Low NOx Burner, Over-fired Air and Gas Reburn	Low NOx Burner

SCC	SCC Description	Stringency Level (Control technologies highlighted in grey were assessed in prior tasks but are not evaluated in this white paper) [a]		
		High	Medium	Low
30301522	Industrial Processes; Primary Metal Production; Integrated Iron and Steel Manufacturing; Basic Oxygen Furnace (BOF): Top Blown Furnace: Primary	Selective Catalytic Reduction	Low NOx Burner, Over-fired Air and Gas Reburn	Low NOx Burner
30301526	Industrial Processes; Primary Metal Production; Integrated Iron and Steel Manufacturing; Basic Oxygen Furnace (BOF): Open Hood Stack	Low NOx Burner, Over-fired Air and Gas Reburn	Low NOx Burner, Over-fired Air and Gas Reburn	Low NOx Burner, Over-fired Air and Gas Reburn
30301532	Industrial Processes; Primary Metal Production; Integrated Iron and Steel Manufacturing; Electric Arc Furnace (EAF): Specialty Steel	Selective Catalytic Reduction	Selective Catalytic Reduction	Selective Catalytic Reduction
30301544	Industrial Processes; Primary Metal Production; Integrated Iron and Steel Manufacturing; Electric Arc Furnace (EAF): Carbon Steel	Selective Catalytic Reduction	Selective Catalytic Reduction	Selective Catalytic Reduction
30301575	Industrial Processes; Primary Metal Production; Integrated Iron and Steel Manufacturing; Coating: Tin, Zinc, etc.	Low NOx Burner and Flue Gas Recirculation	Low NOx Burner	Low NOx Burner
30301587	Industrial Processes; Primary Metal Production; Integrated Iron and Steel Manufacturing; Heat Treating Furnace: Annealing	Low NOx Burner and Selective Catalytic Reduction	Low NOx Burner and Flue Gas Recirculation	Low NOx Burner
30301599	Industrial Processes; Primary Metal Production; Integrated Iron and Steel Manufacturing; Other Not Classified	Low NOx Burner and Flue Gas Recirculation	Low NOx Burner	Low Excess Air

[a] Control measure assignments for each SCC were based on EPA's Control Strategy Tool (CoST), version 3.7[60].

Iron and steel NOx emissions and emission reductions by LADCO state are presented in Table 9-5 and by LADCO NAA in Table 9-6. The number of units with 2016 NOx emissions is available in Appendix B.

There are emissions from iron and steel sources above APTE level evaluated herein for Illinois, Michigan and Ohio, but not for Wisconsin and Minnesota. 2016 NOx emissions from iron and steel sources are from Chicago, IN (59%), Ohio (25%), Illinois (11%), and Michigan (6%). Emission reductions in Illinois and Michigan occurred only under the high stringency scenario because the emissions associated with SCC 30301587 under the medium stringency scenario (as shown in Table

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[60] Control Strategy Tool. https://www.epa.gov/economic-and-cost-analysis-air-pollution-regulations/cost-analysis-modelstools-air-pollution#control%20strategy%20tool, Accessed January 2021.

9-4) are too low to be included under any APTE level whereas emission reductions in Ohio occurred under medium and high stringency scenarios.

There are NOx emission reductions in six out of fifteen NAAs. Emission reductions for the Chicago, IN NAA are much larger than any other NAA.

9.5 Cost-effectiveness

Table 9-7 summarizes typical cost-effectiveness estimates for each control measure considered. Facility specific costs will vary based on raw material, fuel characteristics, equipment configuration, and other source specific factors. Table 9-8 and Table 9-9 show statewide cost and cost-effectiveness estimates, respectively. Table 9-10 and Table 9-11 show cost and cost-effectiveness estimates, respectively, by NAA.

Table 9-5. Statewide 2016 NOx emission reductions from iron and steel sources.[26] [61]

State	2016 NOx Emissions (tons/year)	2016 NOx Emission Reductions (tons/year)											
		APTE = 10 tons/year			APTE = 25 tons/year			APTE = 50 tons/year			APTE = 100 tons/year		
		Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
IL	450	-	-	374	-	-	343	-	-	343	-	-	254
MI	231	-	-	61	-	-	44	-	-	-	-	-	-
MN	-	-	-	-	-	-	-	-	-	-	-	-	-
OH	1,020	-	183	458	-	121	414	-	94	277	-	47	49
WI	-	-	-	-	-	-	-	-	-	-	-	-	-

Table 9-6. NOx emission reductions from iron and steel sources by NAA.[26] [28]

Non-Attainment Area	2016 NOx Emissions (tons/year)	2016 NOx Emission Reductions (tons/year)											
		APTE = 10 tons/year			APTE = 25 tons/year			APTE = 50 tons/year			APTE = 100 tons/year		
		Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
Allegan, MI	-	-	-	-	-	-	-	-	-	-	-	-	-
Berrien, MI	-	-	-	-	-	-	-	-	-	-	-	-	-
Chicago, IL	12	-	-	11	-	-	-	-	-	-	-	-	-
Chicago, IN	2,448	[a]	[a]	[a]	[a]	[a]	[a]	-	-	1,552	-	-	1,317
Chicago, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
Cincinnati, OH	57	-	19	-	-	19	-	-	19	-	-	-	-
Cleveland, OH	269	-	28	146	-	28	136	-	28	90	-	-	-
Columbus, OH	-	-	-	-	-	-	-	-	-	-	-	-	-
Detroit, MI	228	-	-	61	-	-	44	-	-	-	-	-	-
Door, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
Manitowoc County, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
Muskegon, MI	<1	-	-	-	-	-	-	-	-	-	-	-	-
Northern Milwaukee/Ozaukee, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
Sheboygan, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
St. Louis, IL	46	-	-	38	-	-	32	-	-	32	-	-	-

[a] APTE values of 10 tons/year and 25 tons/year are not applicable to Chicago, IN

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[61] Cells populated with "-" indicate zero NOx emissions in the inventory and thus no emission reductions.

Table 9-7. Typical cost-effectiveness for each control measure.

Stringency Level	Control Measure	Cost-effectiveness (2020$/ton)	Reference
High	Selective Catalytic Reduction	4,702	EPA CoST[27]
	Low NOx Burner and Flue Gas Recirculation	1,149 or 752 [a]	EPA CoST[27]
Medium	Low NOx Burner and Flue Gas Recirculation	1,485	EPA CoST[27]

[b] The cost-effectiveness is $1,149/ton for Low NOx Burner and Flue Gas Recirculation - Iron & Steel Mills - Galvanizing. The cost-effectiveness is $752/ton for Low NOx Burner and Flue Gas Recirculation - Iron and Steel Production; Blast Heating or Reheating.

Table 9-8. Statewide total cost of iron and steel sources emissions reduction.[26] [62]

State	Total Cost (thousands of 2020$)											
	APTE = 10 tons/year			APTE = 25 tons/year			APTE = 50 tons/year			APTE = 100 tons/year		
	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
IL	-	-	1,288	-	-	1,217	-	-	1,217	-	-	798
MI	-	-	253	-	-	206	-	-	-	-	-	-
MN	-	-	-	-	-	-	-	-	-	-	-	-
OH	-	272	1,627	-	180	1,593	-	140	1,110	-	70	37
WI	-	-	-	-	-	-	-	-	-	-	-	-

Table 9-9. Statewide cost-effectiveness of iron and steel sources emissions reduction.[26] [29]

State	Cost-effectiveness (2020$/ton)											
	APTE = 10 tons/year			APTE = 25 tons/year			APTE = 50 tons/year			APTE = 100 tons/year		
	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
IL	-	-	3,443	-	-	3,547	-	-	3,547	-	-	3,141
MI	-	-	4,137	-	-	4,702	-	-	-	-	-	-
MN	-	-	-	-	-	-	-	-	-	-	-	-
OH	-	1,485	3,555	-	1,485	3,853	-	1,485	4,003	-	1,485	752
WI	-	-	-	-	-	-	-	-	-	-	-	-

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[62] Cells populated with "-" indicate zero NOx emissions in the inventory and thus no associated cost or cost-effectiveness.

Table 9-10. Cost of iron and steel sources emissions reduction by NAA.[26] [29]

Non-Attainment Area	Total Cost (thousands of 2020$)											
	APTE = 10 tons/year			APTE = 25 tons/year			APTE = 50 tons/year			APTE = 100 tons/year		
	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
Allegan, MI	-	-	-	-	-	-	-	-	-	-	-	-
Berrien, MI	-	-	-	-	-	-	-	-	-	-	-	-
Chicago, IL	-	-	53	-	-	-	-	-	-	-	-	-
Chicago, IN	[a]	[a]	[a]	[a]	[a]	[a]	-	-	5,646	-	-	4,775
Chicago, WI	-	-	-	-	-	-	-	-	-	-	-	-
Cincinnati, OH	-	28	-	-	28	-	-	28	-	-	-	-
Cleveland, OH	-	42	607	-	42	600	-	42	422	-	-	-
Columbus, OH	-	-	-	-	-	-	-	-	-	-	-	-
Detroit, MI	-	-	253	-	-	206	-	-	-	-	-	-
Door, WI	-	-	-	-	-	-	-	-	-	-	-	-
Manitowoc County, WI	-	-	-	-	-	-	-	-	-	-	-	-
Muskegon, MI	-	-	-	-	-	-	-	-	-	-	-	-
Northern Milwaukee/Ozaukee, WI	-	-	-	-	-	-	-	-	-	-	-	-
Sheboygan, WI	-	-	-	-	-	-	-	-	-	-	-	-
St. Louis, IL	-	-	157	-	-	153	-	-	153	-	-	-

[a] APTE values of 10 tons/year and 25 tons/year are not applicable to Chicago, IN

Table 9-11. Cost-effectiveness of iron and steel sources emissions reduction by NAA.[26] [29]

Non-Attainment Area	Cost-effectiveness (2020$/ton)											
	APTE = 10 tons/year			APTE = 25 tons/year			APTE = 50 tons/year			APTE = 100 tons/year		
	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
Allegan, MI	-	-	-	-	-	-	-	-	-	-	-	-
Berrien, MI	-	-	-	-	-	-	-	-	-	-	-	-
Chicago, IL	-	-	4,702	-	-	-	-	-	-	-	-	-
Chicago, IN	[a]	[a]	[a]	[a]	[a]	[a]	-	-	3,638	-	-	3,625
Chicago, WI	-	-	-	-	-	-	-	-	-	-	-	-
Cincinnati, OH	-	1,485	-	-	1,485	-	-	1,485	-	-	-	-
Cleveland, OH	-	1,485	4,166	-	1,485	4,416	-	1,485	4,702	-	-	-
Columbus, OH	-	-	-	-	-	-	-	-	-	-	-	-
Detroit, MI	-	-	4,137	-	-	4,702	-	-	-	-	-	-
Door, WI	-	-	-	-	-	-	-	-	-	-	-	-
Manitowoc County, WI	-	-	-	-	-	-	-	-	-	-	-	-
Muskegon, MI	-	-	-	-	-	-	-	-	-	-	-	-
Northern Milwaukee/Ozaukee, WI	-	-	-	-	-	-	-	-	-	-	-	-
Sheboygan, WI	-	-	-	-	-	-	-	-	-	-	-	-
St. Louis, IL	-	-	4,111	-	-	4,702	-	-	4,702	-	-	-

[a] APTE values of 10 tons/year and 25 tons/year are not applicable to Chicago, IN

9.6 Geographic Applicability

NOx emission reductions for iron and steel manufacturing can only be achieved in the counties and states in which iron and steel manufacturing facilities are located. According to EPA’s 2016v1 emission inventory, iron and steel manufacturing statewide emissions were limited to Illinois, Michigan, and Ohio. For NAAs, according to EPA’s 2016v1 emission inventory, there are iron and steel manufacturing emissions in close to half of LADCO region NAAs; however NAA emissions of greater than 50 tons/year are limited to Chicago, IN; Cincinnati, OH; Cleveland, OH; and Detroit, MI.

9.7 Responsible Agency

The state air agency is responsible for enforcing SIP-approved and other air permitting rules. Applicable iron and steel manufacturing emissions in the LADCO area are from sources in EPA’s 2016v1 emission inventory with a range of APTE, from 10 tons/year to greater than over 100 tons/year. Sources with APTE over 100 tons/year are expected to be subject to Title V permit requirements; sources not subject to Title V thresholds may be permitted under state permit requirements.

9.8 Implementation Schedule

After a new rule is promulgated, facilities are typically given time to comply with the new rule for planning, analysis, and infrastructure changes necessary to comply. The timeline for existing sources to comply with MACT standards is typically 3-years, but timelines for compliance typically vary from 1-4 years. Assuming that rules to limit iron and steel manufacturing source emissions are adopted in late-2023, and assuming a 2-year period from rule promulgation to controls installation, emission reduction would be achieved by 2026. Depending on regulatory requirements, a more aggressive or less aggressive timeline may be required in rulemakings.

9.9 Implementation Feasibility

There are several regulatory programs which limit iron and steel manufacturing emissions (examples are listed below); however, NOx emission limits have generally not been explicitly prescribed.

- New Source Performance Standard for Steel Plants: Electric Arc Furnaces and Argon Oxygen Decarburization Vessels (NSPS Subpart AA and Subpart AAa)[63]
- Basic Oxygen Process Furnace (BOPF) Steelmaking Facilities Secondary Emissions: New Source Performance Standards (NSPS Subpart Na)[64]

To develop an emission control regulation for iron and steel manufacturing facilities, a facility-level assessment will likely be necessary as facility specific conditions (raw materials, fuels, and existing equipment configurations) will determine the feasibility and cost of controls.

9.10 Public Acceptance

Iron and steel manufacturing facilities can produce substantial emissions of NOx and other pollutants. Iron and steel manufacturing control measures evaluated herein are very cost-effective and therefore can be shown to be a good regional emission reductions strategy. Iron and steel manufacturing facility operators may object to any further regulation of their operations, especially for the more costly control measures. Grant funding can be used to facilitate implementation of control measures.

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[63] https://www.epa.gov/stationary-sources-air-pollution/electric-arc-furnaces-eafs-and-argon-oxygen-decarburization-vessels, accessed in February, 2022

[64] https://www.epa.gov/stationary-sources-air-pollution/basic-oxygen-process-furnace-bopf-steelmaking-facilities-secondary, accessed in February, 2022

9.11 All Controls Results

Analysis in the sections above includes the controls considered under low, medium, and high stringency scenarios, as indicated in Table 9-4 (i.e., those controls not highlighted in grey on Table 9-4). Emission reduction estimates across the full suite of stringency scenario and control combinations are presented in Appendix A, Tables A1 to A2.

10.0 LIME KILNS

10.1 Summary

This section focuses on emissions reductions for lime kilns. Lime kilns are the main source of NOx emissions in lime manufacturing. Table 10-1 summarizes key information for lime kilns control measures evaluated herein. Applicable emissions, emission reductions, and cost-effectiveness are presented in Table 10-1 on a LADCO region-wide basis. State- and NAA-level emissions, emission reductions, and cost-effectiveness are presented in subsections below. Emission reductions across all control measures (i.e., including control measures not selected for evaluation in this white paper) are provided in Appendix A.

Table 10-1. Control measure summary for lime kilns.[65]

2016 Emissions Estimates					
2016 Emissions [a]	NOx:	9,943 tons/year			
Control Measure Summary, Including 2016 Emission Reduction Estimates					
		APTE = 10 tons/year	**APTE = 25 tons/year**	**APTE = 50 tons/year**	**APTE = 100 tons/year**
Low NOx Burner (High/ Medium/ Low Stringency Scenario)	NOx Reduction:	2,410 tons/year	2,379 tons/year	2,813 tons/year	2,758 tons/year
	Cost-effectiveness:	*$1,109/ton*			
	Applicable States:	*MI, MN, OH, WI*			
	Applicable NAAs:	*Cleveland, OH; Detroit, MI; Manitowoc County, WI*		*Chicago, IN; Cleveland, OH; Detroit, MI; Manitowoc County, WI*	

[a] Source: US Environmental Protection Agency (EPA) 2016v1 modeling platform. Available at https://www.epa.gov/air-emissions-modeling/2016v1-platform, accessed in June 2021.

10.2 Source Description

Limestone is a rock containing at least 50% calcium carbonate. Lime can be produced from the calcination of limestone. It can also be produced from other types of rock such as aragonite, chalk, coral, and marble, and seashells. Lime is produced in kilns through the heating of calcium carbonate in the presence of carbon dioxide and calcium oxide.

90% of lime production is conducted with rotary kilns. A rotary kiln is long, cylindrical, slightly inclined, and lined with refractory material (EPA, 1995). Limestone and hot combustion gases produced by coal, oil, or natural gas are passed through the kiln counter-currently. The other major type of kiln used in the US is the vertical kiln. It is an upright steel cylinder lined with refractory material. Limestone is charged at the top of the kiln. As it descends through the kiln, it calcinates. Vertical kilns have a higher average fuel efficiency, but lower production rates and coal cannot be used as a heating source without degrading the quality of the lime produced. An emerging lime production process involves the use of a parallel flow regenerative lime kiln. In a parallel flow regenerative lime kiln, the charge material and combustion gas flow concurrently. A parallel flow regenerative lime kiln is efficient since the multiple-chamber regenerative process allows the charge material to preheat the combustion air. Regenerative lime kilns can have either 2 or 3 shafts.

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[65] Excludes Indiana emissions except for in Chicago, Indiana nonattainment area counties (Lake County and Porter County).

Substantial amounts of NOx are emitted from combustion in the kiln (EPA, 1995). Fuel combustion NOx results from both oxidation of chemically-bound nitrogen in the fuel and thermal fixation of nitrogen in the combustion air. Higher flame temperature and higher fuel nitrogen content result in higher NOx formation. Lime kilns also generate substantial PM.

Table 10-2 lists the applicable SCCs for lime kiln sources in the LADCO stationary point source inventory.

Table 10-2. Applicable SCCs for Lime Kilns.

Description One	Description Two	Description Three	Description Four	SCC
Industrial Processes	Mineral Products	Lime Manufacture	Calcining: Vertical Kiln	30501603
			Calcining: Rotary Kiln (See SCC Codes 3-05-016-18,-19,-20,-21)	30501604
			Calcining: Coal-fired Rotary Kiln	30501618
			Calcining: Coal- and Gas-fired Rotary Kiln	30501620
	Pulp and Paper and Wood Products	Sulfate (Kraft) Pulping	Lime Kiln	30700106

10.3 Selected Control Measures Description

For lime kilns, specific control measures were considered for each stringency level. The selected control measures and their estimated control efficiency are shown in Table 10-3. Descriptions of each control measure are included in the subsections below.

Table 10-3. Applicable control technology and associated control efficiency by stringency level.

Stringency Level	Control Measure	Control Efficiency (%)
High, Medium, Low	Low NOx Burner	30

10.3.1 Low-NOx burner

LNB is a combustion modification control technology that reduces NOx emissions by reducing flame turbulence, delaying fuel/air mixing, and establishing fuel-rich zones for initial combustion (EPA, 2007). Staged combustion is used to lower flame temperatures and reduce thermal NOx formation. Lime kilns in which less than 10% of the total combustion air is primary air are considered indirect-fired kilns. A greater proportion of recycled clinker cooler air is available for use as secondary combustion air in indirect-fired kilns; LNB can only be applied to indirect-fired kilns.

LNB kilns have two combustion zones; the first stage is the primary combustion zone and the second stage is the secondary combustion zone. In the primary combustion zone, flame turbulence and air and fuel mixing are suppressed, reducing the amount of primary air and delaying fuel combustion. Typically, flue gas is recycled into the primary combustion zone to reduce oxygen content and create a fuel-rich atmosphere. Thermal NOx formation is suppressed in the primary combustion zone because less oxygen is available. In the secondary combustion zone, cooler, oxygen-rich air is mixed into the secondary combustion zone, lowering temperature and thereby reducing NOx formation.

10.4 NOx Emission Reductions

Table 10-4 shows the control measures that were implemented for each SCC and stringency level. Existing (as of 2016) NOx controls were accounted for in the analysis; potential emission reductions were calculated as incremental reductions from the existing controls. Existing NOx controls were identified based on "Control ID" in the 2016v1 modeling platform files. If the existing control efficiency was higher than the selected control measure for a unit, no emission reduction or cost was calculated. If the existing control efficiency was lower than the selected control measure, the surplus emission reduction and associated cost are calculated.

Estimated emission reductions are uncertain because 1) information on existing controls is unlikely to be comprehensive and 2) feasibility and emission reduction potential depends on site-specific conditions such as raw materials and fuels used and existing equipment configurations. Emission reductions can be more accurately estimated based on individual facility specific feasibility and emission control analysis. This analysis is a source category-level evaluation; therefore, facility specific analysis is not included.

Table 10-4. Lime kilns control measure applied to each SCC.

SCC	SCC Description	Stringency Level [a]		
		High	Medium	Low
30501603	Industrial Processes; Mineral Products; Lime Manufacture; Calcining: Vertical Kiln	Low NOx Burner		
30501604	Industrial Processes; Mineral Products; Lime Manufacture; Calcining: Rotary Kiln (See SCC Codes 3-05-016-18,-19,-20,-21)	Low NOx Burner		
30501618	Industrial Processes; Mineral Products; Lime Manufacture; Calcining: Coal-fired Rotary Kiln	Low NOx Burner		
30501620	Industrial Processes; Mineral Products; Lime Manufacture; Calcining: Coal- and Gas-fired Rotary Kiln	Low NOx Burner		
30700106	Industrial Processes; Pulp and Paper and Wood Products; Sulfate (Kraft) Pulping; Lime Kiln	Low NOx Burner		

[a] Control measure assignments for each SCC were based on EPA's Control Strategy Tool (CoST), version 3.7[66].

Lime kilns NOx emissions and emission reductions by LADCO state are presented in Table 10-5 and by LADCO NAA in Table 10-6. The number of units with 2016 NOx emissions is available in Appendix B.

There are statewide emission reductions in Michigan, Minnesota, Ohio, and Wisconsin, but not Illinois. Emissions are similar, though not equivalent across APTE levels indicating that most potentially controlled sources have NOx APTE greater than 100 tpy. Emission reductions are equivalent across stringency levels because the same control (low NOx burners) is assumed for all stringency scenarios. 2016 NOx emissions from lime kilns are from Ohio (61%), Chicago, IN (16%), Wisconsin (13%), Michigan (6%), and Minnesota (3%); NOx emission reductions are distributed similarly across stringency scenarios and APTE levels. There are NOx emission reductions in four NAAs, Chicago, IN; Cleveland, OH; Detroit, MI; and Manitowoc County, WI.

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[66] Control Strategy Tool. https://www.epa.gov/economic-and-cost-analysis-air-pollution-regulations/cost-analysis-modelstools-air-pollution#control%20strategy%20tool, Accessed January 2021.

10.5 Cost-effectiveness

Table 10-7 summarizes typical cost-effectiveness estimates for each control measure considered. Facility specific costs will vary based on raw material, fuel characteristics, equipment configuration, and other source specific factors. Table 10-8 and Table 10-9 show statewide cost and cost-effectiveness estimates, respectively. Table 10-10 and Table 10-11 show cost and cost-effectiveness estimates, respectively, by NAA.

Table 10-5. Statewide 2016 NOx emission reductions from lime kilns.[26] [67]

State	2016 NOx Emissions (tons/year)	2016 NOx Emission Reductions (tons/year)											
		APTE = 10 tons/year			APTE = 25 tons/year			APTE = 50 tons/year			APTE = 100 tons/year		
		Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
IL	-	-	-	-	-	-	-	-	-	-	-	-	-
MI	633	186	186	186	186	186	186	178	178	178	170	170	170
MN	318	95	95	95	74	74	74	66	66	66	58	58	58
OH	6,112	1,829	1,829	1,829	1,820	1,820	1,820	1,816	1,816	1,816	1,816	1,816	1,816
WI	1,325	301	301	301	299	299	299	286	286	286	247	247	247

Table 10-6. NOx emission reductions from lime kilns by NAA.[26] [28]

Non-Attainment Area	2016 NOx Emissions (tons/year)	2016 NOx Emission Reductions (tons/year)											
		APTE = 10 tons/year			APTE = 25 tons/year			APTE = 50 tons/year			APTE = 100 tons/year		
		Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
Allegan, MI	-	-	-	-	-	-	-	-	-	-	-	-	-
Berrien, MI	-	-	-	-	-	-	-	-	-	-	-	-	-
Chicago, IL	-	-	-	-	-	-	-	-	-	-	-	-	-
Chicago, IN	1,556	[a]	[a]	[a]	[a]	[a]	[a]	467	467	467	467	467	467
Chicago, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
Cincinnati, OH	-	-	-	-	-	-	-	-	-	-	-	-	-
Cleveland, OH	368	110	110	110	110	110	110	110	110	110	110	110	110
Columbus, OH	-	-	-	-	-	-	-	-	-	-	-	-	-
Detroit, MI	565	170	170	170	170	170	170	170	170	170	170	170	170
Door, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
Manitowoc County, WI	304	69	69	69	69	69	69	64	64	64	64	64	64
Muskegon, MI	-	-	-	-	-	-	-	-	-	-	-	-	-
Northern Milwaukee/Ozaukee, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
Sheboygan, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
St. Louis, IL	-	-	-	-	-	-	-	-	-	-	-	-	-

[a] APTE values of 10 tons/year and 25 tons/year are not applicable to Chicago, IN

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[67] Cells populated with "-" indicate zero NOx emissions in the inventory and thus no emission reductions.

Table 10-7. Typical cost-effectiveness for each control measure.

Stringency Level	Control Measure	Cost-effectiveness (2020$/ton)	Reference
High, Medium, Low	Low NOx Burner	1,109	EPA CoST[27]

Table 10-8. Statewide total cost of lime kilns emissions reduction.[26] [68]

State	Total Cost (thousands of 2020$)											
	APTE = 10 tons/year			APTE = 25 tons/year			APTE = 50 tons/year			APTE = 100 tons/year		
	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
IL	-	-	-	-	-	-	-	-	-	-	-	-
MI	206	206	206	206	206	206	197	197	197	188	188	188
MN	105	105	105	82	82	82	73	73	73	65	65	65
OH	2,028	2,028	2,028	2,018	2,018	2,018	2,014	2,014	2,014	2,014	2,014	2,014
WI	333	333	333	332	332	332	317	317	317	274	274	274

Table 10-9. Statewide cost-effectiveness of lime kilns emissions reduction.[26] [29]

State	Cost-effectiveness (2020$/ton)											
	APTE = 10 tons/year			APTE = 25 tons/year			APTE = 50 tons/year			APTE = 100 tons/year		
	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
IL	-	-	-	-	-	-	-	-	-	-	-	-
MI	1,109	1,109	1,109	1,109	1,109	1,109	1,109	1,109	1,109	1,109	1,109	1,109
MN	1,109	1,109	1,109	1,109	1,109	1,109	1,109	1,109	1,109	1,109	1,109	1,109
OH	1,109	1,109	1,109	1,109	1,109	1,109	1,109	1,109	1,109	1,109	1,109	1,109
WI	1,109	1,109	1,109	1,109	1,109	1,109	1,109	1,109	1,109	1,109	1,109	1,109

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[68] Cells populated with "-" indicate zero NOx emissions in the inventory and thus no associated cost or cost-effectiveness.

Table 10-10. Cost of lime kilns emissions reduction by NAA. [26] [29]

Non-Attainment Area	**Total Cost (thousands of 2020$)**											
	APTE = 10 tons/year			**APTE = 25 tons/year**			**APTE = 50 tons/year**			**APTE = 100 tons/year**		
	Low	**Med**	**High**	**Low**	**Med**	**High**	**Low**	**Med**	**High**	**Low**	**Med**	**High**
Allegan, MI	-	-	-	-	-	-	-	-	-	-	-	-
Berrien, MI	-	-	-	-	-	-	-	-	-	-	-	-
Chicago, IL	-	-	-	-	-	-	-	-	-	-	-	-
Chicago, IN	[a]	[a]	[a]	[a]	[a]	[a]	518	518	518	518	518	518
Chicago, WI	-	-	-	-	-	-	-	-	-	-	-	-
Cincinnati, OH	-	-	-	-	-	-	-	-	-	-	-	-
Cleveland, OH	122	122	122	122	122	122	122	122	122	122	122	122
Columbus, OH	-	-	-	-	-	-	-	-	-	-	-	-
Detroit, MI	188	188	188	188	188	188	188	188	188	188	188	188
Door, WI	-	-	-	-	-	-	-	-	-	-	-	-
Manitowoc County, WI	76	76	76	76	76	76	71	71	71	71	71	71
Muskegon, MI	-	-	-	-	-	-	-	-	-	-	-	-
Northern Milwaukee/Ozaukee, WI	-	-	-	-	-	-	-	-	-	-	-	-
Sheboygan, WI	-	-	-	-	-	-	-	-	-	-	-	-
St. Louis, IL	-	-	-	-	-	-	-	-	-	-	-	-

[a] APTE values of 10 tons/year and 25 tons/year are not applicable to Chicago, IN

Table 10-11. Cost-effectiveness of lime kilns emissions reduction by NAA.[26] [29]

Non-Attainment Area	Cost-effectiveness (2020$/ton)											
	APTE = 10 tons/year			APTE = 25 tons/year			APTE = 50 tons/year			APTE = 100 tons/year		
	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
Allegan, MI	-	-	-	-	-	-	-	-	-	-	-	-
Berrien, MI	-	-	-	-	-	-	-	-	-	-	-	-
Chicago, IL	-	-	-	-	-	-	-	-	-	-	-	-
Chicago, IN	[a]	[a]	[a]	[a]	[a]	[a]	1,109	1,109	1,109	1,109	1,109	1,109
Chicago, WI	-	-	-	-	-	-	-	-	-	-	-	-
Cincinnati, OH	-	-	-	-	-	-	-	-	-	-	-	-
Cleveland, OH	1,109	1,109	1,109	1,109	1,109	1,109	1,109	1,109	1,109	1,109	1,109	1,109
Columbus, OH	-	-	-	-	-	-	-	-	-	-	-	-
Detroit, MI	1,109	1,109	1,109	1,109	1,109	1,109	1,109	1,109	1,109	1,109	1,109	1,109
Door, WI	-	-	-	-	-	-	-	-	-	-	-	-
Manitowoc County, WI	1,109	1,109	1,109	1,109	1,109	1,109	1,109	1,109	1,109	1,109	1,109	1,109
Muskegon, MI	-	-	-	-	-	-	-	-	-	-	-	-
Northern Milwaukee/Ozaukee, WI	-	-	-	-	-	-	-	-	-	-	-	-
Sheboygan, WI	-	-	-	-	-	-	-	-	-	-	-	-
St. Louis, IL	-	-	-	-	-	-	-	-	-	-	-	-

[a] APTE values of 10 tons/year and 25 tons/year are not applicable to Chicago, IN

10.6 Geographic Applicability

NOx emission reductions for lime kilns can only be achieved in the counties and states in which lime kilns are located. According to EPA's 2016v1 emission inventory, lime kiln statewide emissions were limited to Michigan, Minnesota, Ohio and Wisconsin; there were no lime kiln emissions in Illinois. For NAAs, according to EPA's 2016v1 emission inventory, there are lime kiln emissions in the following LADCO region NAAs: Chicago, IN; Cleveland, OH; Detroit, MI; and Manitowoc County, WI. A vast majority of lime kiln emissions are located outside of NAAs for Minnesota, Ohio, and Wisconsin, but not Michigan.

10.7 Responsible Agency

The state air agency is responsible for enforcing SIP-approved and other air permitting rules. Most lime kiln emission source in the LADCO area have NOx APTE emissions in EPA's 2016v1 emission inventory of over 100 tons/year and therefore are expected to be subject Title V permit requirements. Sources not subject to Title V thresholds may be permitted under state permit requirements.

10.8 Implementation Schedule

After a new rule is promulgated, facilities are typically given time to comply with the new rule for planning, analysis, and infrastructure changes necessary to comply. The timeline for existing sources to comply with MACT standards is typically 3-years, but timelines for compliance typically vary from 1-4 years. Assuming that rules to limit lime kiln emissions are adopted in late-2023, and assuming a 2-year period from rule promulgation to controls installation, emission reduction would be achieved by 2026. Depending on regulatory requirements, a more aggressive or less aggressive timeline may be required in rulemakings.

10.9 Implementation Feasibility

Emission requirements for lime kilns may be expressed in mass of NOx emitted per unit of energy consumption. An example of an existing rule to limit NOx emissions from Lime Kilns is San Joaquin Valley Air District: Rule 4313 Lime Kilns[69]. To develop an emission control regulation for lime kilns, a facility-level assessment will likely be necessary as facility specific conditions (raw materials, fuels, and existing equipment configurations) to determine the feasibility and cost of controls.

10.10 Public Acceptance

Lime kilns can produce substantial emissions of NOx and other pollutants. The lime kiln emission control measure evaluated herein is very cost-effective and therefore can be shown to be a good regional emission reductions strategy. Lime kiln facility operators may object to any further regulation of their operations. Grant funding can be used to facilitate implementation of control measures.

10.11 All Controls Results

Analysis in the sections above includes the controls considered under low, medium, and high stringency scenarios, as indicated in Table 10-4 (i.e., those controls not highlighted in grey on Table 10-4). Emission reduction estimates across the full suite of stringency scenario and control combinations are presented in Appendix A, Tables A1 to A2.

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[69] https://www.valleyair.org/rules/currntrules/r4313.pdf, accessed in January, 2022

11.0 PROCESS HEATERS

11.1 Summary

This section focuses on emissions reductions for process heaters. Process heaters, typically fueled by natural gas or process gas, are used in a wide variety of industries for material heating applications. Table 11-1 summarizes key information for process heaters control measures evaluated herein. Applicable emissions, emission reductions, and cost-effectiveness are presented in Table 11-1 on a LADCO region-wide basis. State- and NAA-level emissions, emission reductions, and cost-effectiveness are presented in subsections below. Emission reductions across all control measures (i.e., including control measures not selected for evaluation in this white paper) are provided in Appendix A.

Table 11-1. Control measure summary for process heaters.[70]

2016 Emissions Estimates					
2016 Emissions [a]	NOx:	18,285 tons/year			
Control Measure Summary, Including 2016 Emission Reduction Estimates					
		APTE = 10 tons/year	**APTE = 25 tons/year**	**APTE = 50 tons/year**	**APTE = 100 tons/year**
Low NOx Burner (High Stringency Scenario)	NOx Reduction:	56 tons/year	21 tons/year		*Not Applicable* [d]
	Cost-effectiveness:	*$4,356/ton* [b]			
	Applicable States:	*IL, MI, OH, WI*	*IL*		
	Applicable NAAs:	*Chicago, IL; Cincinnati, OH; Detroit, MI; Manitowoc County, WI*	*Chicago, IL*		
Selective Catalytic Reduction (High Stringency Scenario)	NOx Reduction:	5,542 tons/year	4,629 tons/year	5,176 tons/year	4,354 tons/year
	Cost-effectiveness:	*$4,830, $7,694, or $10,957/ton* [c]			
	Applicable States:	*IL, MI, MN, OH, WI*	*IL, MI, OH, WI*		
	Applicable NAAs:	*Chicago, IL; Cincinnati, OH; Cleveland, OH; Columbus, OH; Detroit, MI; Manitowoc County, WI; Muskegon, MI; Northern Milwaukee/Ozaukee, WI; Sheboygan, WI; St. Louis, IL*	*Chicago, IL; Cincinnati, OH; Cleveland, OH; Detroit, MI; Manitowoc County, WI; Muskegon, MI; Northern Milwaukee/Ozaukee, WI; Sheboygan, WI; St. Louis, IL*	*Chicago, IL; Chicago, IN; Cincinnati, OH; Cleveland, OH; Detroit, MI; Northern Milwaukee/Ozaukee, WI; Sheboygan, WI*	*Chicago, IL; Chicago, IN; Cincinnati, OH; Cleveland, OH; Detroit, MI*
Low NOx Burner (Medium	NOx Reduction:	702 tons/year	536 tons/year	795 tons/year	612 tons/year
	Cost-effectiveness:	*$4,356/ton* [b]			
	Applicable States:	*IL, MI, OH, WI*	*IL, OH, WI*		*OH*

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[70] Excludes Indiana emissions except for in Chicago, Indiana nonattainment area counties (Lake County and Porter County).

2016 Emissions Estimates					
2016 Emissions [a]	NOx:	18,285 tons/year			
Control Measure Summary, Including 2016 Emission Reduction Estimates					
Stringency Scenario)	*Applicable NAAs:*	*Chicago, IL; Cincinnati, OH; Cleveland, OH; Columbus, OH; Detroit, MI; Manitowoc County, WI; Muskegon, MI; Northern Milwaukee/Ozaukee, WI*	*Chicago, IL; Cleveland, OH; Northern Milwaukee/Ozaukee, WI*	*Chicago, IL; Chicago, IN; Cleveland, OH;*	*Chicago, IN; Cleveland, OH;*
Selective Catalytic Reduction (Medium Stringency Scenario)	NOx Reduction:	2,954 tons/year	2,689 tons/year	2,544 tons/year	1,799 tons/year
	Cost-effectiveness:	*$11,080/ton*			
	Applicable States:	*IL, MI, MN, OH*			*IL, MN, OH*
	Applicable NAAs:	*Chicago, IL; Detroit, MI; St. Louis, IL*		*Chicago, IL; Chicago, IN; Detroit, MI; St. Louis, IL*	*Chicago, IL; Chicago, IN; St. Louis, IL*
Ultra-low NOx Burner (Medium Stringency Scenario)	NOx Reduction:	2,954 tons/year	2,689 tons/year	*Not Applicable* [d]	*Not Applicable* [d]
	Cost-effectiveness:	*$3,090/ton*			
	Applicable States:	*WI*			
	Applicable NAAs:	*None* [e]			
Excess O2 Control (Low Stringency Scenario)	NOx Reduction:	2,499 tons/year	2,253 tons/year	1,982 tons/year	1,475 tons/year
	Cost-effectiveness:	*$72/ton*			
	Applicable States:	*IL, MI, MN, OH*			*IL, MN, OH*
	Applicable NAAs:	*Chicago, IL; Detroit, MI; St. Louis, IL*		*Chicago, IL; Chicago, IN; Detroit, MI; St. Louis, IL*	*Chicago, IL; Chicago, IN; St. Louis, IL*

2016 Emissions Estimates					
2016 Emissions [a]	NOx:	18,285 tons/year			
Control Measure Summary, Including 2016 Emission Reduction Estimates					
Low NOx Burner (Low Stringency Scenario)	NOx Reduction:	1,186 tons/year	952 tons/year	1,483 tons/year	1,252 tons/year
	Cost-effectiveness:	*$4,356, $5,193 or $4,533/ton* [b]		*$4,356 or $5,193/ton* [b]	
	Applicable States:	*IL, MI, OH, WI*			*MI, OH*
	Applicable NAAs:	*Chicago, IL; Cincinnati, OH; Cleveland, OH; Columbus, OH; Detroit, MI; Manitowoc County, WI; Muskegon, MI; Northern Milwaukee/Ozaukee, WI; St. Louis, IL*	*Chicago, IL; Cleveland, OH; Detroit, MI; Northern Milwaukee/Ozaukee, WI*	*Chicago, IL; Chicago, IN; Cleveland, OH; Detroit, MI*	*Chicago, IN; Cleveland, OH; Detroit, MI*

[a] Source: US Environmental Protection Agency (EPA) 2016v1 modeling platform. Available at https://www.epa.gov/air-emissions-modeling/2016v1-platform, accessed in June 2021.

[b] The cost-effectiveness is $5,193/ton for Low NOx Burner - Process Heaters - Other Fuel. The cost-effectiveness is $4,533/ton for Low NOx Burner - Process Heaters – Process Gas. The cost-effectiveness is $4,356/ton for all other LNB control measures.

[c] The cost-effectiveness is $4,830/ton for Selective Catalytic Reduction - Indust. Incinerators. The cost-effectiveness is $7,694/ton for Selective Catalytic Reduction - In-Process Fuel Use; Natural Gas; Gen. The cost-effectiveness is $10,957/ton for Selective Catalytic Reduction - ICI Boilers – Gas.

[d] There were no process heater sources in the APTE level.

[e] There were no process heater emissions in any LADCO NAA.

11.2 Source Description

Process heaters are used for material heating applications using fuel combustion within a production process (EPA, 2004). Process heaters are composed of burner(s), combustion chamber(s), and tubes. There are two main types of process heaters: indirect-fired process heaters in which direct flame contact with the material being processed does not occur, and direct-fire process heaters where the material is directly heated.

Emissions from indirect-fired units consist of combustion products, while direct-fired units also generate emissions from the process material itself. Heated feed process heaters heat a process fluid stream before it goes through additional processing and are used in petroleum refining and chemical manufacturing. Reaction feed process heaters provide heat for a chemical reaction to occur inside the tubes that are being heated. Air is introduced to the burners through either natural draft, where ductwork systems route ambient air into the burners, or mechanical draft, where fans are used to feed often preheated air into the burners.

Emissions from process heaters mainly come from combustion and include NO_x and other pollutants.

Table 11-2 lists the applicable SCCs for process heater sources in the LADCO stationary point source inventory.

Table 11-2. Applicable SCCs for Process Heaters.

Description One	Description Two	Description Three	Description Four	SCC
Industrial Processes	Chemical Manufacturing	Fuel Fired Equipment	Process Heater: Natural Gas	30190003
			Process Heater: Process Gas	30190004
			Incinerator: Natural Gas	30190013
	Food and Agriculture		Natural Gas: Process Heaters	30290003
	Primary Metal Production		Natural Gas: Process Heaters	30390003
			Process Gas: Process Heaters	30390004
	Secondary Metal Production		Natural Gas: Process Heaters	30490003
	Mineral Products		Natural Gas: Process Heaters	30590003
	Petroleum Industry	Process Heaters	Gas	30600104
			Natural Gas	30600105
			Process Gas	30600106
	Fabricated Metal Products	Fuel Fired Equipment	Natural Gas: Process Heaters	30990003
	In-process Fuel Use	Natural Gas	General	39000699
		Process Gas	General	39000797
	Miscellaneous Manufacturing Industries	Process Heater/Furnace	Natural Gas	39900601
			Digester Gas	39900721
		Miscellaneous Manufacturing Industries	Natural Gas: Process Heaters	39990003

Description One	Description Two	Description Three	Description Four	SCC
Chemical Evaporation	Surface Coating Operations	Coating Oven Heater	Natural Gas	40201001

11.3 Selected Control Measures Description

For process heaters, specific control measures were considered for each stringency level. The selected control measures and their estimated control efficiency are shown in Table 11-3. Descriptions of each control measure are included in the subsections below.

Table 11-3. Applicable control technology and associated control efficiency by stringency level.

Stringency Level	Control Measure	Control Efficiency (%)
High, Medium, Low	Low NOx Burner	50
High	Selective Catalytic Reduction	90 or 85 [a]
Medium	Selective Catalytic Reduction	71
	Ultra-Low NOx Burner	75
Low	Low NOx Burner	50 or 37 [b]
	Excess O2 Control	37

[a] The control efficiency is 90% for Selective Catalytic Reduction - Indust. Incinerators and Selective Catalytic Reduction - In-Process Fuel Use; Natural Gas; Gen. The control efficiency is 85% for Selective Catalytic Reduction - ICI Boilers – Gas.

[b] The control efficiency is 37% for Low NOx Burner - Process Heaters - Other Fuel. The control efficiency is 50% for all other LNB control measures.

11.3.1 Excess O2 Control

Excess oxygen control optimizes the amount of air available for combustion to reduce NOx formation and fuel consumption (EPA, 1993). Decreased oxygen concentration in the combustion zone causes a reducing condition which inhibits formation of both fuel and thermal NOx formation. Flue gas temperature is also lowered which further reduces thermal NOx formation. Heat loss is decreased, resulting in lower fuel consumption. Optimal excess oxygen levels differ for each heater based on draft type, fuel type, burner type, and degree of combustion air preheat. Retrofitting older heaters can be cost-intensive due to required equipment configuration changes.

11.3.2 Low NOx Burner

Low NOx burners spread combustion over multiple stages allowing for control of both stoichiometric and temperature profiles during combustion (EPA, 1994). Emission reductions are achieved by one or more of the following:

- Reducing oxygen content in the combustion zone, limiting fuel NOx formation;
- Reducing flame temperature, limiting thermal NOx formation;
- Reducing residence time at peak temperature, limiting thermal NOx formation;

Low NOx burners may be designed to delay the combustion process resulting in a cooler flame thereby suppressing thermal NOx or to create stratified fuel-rich and fuel-lean regions in or near the burner. In fuel-rich regions, fuel NOx formation is reduced; in fuel-lean regions, thermal NOx formation is reduced.

11.3.3 Selective Catalytic Reduction

SCR is a post-combustion control technology. An SCR emission control system uses a catalyst, typically ammonia or urea, to selectively reduce NOx emissions from exhaust gases (EPA, 2007). NOx is chemically reduced into molecular N_2 and water vapor. The catalyst is not consumed but allows the reactions to occur at a lower temperature.

The SCR system can be installed at different locations including upstream of an air heater and particulate control device, or downstream of the air heater, particulate control device, and flue gas desulfurization systems.

11.3.4 Ultra-Low NOx Burner

Similar to Low NOx burners, ultra-low NOx burners spread combustion over multiple stages allowing for control of both stoichiometric and temperature profiles during combustion. Emission reductions are achieved by one or more of the following:

- Reducing oxygen content in the combustion zone, limiting fuel NOx formation;
- Reducing flame temperature, limiting thermal NOx formation;
- Reducing residence time at peak temperature, limiting thermal NOx formation;

An ultra-low NOx burner is typically designed to recirculate oxygen depleted flue gas back into the combustion zone, reducing oxygen concentration in the flame and thereby reducing fuel NOx formation. Ultra-low NOx burners may require changes to boiler configuration when used as a retrofit.

11.4 NOx Emission Reductions

Table 11-4 shows the control measures that were implemented for each SCC and stringency level. Existing (as of 2016) NOx controls were accounted for in the analysis; potential emission reductions were calculated as incremental reductions from the existing controls. Existing NOx controls were identified based on "Control ID" in the 2016v1 modeling platform files. If the existing control efficiency was higher than the selected control measure for a unit, no emission reduction or cost was calculated. If the existing control efficiency was lower than the selected control measure, the surplus emission reduction and associated cost are calculated.

Estimated emission reductions are uncertain because 1) information on existing controls is unlikely to be comprehensive and 2) feasibility and emission reduction potential depends on site-specific conditions such as raw materials and fuels used and existing equipment configurations. Emission reductions can be more accurately estimated based on individual facility specific feasibility and emission control analysis. This analysis is a source category-level evaluation; therefore, facility specific analysis is not included.

Table 11-4. Process heaters control measure applied to each SCC.

SCC	SCC Description	Stringency Level (Control technologies highlighted in grey were assessed in prior tasks but are not evaluated in this white paper) [a]		
		High	Medium	Low
30190003	Industrial Processes; Chemical Manufacturing; Fuel Fired Equipment; Process Heater: Natural Gas	Selective Catalytic Reduction	Regenerative Selective Catalytic Reduction	Selective Non-Catalytic Reduction
30190004	Industrial Processes; Chemical Manufacturing; Fuel Fired Equipment; Process Heater: Process Gas	Low NOx Burner and Selective Catalytic Reduction	Ultra-Low NOx Burner	Low NOx Burner

SCC	SCC Description	Stringency Level (Control technologies highlighted in grey were assessed in prior tasks but are not evaluated in this white paper) [a] High	Medium	Low
30190013	Industrial Processes; Chemical Manufacturing; Fuel Fired Equipment; Incinerator: Natural Gas	Selective Catalytic Reduction	Selective Non-Catalytic Reduction	Selective Non-Catalytic Reduction
30290003	Industrial Processes; Food and Agriculture; Fuel Fired Equipment; Natural Gas: Process Heaters	Low NOx Burner and Selective Catalytic Reduction	Regenerative Selective Catalytic Reduction	Selective Non-Catalytic Reduction
30390003	Industrial Processes; Primary Metal Production; Fuel Fired Equipment; Natural Gas: Process Heaters	Selective Catalytic Reduction	Low NOx Burner and Flue Gas Recirculation	Low NOx Burner
30390004	Industrial Processes; Primary Metal Production; Fuel Fired Equipment; Process Gas: Process Heaters	Low NOx Burner and Selective Non-Catalytic Reduction	Low NOx Burner and Flue Gas Recirculation	Low NOx Burner and Flue Gas Recirculation
30490003	Industrial Processes; Secondary Metal Production; Fuel Fired Equipment; Natural Gas: Process Heaters	Selective Catalytic Reduction	Regenerative Selective Catalytic Reduction	Selective Non-Catalytic Reduction
30590003	Industrial Processes; Mineral Products; Fuel Fired Equipment; Natural Gas: Process Heaters	Low NOx Burner and Selective Catalytic Reduction	Regenerative Selective Catalytic Reduction	Selective Non-Catalytic Reduction
30600104	Industrial Processes; Petroleum Industry; Process Heaters; Gas	Selective Catalytic Reduction	Low NOx Burner and Flue Gas Recirculation	Excess O2 Control
30600105	Industrial Processes; Petroleum Industry; Process Heaters; Natural Gas	Low NOx Burner and Selective Catalytic Reduction	Regenerative Selective Catalytic Reduction	Excess O2 Control
30600106	Industrial Processes; Petroleum Industry; Process Heaters; Process Gas	Low NOx Burner and Selective Catalytic Reduction	Selective Catalytic Reduction	Excess O2 Control
30990003	Industrial Processes; Fabricated Metal Products; Fuel Fired Equipment; Natural Gas: Process Heaters	Low NOx Burner and Selective Catalytic Reduction	Regenerative Selective Catalytic Reduction	Selective Non-Catalytic Reduction
39000699	Industrial Processes; In-process Fuel Use; Natural Gas; General	Selective Catalytic Reduction	Low NOx Burner	Low NOx Burner
39000797	Industrial Processes; In-process Fuel Use; Process Gas; General	Low NOx Burner and Flue Gas Recirculation	Low NOx Burner	Low NOx Burner

SCC	SCC Description	Stringency Level (Control technologies highlighted in grey were assessed in prior tasks but are not evaluated in this white paper) [a]		
		High	Medium	Low
39900601	Industrial Processes; Miscellaneous Manufacturing Industries; Process Heater/Furnace; Natural Gas	Selective Catalytic Reduction	Regenerative Selective Catalytic Reduction	Selective Non-Catalytic Reduction
39900721	Industrial Processes; Miscellaneous Manufacturing Industries; Process Heater/Furnace; Digester Gas	Low NOx Burner and Flue Gas Recirculation	Low NOx Burner and Flue Gas Recirculation	Low NOx Burner and Flue Gas Recirculation
39990003	Industrial Processes; Miscellaneous Manufacturing Industries; Miscellaneous Manufacturing Industries; Natural Gas: Process Heaters	Selective Catalytic Reduction	Regenerative Selective Catalytic Reduction	Selective Non-Catalytic Reduction
40201001	Chemical Evaporation; Surface Coating Operations; Coating Oven Heater; Natural Gas	Low NOx Burner	Low NOx Burner	Low NOx Burner

[a] Control measure assignments for each SCC were based on EPA's Menu of Control Measures[71] and EPA's Control Strategy Tool (CoST), version 3.7[72].

Process heaters NOx emissions and emission reductions by LADCO state are presented in Table 11-5 and by LADCO NAA in Table 11-6. The number of units with 2016 NOx emissions is available in Appendix B.

2016 NOx emissions from process heaters are from Illinois (29%), Ohio (23%), Chicago, IN (18%), Michigan (13%), Minnesota (9%), Wisconsin (6%). State-level emission reductions differ under each APTE level indicating that potentially controlled sources have a range of NOx APTE from 10 tons/year to greater than 100 tons/year. There are NOx emission reductions in all but two NAAs, Chicago, WI and Door, WI.

11.5 Cost-effectiveness

Table 11-7 summarizes typical cost-effectiveness estimates for each control measure considered. Facility specific costs will vary based on raw material, fuel characteristics, equipment configuration, and other source specific factors. Table 11-8 and Table 11-9 show statewide cost and cost-effectiveness estimates, respectively. Table 11-10 and Table 11-11 show cost and cost-effectiveness estimates, respectively, by NAA.

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[71] Menu of Control Measures for NAAQS Implementation. https://www.epa.gov/air-quality-implementation-plans/menu-control-measures-naaqs-implementation, Accessed January 2021.

[72] Control Strategy Tool. https://www.epa.gov/economic-and-cost-analysis-air-pollution-regulations/cost-analysis-modelstools-air-pollution#control%20strategy%20tool, Accessed January 2021.

Table 11-5. Statewide 2016 NOx emission reductions from process heaters.[26] [73]

State	2016 NOx Emissions (tons/year)	2016 NOx Emission Reductions (tons/year)											
		APTE = 10 tons/year			APTE = 25 tons/year			APTE = 50 tons/year			APTE = 100 tons/year		
		Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
IL	5,349	1,182	1,121	1,849	1,016	1,028	1,492	871	945	1,192	602	597	936
MI	2,445	508	139	1,239	445	88	1,085	348	66	758	275	-	633
MN	1,728	525	910	5	462	788	-	265	437	-	173	292	-
OH	4,278	1,301	1,339	1,900	1,188	1,244	1,659	1,045	1,136	1,420	862	879	1,315
WI	1,123	170	169	605	94	94	414	1	1	183	-	-	48

Table 11-6. NOx emission reductions from process heaters by NAA.[26] [28]

Non-Attainment Area	2016 NOx Emissions (tons/year)	2016 NOx Emission Reductions (tons/year)											
		APTE = 10 tons/year			APTE = 25 tons/year			APTE = 50 tons/year			APTE = 100 tons/year		
		Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
Allegan, MI	8	-	-	-	-	-	-	-	-	-	-	-	-
Berrien, MI	11	-	-	-	-	-	-	-	-	-	-	-	-
Chicago, IL	2,301	476	226	1,260	389	189	1,045	349	169	939	260	84	767
Chicago, IN	3,361	[a]	[a]	[a]	[a]	[a]	[a]	935	754	1,644	814	643	1,421
Chicago, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
Cincinnati, OH	204	3	3	113	-	-	77	-	-	47	-	-	47
Cleveland, OH	1,071	470	466	787	410	410	696	410	410	696	372	372	670
Columbus, OH	56	6	6	10	-	-	-	-	-	-	-	-	-
Detroit, MI	1,687	485	139	1,038	432	88	958	348	66	720	275	-	633
Door, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
Manitowoc County, WI	61	13	13	32	-	-	12	-	-	-	-	-	-
Muskegon, MI	51	2	-	16	-	-	11	-	-	-	-	-	-
Northern Milwaukee/Ozaukee, WI	229	15	15	130	12	12	98	-	-	64	-	-	-
Sheboygan, WI	42	-	-	28	-	-	28	-	-	28	-	-	-
St. Louis, IL	1,472	483	892	88	447	839	53	405	776	-	267	513	-

[a] APTE values of 10 tons/year and 25 tons/year are not applicable to Chicago, IN

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[73] Cells populated with "-" indicate zero NOx emissions in the inventory and thus no emission reductions.

Table 11-7. Typical cost-effectiveness for each control measure.

Stringency Level	Control Measure	Cost-effectiveness (2020$/ton)	Reference
High, Medium, Low	Low NOx Burner	4,356 [a]	EPA CoST[27]
High	Selective Catalytic Reduction	4,830, 7,694, or 10,957 [b]	EPA CoST[27]
Medium	Selective Catalytic Reduction	11,080	EPA CoST[27]
	Ultra-Low NOx Burner	3,090	EPA Menu of Control Measures[7]
Low	Low NOx Burner	5,193 or 4,533 [a]	EPA Menu of Control Measures[7]
	Excess O2 Control	72	EPA CoST[27]

[a] The cost-effectiveness is $5,193/ton for Low NOx Burner - Process Heaters - Other Fuel. The cost-effectiveness is $4,533/ton for Low NOx Burner - Process Heaters – Process Gas. The cost-effectiveness is $4,356/ton for all other LNB control measures.

[b] The cost-effectiveness is $4,830/ton for Selective Catalytic Reduction - Indust. Incinerators. The cost-effectiveness is $7,694/ton for Selective Catalytic Reduction - In-Process Fuel Use; Natural Gas; Gen. The cost-effectiveness is $10,957/ton for Selective Catalytic Reduction - ICI Boilers – Gas.

Table 11-8. Statewide total cost of process heaters emissions reduction.[26] [74]

State	Total Cost (thousands of 2020$)											
	APTE = 10 tons/year			APTE = 25 tons/year			APTE = 50 tons/year			APTE = 100 tons/year		
	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
IL	365	12,175	19,902	162	11,253	16,085	152	10,332	12,797	43	6,620	10,256
MI	2,276	1,502	13,319	2,076	972	11,893	1,631	731	8,308	1,430	-	6,934
MN	38	10,086	51	33	8,728	-	19	4,840	-	12	3,230	-
OH	2,313	11,383	17,591	1,963	10,842	15,340	1,886	9,745	12,817	1,657	7,234	11,740
WI	749	711	5,696	415	388	4,015	3	3	1,934	-	-	531

Table 11-9. Statewide cost-effectiveness of process heaters emissions reduction.[26] [29]

State	Cost-effectiveness (2020$/ton)											
	APTE = 10 tons/year			APTE = 25 tons/year			APTE = 50 tons/year			APTE = 100 tons/year		
	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
IL	309	10,865	10,762	159	10,945	10,783	174	10,933	10,739	72	11,080	10,957
MI	4,483	10,837	10,753	4,667	11,080	10,957	4,687	11,080	10,957	5,193	-	10,957
MN	72	11,080	10,957	72	11,080	-	72	11,080	-	72	11,080	-
OH	1,778	8,501	9,259	1,652	8,713	9,247	1,805	8,578	9,024	1,921	8,233	8,925
WI	4,408	4,197	9,409	4,426	4,125	9,709	4,356	4,356	10,583	-	-	10,957

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[74] Cells populated with "-" indicate zero NOx emissions in the inventory and thus no associated cost or cost-effectiveness.

Table 11-10. Cost of process heaters emissions reduction by NAA.[26] [29]

Non-Attainment Area	Total Cost (thousands of 2020$)											
	APTE = 10 tons/year			APTE = 25 tons/year			APTE = 50 tons/year			APTE = 100 tons/year		
	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
Allegan, MI	-	-	-	-	-	-	-	-	-	-	-	-
Berrien, MI	-	-	-	-	-	-	-	-	-	-	-	-
Chicago, IL	283	2,280	13,584	117	1,953	11,315	114	1,731	10,147	19	933	8,402
Chicago, IN	[a]	[a]	[a]	[a]	[a]	[a]	3,487	5,997	15,945	2,952	5,510	14,165
Chicago, WI	-	-	-	-	-	-	-	-	-	-	-	-
Cincinnati, OH	12	12	1,216	-	-	848	-	-	511	-	-	511
Cleveland, OH	2,052	2,032	6,171	1,787	1,787	5,436	1,787	1,787	5,436	1,621	1,621	5,154
Columbus, OH	24	24	78	-	-	-	-	-	-	-	-	-
Detroit, MI	2,155	1,502	11,342	2,010	972	10,499	1,631	731	7,893	1,430	-	6,934
Door, WI	-	-	-	-	-	-	-	-	-	-	-	-
Manitowoc County, WI	57	57	268	-	-	131	-	-	-	-	-	-
Muskegon, MI	11	-	178	-	-	122	-	-	-	-	-	-
Northern Milwaukee/Ozaukee, WI	66	66	1,336	53	53	1,001	-	-	701	-	-	-
Sheboygan, WI	-	-	305	-	-	305	-	-	305	-	-	-
St. Louis, IL	55	9,883	966	32	9,300	575	29	8,601	-	19	5,687	-

[a] APTE values of 10 tons/year and 25 tons/year are not applicable to Chicago, IN

Table 11-11. Cost-effectiveness of process heaters emissions reduction by NAA.[26] [29]

Non-Attainment Area	Cost-effectiveness (2020$/ton)											
	APTE = 10 tons/year			APTE = 25 tons/year			APTE = 50 tons/year			APTE = 100 tons/year		
	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
Allegan, MI	-	-	-	-	-	-	-	-	-	-	-	-
Berrien, MI	-	-	-	-	-	-	-	-	-	-	-	-
Chicago, IL	593	10,095	10,784	300	10,343	10,826	326	10,255	10,811	72	11,080	10,957
Chicago, IN	[a]	[a]	[a]	[a]	[a]	[a]	3,728	7,949	9,702	3,626	8,574	9,967
Chicago, WI	-	-	-	-	-	-	-	-	-	-	-	-
Cincinnati, OH	4,356	4,356	10,792	-	-	10,957	-	-	10,957	-	-	10,957
Cleveland, OH	4,363	4,356	7,837	4,356	4,356	7,815	4,356	4,356	7,815	4,356	4,356	7,694
Columbus, OH	4,356	4,356	7,694	-	-	-	-	-	-	-	-	-
Detroit, MI	4,449	10,837	10,925	4,651	11,080	10,957	4,687	11,080	10,957	5,193	-	10,957
Door, WI	-	-	-	-	-	-	-	-	-	-	-	-
Manitowoc County, WI	4,356	4,356	8,430	-	-	10,957	-	-	-	-	-	-
Muskegon, MI	5,193	-	10,957	-	-	10,957	-	-	-	-	-	-
Northern Milwaukee/Ozaukee, WI	4,356	4,356	10,273	4,356	4,356	10,221	-	-	10,957	-	-	-
Sheboygan, WI	-	-	10,957	-	-	10,957	-	-	10,957	-	-	-
St. Louis, IL	113	11,080	10,957	72	11,080	10,957	72	11,080	-	72	11,080	-

[a] APTE values of 10 tons/year and 25 tons/year are not applicable to Chicago, IN

11.6 Geographic Applicability

NOx emission reductions for process heaters can only be achieved in the counties and states in which process heaters are located. According to EPA's 2016v1 emission inventory, process heater emissions occur in all LADCO states. For NAAs, according to EPA's 2016v1 emission inventory, there are process heater emissions, at APTE levels evaluated herein, in all but two LADCO region NAAs; however NAA emissions of greater than 50 tons/year are limited to Chicago, IL; Chicago, IN; Cincinnati, OH; Cleveland, OH; Columbus, OH; Detroit, MI; Manitowoc County, WI; Muskegon, MI; Northern Milwaukee/Ozaukee, WI; and St. Louis, IL.

11.7 Responsible Agency

The state air agency is responsible for enforcing SIP-approved and other air permitting rules. Applicable process heaters emissions in the LADCO area are from sources in EPA's 2016v1 emission inventory with a wide range of APTE from 10 tons/year to greater than over 100 tons/year. Sources with APTE over 100 tons/year are expected to be subject to Title V permit requirements; sources not subject to Title V thresholds may be permitted under state permit requirements.

11.8 Implementation Schedule

After a new rule is promulgated, facilities are typically given time to comply with the new rule for planning, analysis, and infrastructure changes necessary to comply. The timeline for existing sources to comply with MACT standards is typically 3-years, but timelines for compliance typically vary from 1-4 years. Assuming that rules to limit process heaters emissions are adopted in late-2023, and assuming a 2-year period from rule promulgation to controls installation, emission reduction would be achieved by 2026. Depending on regulatory requirements, a more aggressive or less aggressive timeline may be required in rulemakings.

11.9 Implementation Feasibility

There are several regulatory programs which limit process heater emissions (examples are listed below). Emission requirements may be expressed in mass of NOx emitted per unit of energy consumed.

- New Source Performance Standard for Industrial-Commercial-Institutional Steam Generating Units (NSPS 40 CFR Part 60 Subpart Db and 40 CFR Part 60 Subpart Dc)[75]
- Texas Commission on Environmental Quality, 30 TAC Chapter 117, Subchapter E, Division 3[76]
- South Coast Air Quality Management District, Rule 1146.2: Emissions of Oxides of Nitrogen from Large Water Heaters and Small Boilers and Process Heaters[77]

To develop an emission control regulation for process heaters, a facility-level assessment may be necessary as facility specific conditions (fuels and existing equipment configurations) to determine the feasibility and cost of controls.

11.10 Public Acceptance

Process heaters can produce substantial emissions of NOx and other pollutants. Several process heater emission control measures evaluated herein are very cost-effective, and therefore can be shown to be a good regional emission reductions strategy. Process heater operators may object to any further regulation of their operations, especially for the more costly control measures. Grant funding can be used to facilitate implementation of control measures.

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[75] https://www.epa.gov/stationary-sources-air-pollution/industrial-commercial-institutional-steam-generating-units-new, accessed in January, 2022

[76] https://www.tceq.texas.gov/airquality/stationary-rules/nox/water-heaters, accessed in January, 2022

[77] https://www.aqmd.gov/docs/default-source/rule-book/reg-xi/rule-1146-2.pdf?sfvrsn=4, accessed in January, 2022

11.11 All Controls Results

Analysis in the sections above includes the controls considered under low, medium, and high stringency scenarios, as indicated in Table 11-4 (i.e., those controls not highlighted in grey on Table 3-4). Emission reduction estimates across the full suite of stringency scenario and control combinations are presented in Appendix A, Tables A1 to A2.

12.0 REFERENCES

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EPA 2007. “Alternative Control Techniques Document Update - NOx Emissions from New Cement Kilns,” EPA-453/R-07-006, November 2007.

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EPA 2019a. “Toxics Release Inventory Guidance for Reporting the Dioxin and Dioxin-like Compounds Category,” EPA 745-B-19-004, March 2019.

EPA 2019b. “EPA Air Pollution Control Cost Manual - Sixth Edition,” EPA 452/B-02-001, April 2019.

APPENDIX A

All LADCO Reviewed Technologies NOx Emission Reductions

APPENDIX A. ALL LADCO REVIEWED TECHNOLOGIES NOX EMISSION REDUCTIONS

Table A-1. All LADCO reviewed technologies statewide 2016 NOx emission reductions for each white paper group.[78]

State	2016 NOx Emissions (tons/year)	2016 NOx Emission Reductions (tons/year)											
		APTE = 10 tons/year			APTE = 25 tons/year			APTE = 50 tons/year			APTE = 100 tons/year		
		Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
Cement Kiln													
IL	3,066	828	1,533	2,760	828	1,533	2,760	828	1,533	2,760	828	1,533	2,760
MI	6,882	1,775	3,441	6,193	1,775	3,441	6,193	1,775	3,441	6,193	1,775	3,441	6,193
MN	-	-	-	-	-	-	-	-	-	-	-	-	-
OH	1,460	274	508	1,134	274	508	1,134	274	508	1,134	274	508	1,134
WI	-	-	-	-	-	-	-	-	-	-	-	-	-
Coal Non-EGU													
IL	757	340	447	662	340	447	662	340	447	662	340	447	662
MI	360	159	249	306	159	249	306	159	249	306	119	185	225
MN	2,714	1,221	1,895	2,369	1,221	1,895	2,369	1,221	1,895	2,369	1,221	1,895	2,369
OH	1,960	857	1,324	1,721	844	1,304	1,696	829	1,281	1,666	773	1,195	1,561
WI	6,623	2,519	3,918	4,758	2,504	3,895	4,729	2,497	3,884	4,716	2,469	3,841	4,664
Coke													
IL	376	220	220	220	215	215	215	215	215	215	215	215	215
MI	521	313	313	313	313	313	313	313	313	313	313	313	313
MN	-	-	-	-	-	-	-	-	-	-	-	-	-
OH	1,023	613	613	613	613	613	613	613	613	613	613	613	613
WI	-	-	-	-	-	-	-	-	-	-	-	-	-
Gas-fired External Combustion Sources													
IL	5,800	1,413	2,572	3,448	880	1,606	2,165	609	1,107	1,473	424	733	957
MI	4,751	1,194	2,339	3,317	922	1,848	2,631	612	1,252	1,774	454	942	1,314
MN	4,466	1,198	2,164	2,835	884	1,569	2,041	657	1,156	1,501	376	660	855
OH	6,633	2,224	3,765	4,915	1,929	3,256	4,241	1,602	2,703	3,494	1,309	2,197	2,855
WI	4,776	1,569	2,576	3,286	1,166	1,888	2,404	923	1,476	1,881	650	1,011	1,259
Glass													
IL	3,345	1,110	2,174	2,623	1,110	2,174	2,623	1,110	2,174	2,623	1,058	2,090	2,525
MI	1,005	-	419	670	-	419	670	-	419	670	-	382	611
MN	662	265	430	496	265	430	496	265	430	496	265	430	496
OH	2,195	786	1,426	1,692	783	1,421	1,685	783	1,421	1,685	783	1,421	1,685
WI	3,105	-	1,250	1,999	-	1,250	1,999	-	1,250	1,999	-	1,250	1,999

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[78] Cells populated with "-" indicate zero NOx emissions in the inventory and thus no emission reductions.

State	2016 NOx Emissions (tons/year)	2016 NOx Emission Reductions (tons/year)											
		APTE = 10 tons/year			APTE = 25 tons/year			APTE = 50 tons/year			APTE = 100 tons/year		
		Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
Diesel-fired Internal Combustion Engines													
IL	899	116	116	381	68	68	221	46	46	147	-	-	-
MI	1,740	337	337	1,242	305	305	1,132	288	288	1,075	288	288	1,054
MN	1,394	203	203	742	146	146	541	88	88	322	48	48	177
OH	375	58	58	186	43	43	137	39	39	125	39	39	125
WI	264	41	41	147	29	29	107	7	7	24	-	-	-
Gas-fired Internal Combustion Engines													
IL	1,204	513	608	807	468	553	726	332	387	520	279	325	448
MI	817	328	391	480	304	351	434	242	283	333	68	80	94
MN	215	84	98	121	68	79	93	52	61	72	52	61	72
OH	770	340	466	624	280	396	529	251	362	481	245	337	451
WI	486	158	175	219	122	137	166	116	131	157	100	115	134
Iron and Steel													
IL	450	280	357	374	260	329	343	260	329	343	171	240	254
MI	231	139	146	150	132	132	132	59	59	59	-	-	-
MN	-	-	-	-	-	-	-	-	-	-	-	-	-
OH	1,020	514	640	762	455	540	626	315	364	418	47	89	119
WI	-	-	-	-	-	-	-	-	-	-	-	-	-
Lime Kiln													
IL	-	-	-	-	-	-	-	-	-	-	-	-	-
MI	633	186	186	186	186	186	186	178	178	178	170	170	170
MN	318	95	95	95	74	74	74	66	66	66	58	58	58
OH	6,112	1,829	1,829	1,829	1,820	1,820	1,820	1,816	1,816	1,816	1,816	1,816	1,816
WI	1,325	301	301	301	299	299	299	286	286	286	247	247	247
Process Heaters													
IL	5,349	1,701	2,873	3,933	1,384	2,379	3,261	1,135	1,971	2,691	799	1,396	1,924
MI	2,445	764	1,203	1,734	613	971	1,412	414	664	992	308	488	755
MN	1,728	532	1,094	1,450	462	960	1,279	265	574	774	173	370	496
OH	4,278	1,443	2,073	3,063	1,282	1,868	2,767	1,123	1,608	2,366	927	1,293	1,957
WI	1,123	329	434	636	217	300	434	86	134	183	26	40	48

Table A-2. All LADCO reviewed technologies NAA 2016 NOx emission reductions for each white paper group.[79] 78

Non-Attainment Area	2016 NOx Emissions (tons/year)	2016 NOx Emission Reductions (tons/year)											
		APTE = 10 tons/year			APTE = 25 tons/year			APTE = 50 tons/year			APTE = 100 tons/year		
		Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
Cement Kiln													
Allegan, MI	-	-	-	-	-	-	-	-	-	-	-	-	-
Berrien, MI	-	-	-	-	-	-	-	-	-	-	-	-	-
Chicago, IL	-	-	-	-	-	-	-	-	-	-	-	-	-
Chicago, IN	-	-	-	-	-	-	-	-	-	-	-	-	-
Chicago, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
Cincinnati, OH	-	-	-	-	-	-	-	-	-	-	-	-	-
Cleveland, OH	-	-	-	-	-	-	-	-	-	-	-	-	-
Columbus, OH	-	-	-	-	-	-	-	-	-	-	-	-	-
Detroit, MI	-	-	-	-	-	-	-	-	-	-	-	-	-
Door, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
Manitowoc County, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
Muskegon, MI	-	-	-	-	-	-	-	-	-	-	-	-	-
Northern Milwaukee/Ozaukee, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
Sheboygan, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
St. Louis, IL	-	-	-	-	-	-	-	-	-	-	-	-	-
Coal Non-EGU													
Allegan, MI	-	-	-	-	-	-	-	-	-	-	-	-	-
Berrien, MI	-	-	-	-	-	-	-	-	-	-	-	-	-
Chicago, IL	-	-	-	-	-	-	-	-	-	-	-	-	-
Chicago, IN	-	-	-	-	-	-	-	-	-	-	-	-	-
Chicago, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
Cincinnati, OH	414	185	285	374	180	278	364	165	255	334	165	255	334
Cleveland, OH	103	23	36	43	23	36	43	23	36	43	23	36	43

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[79] Cells populated with "-" indicate zero NOx emissions in the inventory and thus no emission reductions.

Non-Attainment Area	2016 NOx Emissions (tons/year)	2016 NOx Emission Reductions (tons/year)											
		APTE = 10 tons/year			APTE = 25 tons/year			APTE = 50 tons/year			APTE = 100 tons/year		
		Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
Columbus, OH	-	-	-	-	-	-	-	-	-	-	-	-	-
Detroit, MI	-	-	-	-	-	-	-	-	-	-	-	-	-
Door, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
Manitowoc County, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
Muskegon, MI	-	-	-	-	-	-	-	-	-	-	-	-	-
Northern Milwaukee/Ozaukee, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
Sheboygan, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
St. Louis, IL	-	-	-	-	-	-	-	-	-	-	-	-	-
Coke													
Allegan, MI	-	-	-	-	-	-	-	-	-	-	-	-	-
Berrien, MI	-	-	-	-	-	-	-	-	-	-	-	-	-
Chicago, IL	-	-	-	-	-	-	-	-	-	-	-	-	-
Chicago, IN	3,602	2,161	2,161	2,161	2,161	2,161	2,161	2,161	2,161	2,161	2,161	2,161	2,161
Chicago, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
Cincinnati, OH	280	168	168	168	168	168	168	168	168	168	168	168	168
Cleveland, OH	-	-	-	-	-	-	-	-	-	-	-	-	-
Columbus, OH	-	-	-	-	-	-	-	-	-	-	-	-	-
Detroit, MI	521	313	313	313	313	313	313	313	313	313	313	313	313
Door, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
Manitowoc County, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
Muskegon, MI	-	-	-	-	-	-	-	-	-	-	-	-	-
Northern Milwaukee/Ozaukee, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
Sheboygan, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
St. Louis, IL	376	220	220	220	215	215	215	215	215	215	215	215	215
Gas-fired External Combustion Sources													
Allegan, MI	64	11	20	26	5	10	12	-	-	-	-	-	-

Non-Attainment Area	2016 NOx Emissions (tons/year)	2016 NOx Emission Reductions (tons/year)											
		APTE = 10 tons/year			APTE = 25 tons/year			APTE = 50 tons/year			APTE = 100 tons/year		
		Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
Berrien, MI	21	6	10	13	-	-	-	-	-	-	-	-	-
Chicago, IL	2,694	563	1,026	1,362	301	553	736	191	355	474	108	184	239
Chicago, IN	5,892	2,376	3,846	5,050	2,283	3,689	4,840	2,185	3,524	4,595	1,998	3,210	4,170
Chicago, WI	38	11	18	22	-	-	-	-	-	-	-	-	-
Cincinnati, OH	2,229	830	1,430	1,888	761	1,312	1,731	674	1,168	1,533	597	1,037	1,358
Cleveland, OH	593	155	260	349	95	158	214	36	62	81	-	-	-
Columbus, OH	302	67	124	165	43	80	105	33	58	72	-	-	-
Detroit, MI	1,700	480	807	1,110	336	562	769	155	257	343	107	175	233
Door, WI	<1	-	-	-	-	-	-	-	-	-	-	-	-
Manitowoc County, WI	21	3	4	5	-	-	-	-	-	-	-	-	-
Muskegon, MI	53	10	17	22	6	10	13	-	-	-	-	-	-
Northern Milwaukee/Ozaukee, WI	726	192	330	447	154	266	366	140	243	340	140	243	318
Sheboygan, WI	36	6	11	14	-	-	-	-	-	-	-	-	-
St. Louis, IL	247	46	99	140	23	61	90	-	13	22	-	-	-
Glass													
Allegan, MI	-	-	-	-	-	-	-	-	-	-	-	-	-
Berrien, MI	-	-	-	-	-	-	-	-	-	-	-	-	-
Chicago, IL	190	76	123	142	76	123	142	76	123	142	24	39	45
Chicago, IN	-	-	-	-	-	-	-	-	-	-	-	-	-
Chicago, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
Cincinnati, OH	<1	-	-	-	-	-	-	-	-	-	-	-	-
Cleveland, OH	-	-	-	-	-	-	-	-	-	-	-	-	-
Columbus, OH	542	217	352	406	217	352	406	217	352	406	217	352	406
Detroit, MI	1,005	-	419	670	-	419	670	-	419	670	-	382	611
Door, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
Manitowoc County, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
Muskegon, MI	-	-	-	-	-	-	-	-	-	-	-	-	-

Non-Attainment Area	2016 NOx Emissions (tons/year)	2016 NOx Emission Reductions (tons/year)											
		APTE = 10 tons/year			APTE = 25 tons/year			APTE = 50 tons/year			APTE = 100 tons/year		
		Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
Northern Milwaukee/Ozaukee, WI	106	-	-	-	-	-	-	-	-	-	-	-	-
Sheboygan, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
St. Louis, IL	-	-	-	-	-	-	-	-	-	-	-	-	-
Diesel-fired Internal Combustion Engines													
Allegan, MI	<1	-	-	-	-	-	-	-	-	-	-	-	-
Berrien, MI	11	2	2	10	-	-	-	-	-	-	-	-	-
Chicago, IL	519	63	63	209	24	24	80	7	7	22	-	-	-
Chicago, IN	77	15	15	48	13	13	42	-	-	-	-	-	-
Chicago, WI	<1	-	-	-	-	-	-	-	-	-	-	-	-
Cincinnati, OH	6	-	-	-	-	-	-	-	-	-	-	-	-
Cleveland, OH	196	42	42	134	39	39	125	39	39	125	39	39	125
Columbus, OH	3	-	-	-	-	-	-	-	-	-	-	-	-
Detroit, MI	1,121	213	213	829	191	191	758	180	180	721	180	180	699
Door, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
Manitowoc County, WI	41	10	10	35	10	10	35	7	7	24	-	-	-
Muskegon, MI	31	6	6	19	6	6	19	-	-	-	-	-	-
Northern Milwaukee/Ozaukee, WI	74	11	11	40	7	7	23	-	-	-	-	-	-
Sheboygan, WI	<1	-	-	-	-	-	-	-	-	-	-	-	-
St. Louis, IL	23	3	3	10	-	-	-	-	-	-	-	-	-
Gas-fired Internal Combustion Engines													
Allegan, MI	77	55	65	76	55	65	76	55	65	76	-	-	-
Berrien, MI	<1	-	-	-	-	-	-	-	-	-	-	-	-
Chicago, IL	450	190	230	357	170	206	322	91	106	191	38	45	120
Chicago, IN	13	3	5	12	3	5	12	-	-	-	-	-	-
Chicago, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
Cincinnati, OH	83	48	56	66	15	17	21	-	-	-	-	-	-
Cleveland, OH	64	25	29	40	-	-	-	-	-	-	-	-	-

Non-Attainment Area	2016 NOx Emissions (tons/year)	2016 NOx Emission Reductions (tons/year)											
		APTE = 10 tons/year			APTE = 25 tons/year			APTE = 50 tons/year			APTE = 100 tons/year		
		Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
Columbus, OH	-	-	-	-	-	-	-	-	-	-	-	-	-
Detroit, MI	563	200	226	261	180	206	239	144	168	197	68	80	94
Door, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
Manitowoc County, WI	51	10	10	15	10	10	15	10	10	15	10	10	15
Muskegon, MI	29	5	20	24	-	-	-	-	-	-	-	-	-
Northern Milwaukee/Ozaukee, WI	278	114	129	155	101	116	135	98	113	131	90	105	119
Sheboygan, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
St. Louis, IL	<1	-	-	-	-	-	-	-	-	-	-	-	-
Iron and Steel													
Allegan, MI	-	-	-	-	-	-	-	-	-	-	-	-	-
Berrien, MI	-	-	-	-	-	-	-	-	-	-	-	-	-
Chicago, IL	12	11	11	11	-	-	-	-	-	-	-	-	-
Chicago, IN	2,448	1,035	1,467	1,950	1,034	1,463	1,946	987	1,407	1,861	861	1,225	1,627
Chicago, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
Cincinnati, OH	57	16	19	29	16	19	29	16	19	29	-	-	-
Cleveland, OH	269	167	189	218	165	181	208	113	118	132	-	-	-
Columbus, OH	-	-	-	-	-	-	-	-	-	-	-	-	-
Detroit, MI	228	139	146	150	132	132	132	59	59	59	-	-	-
Door, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
Manitowoc County, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
Muskegon, MI	<1	-	-	-	-	-	-	-	-	-	-	-	-
Northern Milwaukee/Ozaukee, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
Sheboygan, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
St. Louis, IL	46	33	37	38	32	32	32	32	32	32	-	-	-
Lime Kiln													
Allegan, MI	-	-	-	-	-	-	-	-	-	-	-	-	-
Berrien, MI	-	-	-	-	-	-	-	-	-	-	-	-	-

Non-Attainment Area	2016 NOx Emissions (tons/year)	2016 NOx Emission Reductions (tons/year)											
		APTE = 10 tons/year			APTE = 25 tons/year			APTE = 50 tons/year			APTE = 100 tons/year		
		Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
Chicago, IL	-	-	-	-	-	-	-	-	-	-	-	-	-
Chicago, IN	1,556	467	467	467	467	467	467	467	467	467	467	467	467
Chicago, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
Cincinnati, OH	-	-	-	-	-	-	-	-	-	-	-	-	-
Cleveland, OH	368	110	110	110	110	110	110	110	110	110	110	110	110
Columbus, OH	-	-	-	-	-	-	-	-	-	-	-	-	-
Detroit, MI	565	170	170	170	170	170	170	170	170	170	170	170	170
Door, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
Manitowoc County, WI	304	69	69	69	69	69	69	64	64	64	64	64	64
Muskegon, MI	-	-	-	-	-	-	-	-	-	-	-	-	-
Northern Milwaukee/Ozaukee, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
Sheboygan, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
St. Louis, IL	-	-	-	-	-	-	-	-	-	-	-	-	-
Process Heaters													
Allegan, MI	8	3	4	5	-	-	-	-	-	-	-	-	-
Berrien, MI	11	5	7	9	-	-	-	-	-	-	-	-	-
Chicago, IL	2,301	777	1,209	1,652	613	961	1,316	543	843	1,153	403	628	874
Chicago, IN	3,361	1,358	1,828	2,798	1,304	1,744	2,663	1,226	1,645	2,490	1,105	1,520	2,268
Chicago, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
Cincinnati, OH	204	61	93	113	41	64	77	25	38	47	25	38	47
Cleveland, OH	1,071	493	503	850	424	431	737	424	431	737	372	372	670
Columbus, OH	56	6	6	10	-	-	-	-	-	-	-	-	-
Detroit, MI	1,687	536	857	1,271	469	749	1,127	348	561	862	275	438	690
Door, WI	-	-	-	-	-	-	-	-	-	-	-	-	-
Manitowoc County, WI	61	19	23	32	6	10	12	-	-	-	-	-	-
Muskegon, MI	51	13	20	26	6	9	11	-	-	-	-	-	-
Northern Milwaukee/Ozaukee, WI	229	70	100	130	52	75	98	34	53	64	-	-	-

Non-Attainment Area	2016 NOx Emissions (tons/year)	2016 NOx Emission Reductions (tons/year)											
		APTE = 10 tons/year			APTE = 25 tons/year			APTE = 50 tons/year			APTE = 100 tons/year		
		Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
Sheboygan, WI	42	15	23	28	15	23	28	15	23	28	-	-	-
St. Louis, IL	1,472	514	969	1,246	469	890	1,136	405	776	984	267	513	651

APPENDIX B

Emission Units by White Paper Group

APPENDIX B. EMISSION UNITS BY WHITE PAPER GROUP

Table B-1. Number of units with 2016 NOx emissions for each white paper group by State.[80]

State	Cement Kilns	Coal Non-EGU	Coke	Gas-fired External Combustion Sources	Glass	Diesel-fired Internal Combustion Engines	Gas-fired Internal Combustion Engines	Iron and Steel	Lime Kiln	Process Heaters
IL	4	4	8	1753	12	769	164	21	-	851
MI	21	6	3	1303	3	563	456	18	32	717
MN	-	10	-	2597	2	1042	179	-	15	151
OH	7	16	7	1046	18	180	104	147	25	1061
WI	-	28	-	1130	4	229	140	-	15	496

Table B-2. Number of units with 2016 NOx emissions for each white paper group by NAA.[80]

State	Cement Kilns	Coal Non-EGU	Coke	Gas-fired External Combustion Sources	Glass	Diesel-fired Internal Combustion Engines	Gas-fired Internal Combustion Engines	Iron and Steel	Lime Kiln	Process Heaters
Allegan, MI	-	-	-	54	-	2	2	-	-	9
Berrien, MI	-	-	-	7	-	2	1	-	-	1
Chicago, IL	-	-	-	991	6	525	93	1	-	422
Chicago, IN	-	-	7	163	-	19	4	36	5	126
Chicago, WI	-	-	-	21	-	6	-	-	-	-
Cincinnati, OH	-	5	2	173	2	6	15	13	-	61
Cleveland, OH	-	3	-	216	-	40	12	16	2	172
Columbus, OH	-	-	-	95	2	2	-	-	-	70
Detroit, MI	-	-	3	748	3	353	380	16	2	430
Door, WI	-	-	-	1	-	-	-	-	-	-
Manitowoc County, WI	-	-	-	17	-	4	2	-	2	41
Muskegon, MI	-	-	-	20	-	9	6	1	-	14
Northern Milwaukee/Ozaukee, WI	-	-	-	176	2	50	53	-	-	121
Sheboygan, WI	-	-	-	20	-	2	-	-	-	5
St. Louis, IL	-	-	8	83	-	17	2	5	-	92

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[80] Cells populated with “-“ indicate zero NOx emissions in the inventory.