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WHITEPAPER

Toward Near-Zero Industrial Nitrous Oxide Emissions

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Table of Contents

Executive summary 4

1. Introduction 5

2. Nitric and adipic acid are main sources of industrial N_2O emissions 6

3. The United States and China are the largest emitters of industrial N_2O 7

4. Further work is needed to quantify industrial N_2O emissions 8

5. Industrial N_2O emissions are projected to increase 8

6. Abatement of industrial N_2O is cost effective and immediately feasible 9

7. Abatement technologies to address industrial N_2O emissions 10

7.1 Catalytic decomposition and thermal destruction are used in adipic acid plants 11

7.1.1 Thermal destruction faces challenges in simultaneously abating N_2O and NOx 13

7.2 Catalytic decomposition and reduction are used in nitric acid plants 13

8. Well-designed financial mechanisms may incentivize permanent abatement of industrial N_2O emissions 16

8.1 The Clean Development Mechanism led to carbon leakage from adipic acid production 16

8.2 Higher-baseline crediting schemes may prevent over-crediting 17

8.3 New crediting schemes are incorporating more guardrails 17

How to achieve real and permanent industrial N_2O abatement: Well-designed voluntary carbon credit mechanisms, regulations, or a combination? 18

9. Insights for reducing industrial N_2O emissions 18

9.1 Addressing N_2O emissions from Chinese adipic acid production 19

9.2 Addressing N_2O emissions from U.S. nitric acid production 20

9.3 Other actions for industrial N_2O abatement 20

10. Conclusion 21

Appendix: Calculation of adipic acid abatement cost 22

Endnotes 23

Executive summary

Nitrous oxide (N_2O) is an extremely potent greenhouse gas and an ozone-depleting substance. While some sources of N_2O are difficult to abate, N_2O emissions from industry are readily abatable with proven, commercialized, and cost-effective technologies. However, more than 100 million metric tons (Mt) per year of CO_2-equivalent (CO_2e) industrial N_2O remains unabated today, with most unabated emissions occurring in China from the production of adipic acid. Industrial N_2O emissions are growing and could reach between a quarter and half a gigaton of CO_2e annually by 2050. The United States is the second-largest emitter of industrial N_2O. Because abatement technologies require capital expenditure and increase operating costs for facilities, a regulatory or market signal is usually required to encourage installation and operation of abatement equipment.

Fortunately, abatement technologies are already proven and commercialized (table ES1). Adipic acid facilities have achieved over 90 percent N_2O abatement since the late 1990s, and more than one in six nitric acid facilities have installed N_2O abatement. Catalytic decomposition for adipic acid plants offers both N_2O abatement and straightforward nitrogen oxides (NOx) reduction options. Tertiary catalytic decomposition in nitric acid plants typically offers the highest operating N_2O abatement and options for concurrent NOx abatement.

TABLE ES1: PREFERRED N_2O ABATEMENT TECHNOLOGIES FOR ADIPIC ACID AND NITRIC ACID PRODUCTION

	Preferred N_2O abatement technology
Adipic acid	Catalytic decomposition
Nitric acid	Tertiary abatement: catalytic decomposition

A handful of climate finance and development mechanisms have aimed to incentivize the installation and operation of N_2O abatement equipment. A voluntary carbon market mechanism called the Clean Development Mechanism was used in the past to financially incentivize industrial N_2O abatement, but poor design led to perverse incentives that likely resulted in increased N_2O emissions. Recently, new protocols with guardrails have been developed to facilitate the participation of U.S. and Chinese industrial N_2O abatement projects in voluntary carbon markets while safeguarding against those perverse incentives. These efforts should be monitored over time to evaluate how well projects that participate in voluntary carbon markets with guardrails achieve real, permanent abatement.

Moving forward, multiple levers can be utilized to eliminate industrial N_2O emissions (figure ES1). N_2O pollution control standards would be the most reliable method to achieve permanent industrial N_2O abatement. When regulatory action is not feasible, or to complement regulatory action, high-integrity market mechanisms can offer financial incentives to offset the additional costs of installing and operating abatement equipment. Other measures include policy support for abatement projects and technology deployment, international agreements that include N_2O action, N_2O-conscious trade policy, and private sector clean procurement of downstream manufactured goods.

Abatement of industrial N_2O cannot wait. There exists a very attainable abatement opportunity of potentially half a gigaton of CO_2e per year by midcentury, and emissions of this super pollutant will continue to grow if no action is taken. Accelerating industrial N_2O abatement by governments and the private sector is an important step that can be taken today to slow global warming and protect the ozone layer.

FIGURE ES1: LEVERS TO ACCELERATE INDUSTRIAL N_2O ABATEMENT

Regulations	Market mechanisms	Other policies	Private sector
N_2O pollution control standards	Regulated compliance markets (E.U. ETS, China ETS)	Support for abatement projects and technology development	Clean procurement
	Voluntary carbon markets	International agreements to reduce N_2O	
		Climate trade policies (CBAM)	

1. Introduction

Nitrous oxide (N_2O) is the third-largest driver of global warming, after carbon dioxide (CO_2) and methane (CH_4). N_2O is 273 times more powerful than CO_2 as a greenhouse gas (GHG) on a per-ton basis, and it lasts in the atmosphere for 120 years.[1] Not only does N_2O contribute to climate change, but it is also the largest category of uncontrolled substances that deplete the stratospheric ozone layer (which protects all life from harmful solar UV radiation). The 2024 United Nations Environment Programme (UNEP) Global Nitrous Oxide Assessment warns that, if current emissions trends continue, overall N_2O emissions growth could cause stratospheric ozone depletion more severe than during the peak chlorofluorocarbon-driven depletion era from 1995 to 2005, before the Montreal Protocol's success in controlling these ozone-depleting halocarbons.[2]

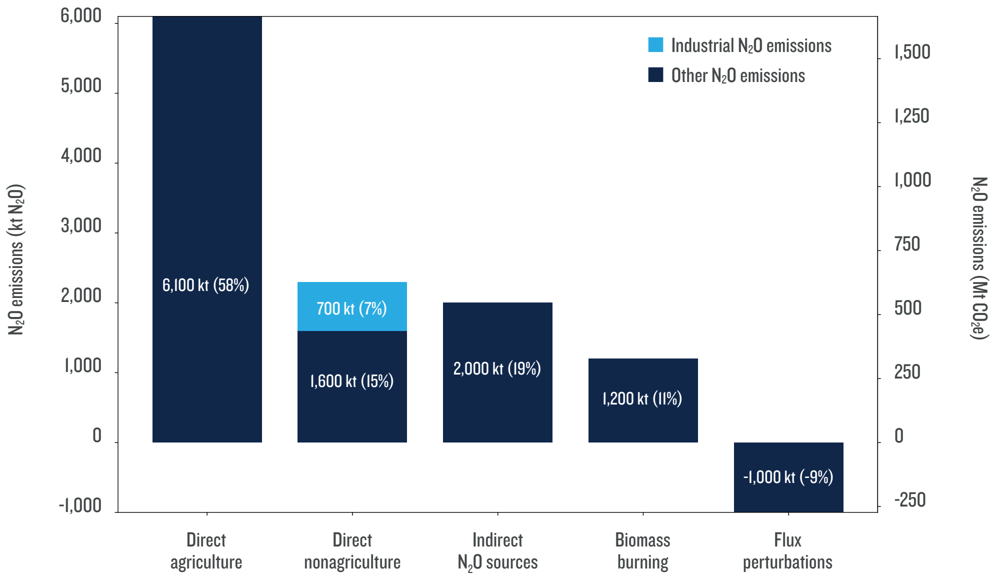
The UNEP Assessment estimates global sources of anthropogenic N_2O in 2020 were the following: direct agricultural emissions (58 percent); nonagricultural emissions (22 percent); indirect emissions from anthropogenic nitrogen additions (19 percent); emissions from burning biomass (11 percent); and N_2O flux perturbations from climate change, CO_2, and land use change (–9 percent) (figure 1).[3] Industrial N_2O emissions made up 7 percent of anthropogenic emissions.

Direct agricultural emissions account for the majority of N_2O emissions, but reducing these emissions requires society-wide, systems-scale changes. In contrast, industrial N_2O emissions are readily addressable with known, commercialized, and cost-effective technologies. Additionally, reducing industrial N_2O emissions is a faster climate mitigation measure than reducing agricultural N_2O emissions. Reducing agricultural N_2O emissions would simultaneously lead to decreases in co-emitted cooling aerosols, so net cooling benefits would not emerge until after 2090.[4]

Despite clear abatement technologies existing for industrial N_2O, many emissions remain unabated. This white paper will examine where industrial N_2O emissions originate (sections 2 and 3), current emissions and projected trends (sections 4 and 5), abatement costs (section 6), and how abatement technologies work (section 7). It will also investigate past and current interventions to encourage abatement and what has led to their failures and successes (section 8). Finally, it will present insights on how both governments and the private sector can bring about effective industrial N_2O abatement (section 9).

FIGURE 1: GLOBAL SOURCES OF ANTHROPOGENIC N_2O IN 2020 FROM THE GLOBAL NITROUS OXIDE ASSESSMENT[5]

Direct nonagricultural sources, which include industry, made up the second-largest source of anthropogenic emissions in 2020. Conversion to million metric tons (Mt) CO_2e was completed using the IPCC AR6 value 273 for N_2O's global warming potential (GWP). *Note:* Figures may not sum due to rounding.



Emissions source	Explanation of emissions source
Direct agricultural emissions	Emissions from nitrogen additions (e.g., fertilizer, manure) in the agricultural sector
Direct nonagricultural emissions	N_2O emitted by nonagricultural activities: chemical industry, fossil fuel combustion, waste and wastewater
Indirect emissions from anthropogenic nitrogen additions	Emissions from nitrogen from human sources ending up in the environment (e.g., fertilizer runoff from soil into bodies of water)
Emissions from biomass burning	Both from human activities and from wildfires
Perturbed fluxes from climate, CO_2, land-cover change	Changes in N_2O fluxes due to effects from changes in climate, atmospheric CO_2 concentration, and land-cover changes.

2. Nitric and adipic acid are main sources of industrial N_2O emissions

In this paper, industrial N_2O emissions refer to emissions that originate from nitric acid production and adipic acid production (see below for a brief discussion of caprolactam). Adipic acid is used mainly to manufacture nylon 66, which is used in applications such as automotive components and high-performance outdoor apparel.[6] Nitric acid is used mainly to produce fertilizers.[7] It is also a raw material in the production of other chemicals, such as adipic acid and nitrobenzene. Adipic acid and nitric acid are produced via separate reaction pathways, but both processes produce a steady stream of by-product N_2O that must be either vented or destroyed.

Technically, industrial sources of N_2O also include caprolactam production in addition to nitric and adipic acid production. Caprolactam is used in the production of nylon 6.[8] In contrast to nylon 66, nylon 6 is used in applications that require less durability, such as apparel.[9] While nitric acid and caprolactam production outweigh adipic acid production, the latter accounts for the largest share of industrial N_2O emissions due to more N_2O produced per ton of adipic acid produced (table 1).[10]

TABLE 1: PRODUCTION AND ASSOCIATED N_2O EMISSIONS FROM INDUSTRIAL SOURCES[11]

Nitric acid and adipic acid account for the vast majority of industrial N_2O emissions. Production is shown in million metric tons (Mt) of product per year.

	Production (Mt/year)	Approx. % of industrial N_2O emissions
Caprolactam	9	5
Nitric acid	60	20
Adipic acid	3	75

In 2021, caprolactam production accounted for only 5 percent of N_2O emissions from industry.[12] Due to this relatively insignificant contribution, this paper focuses on targeting industrial N_2O emissions from nitric acid and adipic acid production. This is consistent with the reasoning and approach in the Global Nitrous Oxide Assessment.[13]

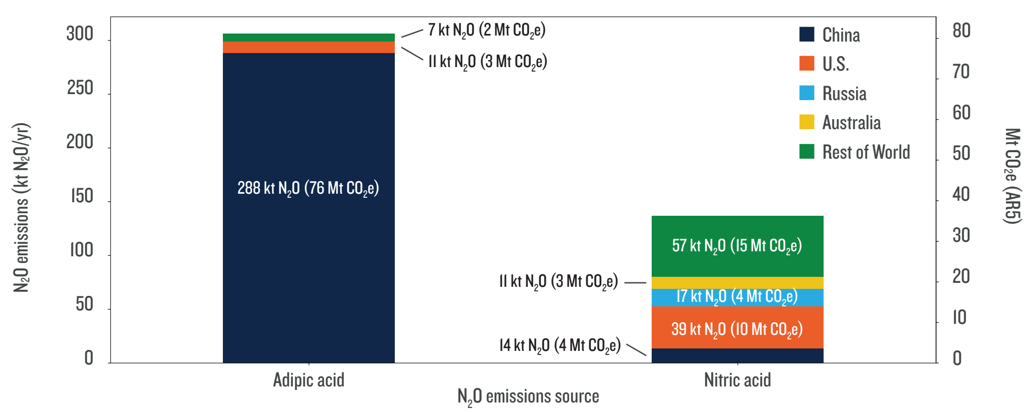
3. The United States and China are the largest emitters of industrial N_2O

Adipic acid is the largest source of global industrial N_2O emissions due to suboptimal abatement in China, which is the largest emitter of industrial N_2O. The United States is the second-largest emitter, due mostly to unabated N_2O emissions from nitric acid production. Cutting N_2O emissions from China's adipic acid production plants could eliminate 65 percent of global industrial N_2O emissions (figure 2). Globally, estimates indicate there are between 21 and 39 adipic acid production facilities.[14] As of August 2020, 11 of those facilities were in China.[15] However, trends indicate China's adipic acid capacity is growing, with new plants being added (e.g., two new plants were added in 2023).[16] China, having many of the world's adipic acid facilities with unknown but likely suboptimal abatement status, accounts for more than 90 percent of the world's N_2O emissions from adipic acid production, according to estimates from the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model (figure 2).[17]

In contrast to the small number of adipic acid production facilities, nitric acid is produced at almost 600 facilities globally, with about 100 of them abating N_2O emissions.[18] Although no single country contributes the majority of N_2O emissions from nitric acid production, the United States is the largest contributor, as only about half of U.S. nitric acid plants have abatement equipment (figure 2).[19] The largest contributors to N_2O emissions from nitric acid production in the rest of the world are as follows: Central Asian countries, 8.8 metric kilotons (kt); Ukraine, 8.2 kt; South Africa, 6.3 kt; and Middle Eastern countries, 5.7 kt.[20]

FIGURE 2: BREAKDOWN OF N_2O EMISSIONS FROM ADIPIC AND NITRIC ACID PRODUCTION BY COUNTRY IN 2020 FROM GAINS MODEL[21]

China accounts for the vast majority of the world's N_2O emissions from adipic acid production.
The United States is the single largest contributor to N_2O emissions from global nitric acid production.
China's adipic acid plants alone contribute up to 65 percent of global N_2O emissions from adipic and nitric acid production.



4. Further work is needed to quantify industrial N_2O emissions

Significant gaps still exist in understanding the magnitude of industrial N_2O emissions. Studies have found global industrial N_2O emissions ranging from 443 to 700 kt N_2O, showing a large variation in estimates (table 2). For example, while the modeled scenarios in the Global Nitrous Oxide Assessment found a baseline of 470 kt N_2O from industrial sources in 2020, the Assessment also cited recent estimates that found industrial sources to have emitted 700 kt of N_2O in 2020.[22] The latter estimate is closely aligned with estimates from the U.S. Environmental Protection Agency (EPA). A recent study found industrial N_2O emissions in China are twice as high as what is modeled by GAINS for China and more than six times higher than data from the Emissions Database for Global Atmospheric Research (EDGAR) v7.0; additionally, emissions data reported by the Chinese government shows emissions from nitric and adipic acid production in 2020 in China alone was 457 kt N_2O, which already exceeds the 2020 global industrial emissions reported by Davidson and Winiwarter and UNEP (table 2).[23] Therefore, global industrial N_2O emissions may be substantially higher than what is presented in figure 2.

TABLE 2: COMPARING INDUSTRIAL N_2O EMISSIONS ESTIMATES IN 2020 FROM VARIOUS ANALYSES

N_2O emissions were provided in million metric tons (Mt) N_2O per year in UNEP's Global Nitrous Oxide Assessment and metric kilotons (kt) N_2O per year in Davidson and Winiwarter. These figures' Mt CO_2e are shown using the conversion in the IPCC Fifth Assessment Report's 100-year GWP for N_2O (265), as was used in the EPA's January 2025 report, to allow comparison among the results.

	2020	Source	Assumptions/methods
Industrial N_2O emissions, kt N_2O (Mt CO_2e [AR5])	700 (186)	Tian et al., 2024 presented in GNA[24]	GHG inventories (EDGAR v7.0, UNFCCC)
	683 (181)	U.S. EPA, 2025[25]	2019 report assumed 3.5 percent annual growth in adipic acid consumption from 2015 to 2030.[26] Emissions projections from 2025 report are lower, suggesting less aggressive assumptions.[27]
	470 (125)	UNEP Global Nitrous Oxide Assessment, 2024[28]	Representative Concentration Pathways 4.5 and Shared Socioeconomic Pathways 2 framework
	443 (117)	Davidson and Winiwarter, 2023[29]	GAINS model

Additional research is needed to refine these estimates to better understand the magnitude of the industrial N_2O problem. The Global Nitrous Oxide Assessment concedes that current N_2O emissions "exceed even the highest emissions scenario" that it modeled, so "the range of possible nitrous oxide futures evaluated in this Assessment are likely too narrow."[30] The Assessment stresses the importance of reconciling these differences among emissions estimates and identifies improved measurement and reporting of N_2O emissions across sectors, including the industrial sector, as a key priority to implement effective abatement measures.[31] One way to increase the accuracy of these estimates would be to conduct a global inventory of current and planned nitric and adipic acid facilities and utilize site-specific data (e.g., measured emissions, production capacity) to better estimate industrial N_2O emissions.

5. Industrial N_2O emissions are projected to increase

Without widespread abatement measures, industrial N_2O emissions are projected to increase substantially through 2050. These emissions increases will be driven mainly by increasing demand for and corresponding production of adipic acid.[32] Nitric acid production is also expected to increase, due primarily to an increase in food demand, which requires fertilizer to meet.[33]

The estimates in global industrial N_2O emissions from the EPA's 2025 non-CO_2 report and UNEP's Global Nitrous Oxide Assessment both show a trend of increasing baseline emissions between 2020 and 2050 (table 3). However, the specific estimates vary considerably between the two sources. As previously discussed, this variation highlights the need for further research and refinement of approaches to understanding and estimating industrial N_2O emissions.

TABLE 3: COMPARING INDUSTRIAL N_2O EMISSIONS IN 2020 AND 2050 FROM EPA AND UNEP ANALYSES[34]

N_2O emissions were provided in million metric tons (Mt) N_2O per year in UNEP's Global Nitrous Oxide Assessment and were converted to Mt CO_2e using the IPCC Fifth Assessment Report's 100-year GWP for N_2O (265), as was used in the EPA's 2025 report, to allow comparison between the two models' results. The 2050 reference scenario represents baseline industrial N_2O emissions in 2050.

	2020	2050 reference scenario	% increase	Source
Industrial N_2O emissions, kt N_2O (Mt CO_2e [AR5])	683 (181)	1,483 (393)	117	U.S. EPA, 2025
	470 (125)	649 (172)	38	UNEP Global Nitrous Oxide Assessment, 2024

Even if one considers the Assessment's lower estimate rather than the EPA's higher one, it still represents an opportunity to abate almost 175 million metric tons (Mt) CO_2e in 2050. Therefore, even with the uncertainty in the exact magnitude of industrial N_2O emissions now and in the future, these estimates underscore the need to abate industrial N_2O emissions as quickly as possible.

6. Abatement of industrial N_2O is cost effective and immediately feasible

Industrial N_2O abatement technology is commercialized and cost effective. N_2O abatement at adipic acid plants has been installed since the late 1990s, and more than 100 nitric acid plants (out of almost 600) already abate their N_2O.[35] While estimates on abatement costs vary, costs are quite manageable.[a] One analysis modeled pathways to mitigate non-CO_2 GHGs in China and found that industrial N_2O emissions in China could be almost entirely eliminated through mitigation measures costing about $5 per metric ton ("ton") CO_2e.[36] A 2010 study of projects funded under the Clean Development Mechanism (further discussed in section 8) found that abatement and transaction costs were below 5 Euro per ton CO_2e (about $8 per ton CO_2e in 2026 USD) for nitric acid plants.[37] A brief analysis of adipic acid project costs under the Clean Development Mechanism and Joint Implementation (discussed in section 8) shows that abatement costs are between $0.25 and $4 per ton CO_2e in 2026 dollars (see Appendix).[b]

Other evidence suggests costs could be higher. Project developer and credit generator ClimeCo claims abatement costs are greater than $1 per ton CO_2e for single abatement systems (which can achieve around 90 percent abatement) and $4 per ton CO_2e for redundant systems (to achieve emissions reductions over 90 percent).[38] ClimeCo currently sells credits from Ascend Performance Material's plant for $13 per ton CO_2e; while this price should not be directly compared with other abatement costs because 1) credits are generated only for incremental

a While marginal abatement cost curves are provided in the EPA's 2025 non-CO_2 report (https://www.epa.gov/system/files/other-files/2025-07/non-co2-report-data-annex-gloabl-domestic-072025.zip), this data is somewhat inconsistent with other data on the cost mitigation potential of these abatement technologies. In 2050, the EPA shows only 65 percent of global industrial N_2O emissions abatable below $20 per ton CO_2e and a maximum technically feasible abatement potential of 80 percent. Other data shows abatement is cheaper and can reach efficiencies above 90 percent and closer to 100 percent. A review of the U.S. EPA's methodology documentation did not explain this discrepancy, so this paper does not show this specific data.

b This figure is derived from a study published in 2010 and only adjusts for inflation between 2010 USD and 2026 USD. It does not incorporate costs (e.g., raw materials, labor, etc.) that may have changed between 2010 and 2026.

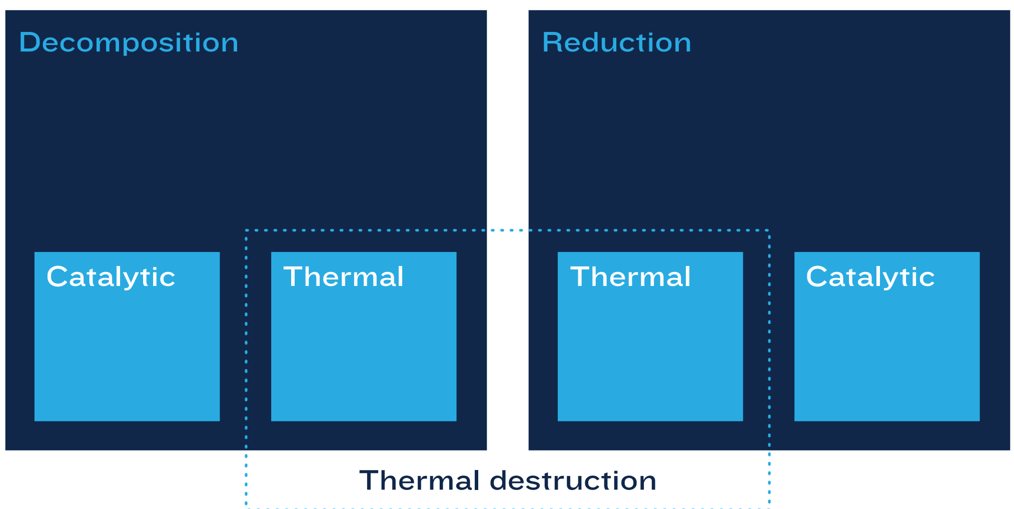
emissions reductions above the historical reductions already implemented by the facility and 2) credit prices include overhead costs for credit generation and certification, the higher credit price may indicate higher costs associated with abatement.[39] Still, $13 per ton of CO_2e is not very high when compared with other mitigation solutions. For example, carbon capture on blast furnace iron and steelmaking can cost $115 per ton of CO_2.[40]

Importantly, N_2O abatement involves substantial up-front capital costs and ongoing operating costs, so there is no abatement potential at or below $0 per ton CO_2e. Still, the relatively low marginal cost of abatement and the resulting climate and public health benefits make industrial N_2O abatement a lever to pull sooner rather than later.

7. Abatement technologies to address industrial N_2O emissions

Industrial facilities can abate N_2O emissions through decomposition or reduction technologies. Both can happen via catalytic or thermal pathways. Within thermal pathways, thermal destruction is the umbrella term that describes both thermal reduction and thermal decomposition (figure 3). These abatement technologies already exist and are operating at commercial scale at some nitric acid and adipic acid facilities. Decomposition breaks down N_2O into N_2 and O_2 (with some NOx formation[c]). Reduction uses hydrocarbons to convert N_2O into N_2, CO_2 (which is a much less potent GHG than N_2O), and water; reduction can also lead to some NOx formation.

FIGURE 3: FRAMEWORK OF ABATEMENT TECHNOLOGIES AVAILABLE FOR INDUSTRIAL N_2O ABATEMENT



c NOx refers to nitrogen oxides, a class of air pollutants that include NO and NO_2.

7.1 Catalytic decomposition and thermal destruction are used in adipic acid plants

Catalytic decomposition and thermal destruction of N_2O are the main methods for N_2O abatement in adipic acid plants. As of 2010, catalytic decomposition was the most installed N_2O abatement pathway for adipic acid plants.[41] A comparison between the two methods is shown in table 4. Catalytic decomposition has a key performance advantage over thermal destruction for N_2O abatement in adipic acid plants since it can include cost-effective NOx abatement.

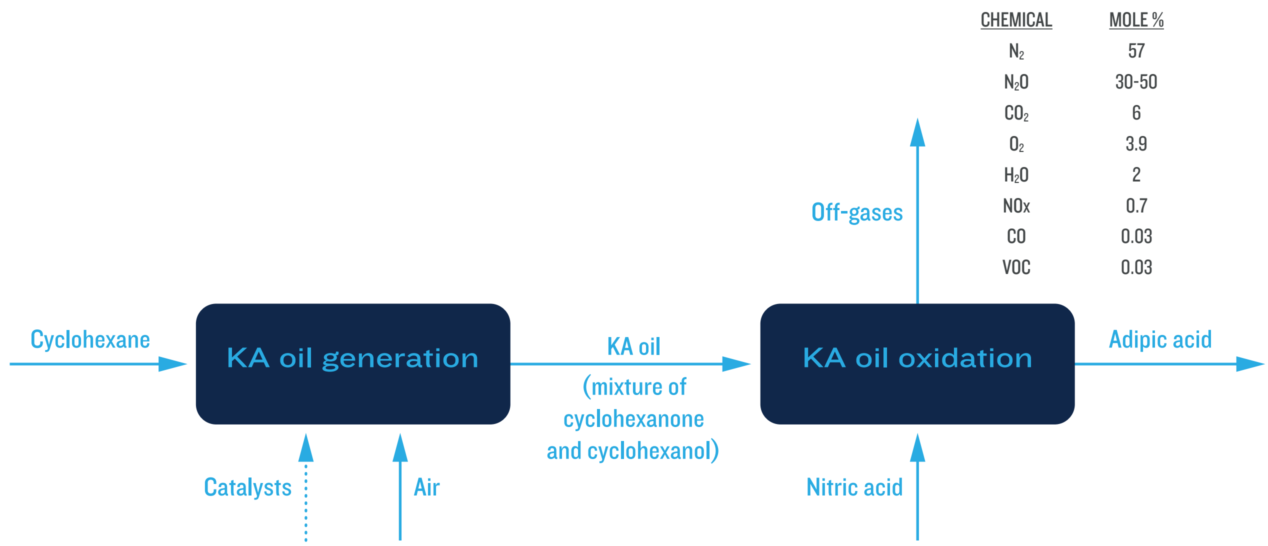
TABLE 4: A COMPARISON BETWEEN CATALYTIC DECOMPOSITION AND THERMAL DESTRUCTION FOR N_2O ABATEMENT IN ADIPIC ACID PLANTS Catalytic decomposition presents an advantage in addressing N_2O emissions from adipic acid production because catalyst systems are able to also incorporate effective NOx abatement.

	Achieved N_2O abatement efficiency, %	Pairable with cost-effective NOx abatement?
Catalytic decomposition	99[42]	Yes[43]
Thermal destruction—thermal reduction units	99[44]	Partially[45]
Thermal destruction—boilers	>98[46]	No[47]

Adipic acid production emits N_2O during the main process step in which nitric acid oxidizes a mixture called KA oil, composed of cyclohexanone and cyclohexanol. The resulting N_2O effluent constitutes 30 to 50 mole percent of the formed off-gases—i.e., 30 to 50 percent of the gas molecules emitted from adipic acid production is N_2O (figure 4).[48] Between 0.75 and 1 mole of N_2O is formed through the main reaction pathway for each mole of adipic acid formed.[49] The two adipic acid facilities in the United States are equipped with N_2O abatement: Invista's facility in Victoria, Texas, has been abating N_2O via catalytic decomposition since 1997 (with an alternate thermal destruction system), and Ascend's Pensacola facility in Cantonment, Florida, abated via thermal destruction for many decades (before 1994) but only recently implemented maximally effective abatement.[50]

FIGURE 4: GENERAL BLOCK FLOW DIAGRAM DEPICTING COMMON ADIPIC ACID PRODUCTION ROUTE WITH REPRESENTATIVE OFF-GAS COMPOSITION FROM UNABATED PRODUCTION[51]

Adipic acid is produced from the oxidation of KA oil by nitric acid. The nitrogen source for the off-gases is nitric acid. N_2O constitutes the largest mole percentage of the off-gases due to N_2O being formed through the main reaction pathway on an almost mole-for-mole basis with adipic acid.



Catalytic decomposition of N_2O uses a catalyst to speed up the thermodynamically favorable decomposition of N_2O into N_2 and O_2 at the lowest possible temperature while minimizing the decomposition of N_2O into NO (a form of NOx) (figures 5 and 6).[52] Catalysis operates at around 500°C and can abate close to 100 percent of N_2O emissions from adipic acid production.[53] Catalytic decomposition can be cheaper than thermal destruction methods due to lower-temperature operating conditions.[54] Accordingly, DuPont determined in 1992 that catalytic abatement was the best option to pursue at multiple adipic acid plants, including its Victoria, Texas, plant, which is now owned by Invista and still runs catalytic N_2O abatement.[55] Given the exothermic nature of N_2O decomposition (i.e., the reaction gives off heat) and catalysts' sensitivity to heat, controlling the temperature in the catalytic reactor is important to maintaining catalyst integrity, and this presents an opportunity to recover heat to use for other processes in a plant.[56] Catalytic systems can also incorporate effective abatement (more than 90 percent) for NOx, CO, and volatile organic compound (VOC) emissions for the adipic acid off-gases.[57]

FIGURE 5: BLOCK FLOW DIAGRAM OF CATALYTIC DECOMPOSITION OF N_2O TAIL GAS FROM ADIPIC ACID PRODUCTION

The decomposition of N_2O into N_2 and O_2 is accelerated by a catalyst and elevated temperatures. Catalysts are designed to minimize the decomposition of N_2O into NO. *Source:* Shimizu et al., 2000, https://doi.org/10.1016/S1465-9972(00)00024-6 at 428–29.

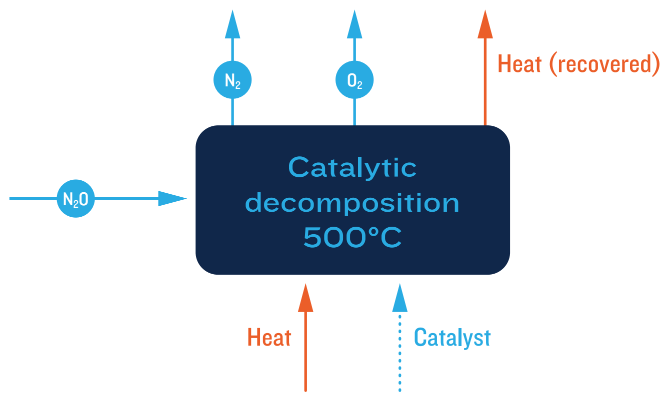


FIGURE 6: REACTION NETWORK FOR N_2O DECOMPOSITION

N_2O thermally decomposes into N_2 and O_2 but can also form NO. *Source:* Shimizu et al., 2000, https://doi.org/10.1016/S1465-9972(00)00024-6 at 427.

$$NO \leftrightarrow N_2O \rightarrow N_2,\ O_2$$

Thermal destruction of N_2O from adipic acid plants includes thermal decomposition and reduction. When N_2O is heated, it decomposes into N_2 and O_2 gas.[58] Mixing in a reducing agent, such as methane, at high temperatures can spontaneously maintain N_2O destruction by converting N_2O into N_2 and water (figure 7).[59] Thermal destruction can occur in boilers or thermal reduction units (TRUs), which use high heat and reducing agents (i.e., hydrocarbon fuel) to destroy N_2O.[60] The functional difference is that a boiler is explicitly used to produce steam, whereas a TRU is an emissions control device (although heat can be recovered from TRUs and subsequently used to produce steam).[61]

FIGURE 7: CHEMICAL EQUATION SHOWING N_2O DESTRUCTION BY METHANE IN A REDUCING FLAME BURNER

Methane (CH_4) is shown as a representative fuel for N_2O destruction. CO_2 emissions from the use of methane as a reducing agent are not a primary concern due to the heat produced from exothermic N_2O destruction; this heat is recycled and displaces fuel consumption elsewhere in the plant.[62] These CO_2 emissions are also accounted for when assessing an abatement project's net GHG reductions for carbon credit issuance. For example, the Adipic Acid Production Protocol developed by Climate Action Reserve includes these CO_2 emissions as part of an adipic acid N_2O abatement project's GHG Assessment Boundary.[63] *Source:* Reimer et al., 1994, https://doi.org/10.1002/ep.670130217 at 135–36.

$$CH_4 + 4N_2O \rightarrow 4N_2 + CO_2 + 2H_2O$$

7.1.1 Thermal destruction faces challenges in simultaneously abating N_2O and NOx

Thermal destruction of N_2O via boiler systems can be very effective at abating N_2O, but addressing the potential increase in NOx emissions can make this approach uneconomical in places (like the United States) with NOx emissions limits.

When N_2O decomposes, it releases heat. Therefore, it would increase energy efficiency to decompose or reduce N_2O in a plant's existing boilers and combine the energy released from N_2O decomposition with the energy from the fuel being burned in the boiler to generate low-cost steam for use in other parts of the facility.[64] In other words, burning N_2O with other fuels in boilers would save costs while abating N_2O. However, existing boilers at adipic acid plants cannot decompose N_2O without running the risk of producing NO and exceeding NOx limits. A plant could install a new boiler that has staged combustion to overcome the NO formation issue, but that is expensive. In the past, the low-NOx boiler design for N_2O abatement was worth the extra investment only when a facility did not have access to low-cost steam.[65] Otherwise, catalytic abatement was, and remains, the preferred economic choice for N_2O abatement.[66]

Another abatement technology that utilizes thermal destruction is TRUs. Ascend's Pensacola facility has two TRUs. A TRU can abate N_2O as well as NOx, CO, and VOCs.[67] However, TRUs cannot fully abate NOx emissions from an adipic acid facility, so when adipic acid production increases, NOx emissions also increase. To prevent NOx emissions from surpassing applicable regulatory limits when adipic acid production increases, facilities will switch from TRUs to selective catalytic reduction (SCR), which abates NOx more effectively; however, SCR does not abate any N_2O, so facilities will subsequently stop abating N_2O.[68] In the case of Ascend's adipic acid plant, TRU efficacy for N_2O abatement was recently maximized by pairing it with another NOx abatement technology. An absorption column first removes about half of the NOx from the off-gases and converts it into nitric acid to be reused for adipic acid production.[69] With a reduced amount of NOx remaining in the off-gases, more of the exhaust can be treated with TRU instead of SCR technology while complying with NOx limits.[70] A second TRU was also added to maximize N_2O destruction.[71] Thus, more N_2O is abated, but there are higher costs associated with redundant abatement. The project at Ascend is funded through participation in voluntary carbon markets (Ascend owns all the credits generated from abatement).[72]

7.2 Catalytic decomposition and reduction are used in nitric acid plants

N_2O abatement methods from nitric acid production can be categorized as primary, secondary, or tertiary abatement depending on their position in the nitric acid production process (figure 8). Generally, tertiary abatement offers the most effective N_2O abatement, followed by secondary (table 5). Within tertiary abatement measures, catalytic decomposition offers higher abatement at a lower cost compared with nonselective catalytic reduction (NSCR) (table 5). Both secondary and tertiary measures are commercialized and utilized in nitric acid plants.[73] Primary abatement is not proven to be as effective for N_2O abatement.[74] About 100 nitric acid facilities out of 580 globally are equipped with N_2O abatement.[75] A summary of N_2O abatement measures for nitric acid production is shown in table 5.

FIGURE 8. GENERAL BLOCK FLOW DIAGRAM DEPICTING NITRIC ACID PRODUCTION ROUTE[76]

Unlike in adipic acid production, N_2O is formed through unwanted side reactions. Primary N_2O abatement occurs in the ammonia burner, secondary N_2O abatement occurs between the burner and the absorber where nitric acid is formed, and tertiary N_2O abatement occurs after the absorber.

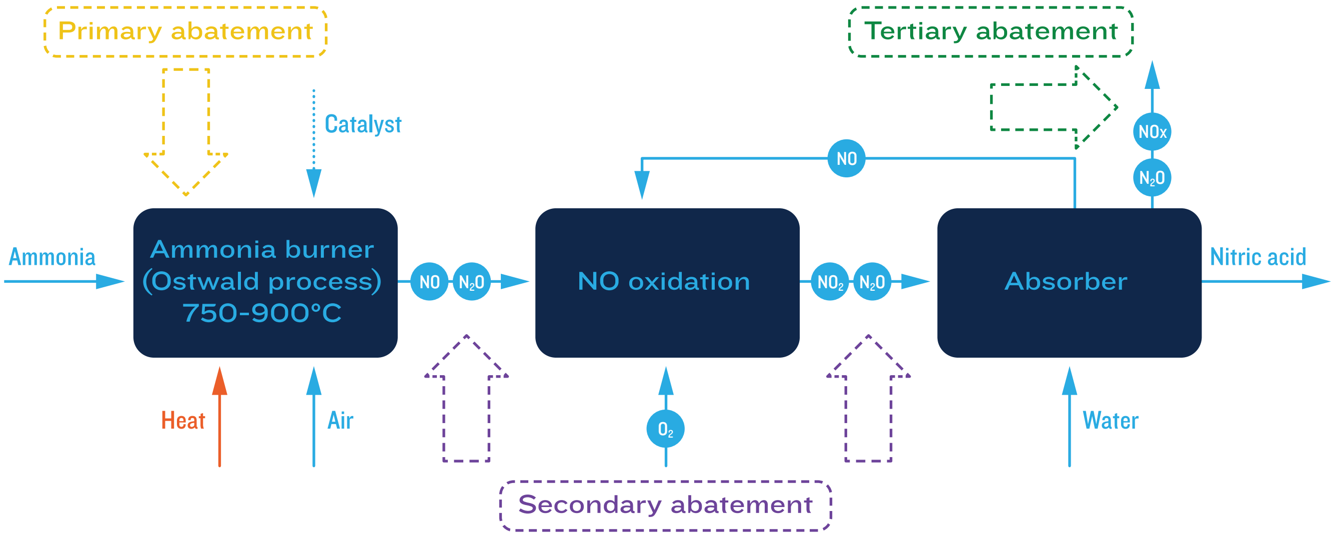


TABLE 5: COMPARISON OF N_2O ABATEMENT MEASURES FOR NITRIC ACID PRODUCTION

Tertiary abatement measures tend to have higher N_2O abatement efficiency than secondary abatement measures. Tertiary N_2O abatement can also abate NOx simultaneously or can be paired with NOx abatement in the same reactor. Nonselective catalytic reduction is effective but has high costs due to high energy use and is not preferred for modern plants. CapEx and OpEx estimates taken from the U.S. Environmental Protection Agency's 2019 non-CO_2 report methodology are shown in million 2010 USD based on a nitric acid plant capacity of 1,000 t/day. CapEx includes costs to purchase and install initial catalyst, related equipment, and process modifications. OpEx includes costs for catalyst replacement, fuel, labor, maintenance, and production losses from process disruptions from catalyst. Primary abatement measures exhibit low N_2O abatement and have little available data on technology cost.

Abatement measure		N_2O abatement[77]	NOx abatement	CapEx ($M)[78]	OpEx ($M/yr)[79]	Time horizon (years)[80]
Primary		Low	None	–	–	–
Secondary		70–90 percent	None	1.3	0.4	15
Tertiary	Catalytic decomposition	Up to 99 percent	Can be paired with NOx abatement in same reactor	2.3	0.2	15
	Nonselective catalytic reduction	80–95 percent	Yes	4.0	2.1	20

Nitric acid is produced commercially using the Ostwald process, in which ammonia is oxidized over a platinum-rhodium catalyst producing NO. The gases are cooled and react with oxygen to produce NO_2. NO_2 is absorbed into water to produce nitric acid and NO, which undergoes oxidation to produce NO_2 (figure 8). However, there is an undesired side reaction that occurs in the ammonia burner and results in N_2O being produced. Additional undesired side reactions of unreacted ammonia and NO form N_2O further downstream as well.[81] Because N_2O is formed from undesired side reactions during nitric acid production, N_2O emissions from nitric acid production on a molar basis are lower than N_2O emissions from adipic acid production.[82] The differences in reaction pathways and off-gas compositions lead to differing N_2O abatement technology options and effectiveness of market mechanisms (discussed in section 8.2) between adipic acid and nitric acid production.

Primary abatement occurs in the ammonia burner and refers to abatement measures that prevent or limit N_2O generation during ammonia oxidation.[83] One method is to use heat to decompose N_2O into nitrogen and oxygen gas. Technically speaking, primary abatement through thermal destruction occurs to some extent in all nitric acid plants because the elevated temperature in the ammonia burner will drive some decomposition of the N_2O that forms.[84] However, to increase N_2O decomposition to meaningful levels, the residence time of the N_2O would need to be increased to more than what is allowed in ammonia burners through design changes, and this option is costly and still limited in N_2O abatement efficacy.[85] Another method for primary abatement is to modify or find alternatives to the ammonia oxidation platinum catalyst to prevent undesired reactions in the burner.[86] This abatement method is only practical for new nitric acid plants, as a new reactor and other plant modifications for a retrofit would be expensive.[87] An additional challenge is that modifying an existing ammonia oxidation catalyst does not yield high N_2O abatement, and designing a new catalyst can decrease nitric acid production.[88] Maximizing primary abatement is therefore an uneconomical and infeasible option for N_2O abatement in nitric acid production. The Nitric Acid Climate Action Group (NACAG), Germany's bilateral initiative to abate N_2O from nitric acid production, does not fund projects that utilize primary abatement measures.[89]

Secondary abatement typically involves the catalytic decomposition of N_2O after ammonia oxidation and before the absorber, with the preferred catalyst location being directly after the ammonia oxidation catalyst gauzes, where the temperature is the highest.[90] Secondary abatement can be very effective (80 to 98 percent N_2O emissions reduction), but the catalysts must be designed to work under extreme conditions, such as high temperatures, and must not decompose NO, as this would hinder nitric acid production.[91] Secondary catalysts tend to have lower practical abatement efficiency—70 to 90 percent—than tertiary catalysts, partially due to the catalyst being consumed over time.[92] However, an advantage of secondary abatement is low investment costs due to placement of the catalyst in existing equipment (if preexisting configurations allow).[93] As of 2010, 53 nitric acid production process lines worldwide had secondary abatement via catalytic decomposition installed.[94] Among these is the Invista nitric acid plant in Victoria, Texas.[95]

Tertiary abatement eliminates N_2O after the absorber, where nitric acid is formed. Abatement can occur through catalytic decomposition or NSCR with a chemical reagent over a catalyst.[d] N_2O reduction efficiency is 80 to 99 percent.[96] (NSCR is typically installed to control NOx emissions, but it also effectively abates N_2O.[97]) Important advantages of tertiary abatement are the elimination of potential interference with nitric acid production (as can happen with secondary abatement), lack of externally determined constraints (i.e., if a new reactor is added, it can be built to optimize N_2O abatement), and the ability to combine N_2O and NOx abatement in a single reactor.[98] Generally, tertiary abatement measures have higher capital cost than secondary abatement due to the need to acquire new equipment.[99] Still, while NACAG funds both secondary and tertiary abatement, it prefers tertiary abatement due to typically higher operating abatement and NOx abatement ability.[100] The downside of tertiary abatement via NSCR compared with catalytic decomposition is that the cost of operation is higher due to the need for reducing reagent, although this cost can be mitigated by recovering heat from the exothermic NSCR process or by using reductant-rich waste gas streams from other chemical processes for nitric acid plants colocated with other chemical processes.[101] NSCR is typically not preferred in modern plants due to this high energy need and resulting high cost.[102] The European Union (E.U.)'s Best Available Techniques Reference Document for nitric acid does not list NSCR as a best available technology for N_2O emissions reductions, while it does list tertiary catalytic decomposition of N_2O and NOx abatement in a single reactor.[103]

d Although CO_2 can be emitted from the use of methane (a common reducing agent) for NSCR of N_2O, there is less than a 3 percent increase in GHGs compared with the GHG reductions from N_2O abatement. However, an important consideration is methane slip—when unburnt methane is released into the atmosphere—which could contribute to significant GHG emissions of a nitric acid plant after N_2O abatement. Therefore, NSCR that uses methane should prioritize minimizing methane slip. *Source:* U.S. EPA, "Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from the Nitric Acid Production Industry," December 2010, 16–17, https://www.epa.gov/sites/default/files/2015-12/documents/nitricacid.pdf.

8. Well-designed financial mechanisms may incentivize permanent abatement of industrial N_2O emissions

Industrial N_2O abatement technologies add costs to nitric acid and adipic acid manufacturing. Carbon credits have been used to incentivize the installation and operation of industrial N_2O abatement equipment, but industrial N_2O carbon credits have suffered from partial carbon leakage and failed to deliver sustained abatement when the market price for credits fell below the cost of continuing to operate N_2O abatement technologies.[e] Newer crediting schemes are incorporating more guardrails to prevent carbon leakage and should ideally be leveraged to encourage emission control standards to ensure indefinite operation of abatement measures (see section 9).

8.1 The Clean Development Mechanism led to carbon leakage from adipic acid production

A prime example of carbon credit failure was the Kyoto Protocol's Clean Development Mechanism (CDM), which established carbon market mechanisms to incentivize industrial N_2O abatement but ended up creating perverse incentives and, ultimately, emissions leakage. In the case of adipic acid production, baseline emissions were set to zero, meaning any amount of N_2O abatement was eligible to receive carbon credits.[104] Due to the large volumes of N_2O generated from adipic acid production combined with the high effectiveness of abatement technologies, the carbon credits for N_2O abatement were extremely lucrative, and CDM profits exceeded profits from selling adipic acid by as much as an order of magnitude.[105] While this did lead to high levels of N_2O abatement, production shifted from non-CDM adipic acid plants (some of which were already abating N_2O emissions) to CDM plants; this shift occurred because CDM plants used the profits from credits to flood the adipic acid market with cheap adipic acid, forcing non-CDM plants out of business.[106] Additionally, adipic acid production at these CDM plants increased.[107] In fact, the production increase incentivized by the credits likely caused additional GHG emissions at a magnitude that "represents 17 percent to 22 percent of CERs [credits] issued . . . which did not result in actual emission reductions."[108]

The overissuance of credits for adipic acid CDM projects contributed to the collapse of the credit market and the cessation of abatement. Once the E.U. (the largest buyer of credits) discovered the gross overvaluation of the credits, it announced it would stop buying N_2O credits starting in 2013.[109] This E.U. regulation dovetailed with wealthier countries scaling back purchases of CDM credits, so the CDM credit market collapsed.[110] Evidence strongly suggests that Chinese adipic acid plants that installed N_2O abatement equipment using funds from the CDM subsequently discontinued or scaled back operating abatement equipment and that non-CDM plants in China today do not fully abate N_2O emissions due to lack of financial incentive or government regulation.[111] The cessation of abatement resulted from a lack of a subsequent regulatory requirement, thereby showcasing that while carbon credits can successfully incentivize abatement technology installation, they alone cannot guarantee sustained operation of said technology.

e The terms *carbon credit* and *carbon leakage* are still used in the context of abating industrial N_2O emissions due to N_2O being a GHG like CO_2. Carbon credits are sold per ton of CO_2 mitigated, so industrial N_2O carbon credits convert the N_2O emissions reductions to CO_2-equivalent reductions. For N_2O, *carbon leakage* refers to the phenomenon whereby industrial N_2O emissions simply shift to other sources that continue emitting (or emit more) N_2O as a result of measures that sought to reduce N_2O emissions.

8.2 Higher-baseline crediting schemes may prevent over-crediting

Carbon crediting schemes that only credit emissions reductions above a high baseline may help address the problem of over-crediting and its consequences. In contrast to CDM adipic acid projects, adipic acid projects under Joint Implementation (JI) (a CDM-like Kyoto Protocol mechanism allowing industrialized countries to invest in emissions reductions projects in developing countries to earn credits) likely did not cause carbon leakage, according to a 2010 study.[112] JI projects essentially used a baseline emissions level of around 90 percent (i.e., credits were issued only for abatement above 90 percent), but investments in abatement for JI projects were still profitable, and the amortization time was still less than a year.[113] (For comparison, CDM project amortization time was under a month, and profits were an order of magnitude higher.)[114] JI projects also experienced great success in installation of effective N_2O abatement technology.[115] Because the JI projects were less wildly profitable than CDM projects, though, they likely did not cause any emissions leakage.[116]

The high baseline is especially pertinent for credits generated from abatement at adipic acid facilities due to the large volumes of N_2O emissions—and subsequent potential for over-crediting—arising from adipic acid production. As previously described, N_2O is produced almost on a mole-for-mole basis with adipic acid in the main reaction pathway. The resulting large volume of credits when abating from a zero percent baseline is what caused the profits from credits of CDM adipic acid plants to exceed profits from selling adipic acid by as much as an order of magnitude.[117] Evidence also suggests that CDM nitric acid plants may not have caused leakage, in part due to the lower volumes of credits generated.[118] Adipic acid production emits 300 kg of N_2O per ton of adipic acid, whereas nitric acid production generally emits less than 10 kg of N_2O per ton of nitric acid.[119] Thus, credits generated from N_2O abatement from nitric acid production result in lower profits than credits generated from abatement (without a high baseline) from adipic acid production when credits are sold for the same price (as was the case under CDM).[120]

8.3 New crediting schemes are incorporating more guardrails

To prevent the pitfalls of the CDM, guardrails have been created to try to ensure that voluntary carbon credits for industrial N_2O abatement are being issued to high-integrity projects. The Integrity Council for the Voluntary Carbon Market (ICVCM) is “an independent non-profit governance body working to establish and maintain worldwide standards for integrity in the voluntary carbon market.”[121] ICVCM has created a list of 10 Core Carbon Principles (CCPs) to set a global benchmark for high integrity in the voluntary carbon market to help credit buyers identify credits that represent real climate impact.[122] The ICVCM approves carbon crediting registries as CCP-Eligible programs, which are then able to develop protocols that are subject to ICVCM approval (CCP-Approved categories); credits can only be issued as CCP-labeled under these CCP-Approved categories.[123] One registry that has been deemed CCP-Eligible and has worked on developing protocols for industrial N_2O abatement is the Climate Action Reserve.[124]

ClimeCo is a project developer and credit generator with more than 15 years of experience in industrial N_2O abatement. In conjunction with ClimeCo, the Climate Action Reserve developed the China Adipic Acid Production Protocol, which allows Chinese adipic acid facilities to generate carbon credits only for N_2O emissions abatement above 90 percent. The Climate Action Reserve, with support from ClimeCo, also developed carbon crediting protocols for N_2O abatement at U.S. adipic acid and nitric acid facilities with the goal of guaranteeing real, additional, permanent N_2O reductions without leakage. The Chinese and U.S. adipic acid production protocols are CCP-Approved, while the U.S. nitric acid protocol was undergoing CCP assessment as of March 2026.[125] In addition to the 90 percent baseline for adipic acid projects in China, the China Adipic Acid Production Protocol mandates production caps for projects.[126] The combination of a high baseline and production caps is meant to prevent the production of more adipic acid for the sole purpose of selling more carbon credits.[127]

HOW TO ACHIEVE REAL AND PERMANENT INDUSTRIAL N_2O ABATEMENT: WELL-DESIGNED VOLUNTARY CARBON CREDIT MECHANISMS, REGULATIONS, OR A COMBINATION?

In July 2024, leaders in the field of industrial N_2O abatement met in Washington, D.C., to discuss options for curbing industrial N_2O emissions from China and the United States. ClimeCo discussed their three adipic acid N_2O abatement projects in China.[128] As ClimeCo leverages voluntary carbon markets, as opposed to regulatory standards, to achieve N_2O abatement, the results of its projects in China will illuminate the effectiveness of a markets-only approach in driving abatement at facilities that have never abated N_2O in the past.

Voluntary carbon markets and regulations working in tandem may be another option to achieve abatement. At the same 2024 meeting, Rick Duke, at the time deputy special envoy for climate in the U.S. Department of State, and Manish Bapna, president of NRDC, both emphasized the complementary nature of carbon markets and regulatory standards to achieve near-total abatement of industrial N_2O.[129] They noted that robust regulations can achieve the vast majority of N_2O abatement (about 90 percent), with high-integrity carbon markets filling the incentive gap for the remaining 10 percent, which can require more costly interventions such as redundant abatement systems.[130]

On the other hand, one former adipic acid industry insider believes regulations alone should be used to incentivize the industry's N_2O abatement. Robin MacDonald, who worked for DuPont, PCI Nylon, and Wood Mackenzie over a career spanning three decades, believes that given the decades-long maturity of industrial N_2O abatement technology, there is no need to financially motivate industry laggards to cut emissions.[131] Instead, he argues, countries should pass regulations mandating industrial N_2O emissions reductions.[132]

9. Insights for reducing industrial N_2O emissions

Multiple levers can be utilized to eliminate industrial N_2O emissions (figure 9). N_2O pollution control standards are seen by policy experts as the most reliable way to ensure consistent, high (around 90 percent) industrial N_2O abatement, with carbon markets potentially playing a supporting role in achieving even higher levels of abatement (exceeding 99 percent) (see call-out box, above).[133] The use of high-integrity voluntary carbon markets to increase existing N_2O abatement rates at the two U.S. adipic acid facilities highlights the ability of markets to provide the extra incentive needed to achieve maximal abatement; however, caution must be taken to protect against perverse incentives and cessation of abatement, as showcased by the failure of the CDM.[134]

FIGURE 9: MEASURES TO REDUCE INDUSTRIAL N_2O EMISSIONS

Regulations are favored for their effectiveness in achieving high levels of sustained abatement, but they are not always feasible.
Well-designed market mechanisms may hold potential for financially incentivizing abatement, especially in the absence of regulations.
Other government policies as well as private sector action can also encourage industrial N_2O abatement.

Regulations	Market mechanisms	Other policies	Private sector
N_2O pollution control standards	Regulated compliance markets (E.U. ETS, China ETS)	Support for abatement projects and technology development	Clean procurement
	Voluntary carbon markets	International agreements to reduce N_2O	
		Climate trade policies (CBAM)	

In the E.U., an explicit combination of standards and markets called the E.U. Emissions Trading System (ETS)—essentially a mandatory carbon market—has financed N_2O abatement at all E.U. adipic and nitric acid facilities and demonstrates the promise of both pollution control standards and carbon markets.[135] Of course, standards or regulated compliance markets are not always politically feasible, so high-quality voluntary market mechanisms alone may be able to serve as a critical bridge incentivizing pre-regulatory abatement. Other actions include government support of abatement technology deployment, multilateral agreements and financing mechanisms to address industrial N_2O emissions, and quantification of embodied N_2O emissions to drive climate-friendly trade policies and private procurement.

9.1 Addressing N_2O emissions from Chinese adipic acid production

A key component of cutting industrial N_2O emissions today is successful N_2O abatement at Chinese adipic acid facilities; some combination of regulations, robust market mechanisms, and other policies could help achieve this. Given that N_2O emissions from about a dozen Chinese adipic acid facilities account for the majority of global N_2O emissions from adipic acid plants, installing and operating abatement technologies at this handful of locations can make a very big impact. A particular barrier to industrial N_2O abatement in China is the reliance on imported catalysts, which increase abatement costs and disincentivize industrial N_2O abatement.[136] Therefore, policy solutions should prioritize the development of cheaper domestic catalysts to achieve industrial N_2O abatement.

Industrial N_2O pollution control standards could be one mechanism for accelerating catalyst development and deployment in China. Although there has been some work to create domestic catalysts in China, one study attributed the lack of large-scale deployment of these domestic catalysts to the lack of regulatory requirements.[137] Accordingly, industrial N_2O pollution control standards in China could provide a needed incentive to deploy cheaper domestic catalysts to abate industrial N_2O.

While China does not currently have N_2O standards, the government has acknowledged the importance of developing N_2O mitigation strategies and is pursuing alternate policies. In August 2025, the Chinese government released its Action Plan for Controlling Industrial-Sector N_2O Emissions ("Action Plan"), which includes policy measures to financially support mitigation projects, promote abatement technology development, and establish an N_2O emissions reporting system.[138] To help implement this Action Plan, the Industry-Academia-Research Alliance for Controlling Industrial-Sector N_2O Emissions ("Alliance") was formed in November 2025, and this Alliance plans to, among other activities, accelerate the deployment of abatement technology and strengthen international cooperation for industrial N_2O abatement.[139] These policy measures and actions can be considered successful if they can achieve high deployment rates of catalysts for industrial N_2O abatement and ultimately pave a path toward standards.

Carbon markets, both mandatory and voluntary, could also hold potential for addressing industrial N_2O emissions in China. China has a mandatory national ETS that covers the power, cement, steel, and aluminum sectors, albeit with weak production intensity-based reduction requirements rather than mass-based caps.[140] Though industrial N_2O emissions are not currently covered, the inclusion of non-CO_2 perfluorocarbons from the aluminum sector is a promising sign that other non-CO_2 GHGs like N_2O could be included in future expansions of the ETS.[141] The success of the E.U. ETS in financing abatement at all nitric and adipic acid facilities in the E.U. may indicate the potential effectiveness of a similar scheme in China.

The effectiveness of a voluntary carbon market in reducing Chinese industrial N_2O emissions, particularly from adipic acid production, remains to be seen. China's Action Plan includes provisions to incentivize N_2O abatement through China's voluntary greenhouse gas emissions trading program, which was relaunched in 2024 and complements its ETS, in addition to developing a monitoring standard.[142] Guardrails around monitoring, reporting, and verification, a key focus of the Alliance, will be essential to preventing perverse market incentives. With regard to global voluntary carbon markets, ClimeCo is pursuing three Chinese adipic acid N_2O abatement projects that will be subject to a 90 percent abatement baseline and incentivized through participation in global voluntary carbon markets.[143] All three of these adipic acid plants have never abated N_2O in the past and are installing catalytic abatement using technology licensed by Invista.[144] A potential marker of success would be the development of cheaper, domestic catalysts in China to reduce reliance on imported, expensive catalysts and, therefore, carbon markets, to ensure sustained N_2O abatement. More fundamentally, China could ensure sustained abatement by setting standards requiring deep abatement of industrial N_2O. This could be a key opportunity to deliver on its 2035 nationally determined contribution target that now includes non-CO_2 GHGs, consistent with the U.S.-China Sunnylands Statement issued in 2023.[145]

9.2 Addressing N_2O emissions from U.S. nitric acid production

In the United States, which is the second-largest emitter of industrial N_2O globally and the largest emitter of N_2O from nitric acid production, federal regulations don't directly prohibit release of N_2O by-product from nitric acid production. However, purpose-built future regulations could do so and have the potential to ensure a consistent, high level of N_2O destruction. Regulations could be implemented on the basis of either N_2O's ozone depletion potential or its global warming potential. National Ambient Air Quality Standards (NAAQS) for NOx have resulted in N_2O abatement in roughly half of the United States' nitric acid production facilities (due to co-destruction co-benefits) in areas that are out of compliance with federal limits on NOx air pollution.[146] Further strengthening those standards or targeting N_2O-emitting facilities as part of NAAQS compliance could result in additional N_2O abatement.

Voluntary carbon markets with strong guardrails may also be able to maintain existing progress and make additional progress in industrial N_2O abatement. ClimeCo claims that its U.S. projects have achieved more than 40 Mt CO_2e in emissions reductions over the past 15+ years from nitric and adipic acid production.[147] Given that only about half of U.S. nitric acid facilities are abating N_2O, increasing the number of participating facilities in voluntary carbon markets with guardrails could thus be one option for moving forward on industrial N_2O abatement in the absence of regulation. An important consideration, however, is that the Climate Action Reserve's current Nitric Acid Production Protocol (Version 3.0) does not have an above-zero baseline for abatement to qualify for credits.[148] The protocol does have an additionality requirement, which 1) prevents N_2O abatement resulting from federally mandated NOx abatement activity from being eligible for carbon credits and 2) requires the abatement technology to be a secondary catalyst, tertiary catalyst, or a combination of the two. These additionality requirements may be sufficient to guard against consequences such as carbon leakage, but projects credited under this protocol should be monitored to ensure high-integrity abatement results from these credits.

9.3 Other actions for industrial N_2O abatement

Beyond the United States and China, other bilateral and multilateral efforts could lead to more industrial N_2O abatement. Germany's bilateral NACAG initiative—launched at the 2015 COP21 meeting—provides technical, financial, and policy support to Official Development Assistance countries to install N_2O abatement equipment at nitric acid facilities as long as these countries commit to maintaining emissions reductions measures.[149] The initiative was launched to revitalize abandoned industrial N_2O projects in the aftermath of the CDM credit crisis and to incentivize abatement at plants that had not been covered under the CDM.[150] As of September 2025, 11 countries were eligible for NACAG funding, and there have been seven successful tenders (whose costs are fully covered by NACAG) for procurement of N_2O monitoring and abatement equipment at nitric acid plants in South Africa, Mexico, Georgia, Tunisia, Colombia, and Jordan.[151] Continuing NACAG and launching other efforts like it are essential for accelerating the successful installation and operation of N_2O abatement technologies at facilities around the world.

Multilaterally, parties to the Paris Climate Agreement and the Vienna Convention could consider more action to abate N_2O, and the Montreal Protocol could be amended to control N_2O emissions. For HFC-23, one of the hydrofluorocarbons controlled by the treaty, there is a mandatory obligation to destroy HFC-23 by-product emissions generated in the production of other substances. The Montreal Protocol would need to be amended to add N_2O as a controlled substance, and modeling the control of N_2O after that of HFC-23 could be one way of amending the treaty.

Since nitric and adipic acid are typically intermediate products, the concept of embodied emissions, meaning the total emissions associated with the life cycle of a product, could play a role in clean procurement by the private sector downstream of nitric and adipic acid manufacturing. One example of potential private sector action is automobile manufacturers procuring nylon sourced from adipic acid plants with N_2O abatement (i.e., buying nylon with lower embodied emissions).[152] One study found that 83 percent of global adipic acid is used to produce nylon 66 and that the automotive industry consumes 65 percent of this nylon 66; this means the automotive industry represents more than half of the N_2O emissions from global adipic acid production.[153] This study also found that the average passenger vehicle's embodied N_2O emissions is just under 1 ton CO_2e per vehicle.[154] Therefore, total abatement costs per vehicle would be quite manageable ($5 per vehicle for an abatement cost of $5 per ton CO_2e; see section 6). At such low cost, automobile manufacturers could be incentivized to include upstream N_2O abatement in voluntary emissions reduction goals.

Embodied N_2O could also drive trade policies, such as carbon border adjustments. Imported products with N_2O emissions associated with their production (such as fertilizer, nylon, and polyurethane) would be subject to an import tariff based on the N_2O emissions intensity of the products.[155] The E.U. currently has a Carbon Border Adjustment Mechanism (CBAM) that covers, among other emissions, N_2O emissions for fertilizer—including emissions from upstream nitric acid production.[156] Expanding the E.U. CBAM to include all industrial N_2O emissions could send a market signal that increases demand for N_2O-abated industrial products. Developing CBAMs, especially in countries that are large importers of N_2O-embedded products, could further strengthen this market signal.

10. Conclusion

Industrial N_2O emissions must be reduced to lessen this important driver of climate change and stratospheric ozone depletion. Industrial N_2O abatement can be achieved today with proven, commercialized, and cost-effective technologies. Still, the additional expenses of installing and operating abatement equipment require incentives, such as regulations or financial mechanisms. Actions to accelerate achievable industrial N_2O abatement by governments and the private sector are therefore imperative.

Appendix: Calculation of adipic acid abatement cost

Below is an excerpt of a table showing costs of abatement for adipic acid projects under the CDM in 2010 USD in Flederbach and Winch (2019), adapted from Schneider, Lazarus, and Kollmuss (2010).

Technology	Unit	CDM	JI
Adipic acid production	kt/year	150	150
Baseline emission factor	kg N_2O/t adipic acid	270	30
Abatement costs			
Investment costs	\$M	11.12	18.07
Operational costs	\$M/year	1.39	2.1
Technical lifetime	Years	20	20
Abatement cost	\$/t CO_2e	0.18	2.44
Total abatement cost	\$/t CO_2e	2.61	

Abatement cost is calculated using the following formula:

$$\frac{(\text{investment cost}+\text{operational cost} * \text{technical lifetime})}{\text{technical lifetime}} \div \text{adipic acid production}$$
$$\div \text{ baseline emission factor} \div N_2O \text{ GWP}$$

The CDM projects' baseline emission factor is 270 kg N_2O/t adipic acid, which represents about 90 percent of the emissions from adipic acid production, i.e., a 90 percent reduction in emissions. The JI projects' baseline emission factor is 30 kg N_2O/t adipic acid, which represents the final 10 percent of emissions, as JI projects had already been abating to about a 90 percent level. Therefore, total abatement cost to fully abate a model 150 kt/year adipic acid plant is the sum of the CDM and JI abatement costs: \$0.18/t CO_2e + \$2.44/t CO_2e = \$2.62/t CO_2e.

Utilizing the Bureau of Labor Statistics Inflation Calculator, \$2.61 in October 2010 (when Schneider, Lazarus, and Kollmuss was published) corresponds to \$4.00 in buying power in June 2026 (the latest data available).

An important note is that CDM projects evaluated in Schneider, Lazarus, and Kollmuss (2010) actually achieved 99 percent abatement efficiency. Adjusting the baseline emission factor to 300 kg N_2O/t adipic acid * 0.99 = 297 kg N_2O/t adipic acid would yield an abatement cost of \$0.16/t CO_2e (\$0.24/t CO_2e in June 2026) to achieve 99 percent abatement.

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