Urgent abatement of industrial sources of nitrous oxide

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Industrial emissions of nitrous oxide, a potent greenhouse gas and stratospheric ozone-depleting substance, have increased since 2010 but offer excellent opportunity for abatement through existing, low-cost technologies.

Nitrous oxide (N_2O) is the third most important anthropogenic greenhouse gas, after carbon dioxide (CO_2) and methane (CH_4), contributing about 6% of total effective radiative forcing for the 1960-2019 period[1]. It is also currently the most abundantly emitted stratospheric ozone-depleting substance, equal to more than twice the ozone-depleting-potential-weighted emissions from all chlorofluorocarbons in 2020[2]. The rate of increase in atmospheric N_2O concentration has accelerated in recent decades, mostly from increased agricultural emissions, which contribute about two-thirds of the global anthropogenic N_2O emissions[3] (Table 1). Reducing emissions from the agricultural sector is particularly challenging. In contrast, the energy and industry sectors are responsible for only about 14% of global anthropogenic N_2O emissions but offer crucial opportunities for near-term, cost-effective abatement with existing technologies. However, these abatement opportunities are not being pursued as widely as needed.

Releases of N_2O are an unintended by-product from fossil fuel combustion, and industrial production of: adipic acid, used in nylon production and other synthetic fibers; and nitric acid, used mainly for the synthesis of N fertilizers, adipic acid, and explosives; while a small fraction of N_2O emissions is a result of caprolactam production, used mostly for nylon; glyoxal, used in polymer chemistry; and niacin, a dietary vitamin.

Current and projected emissions

Global demand for adipic acid is projected to grow 87% from 2015 to 2030[5], but N_2O emission trends will mostly depend on whether abatement technologies are implemented and used. Of the 21 adipic acid plants worldwide, 11 are in China, making it the largest emitter of N_2O (Table 1). The remaining 10 plants are distributed among 7 countries. Global emissions decreased from 1990 to 1995 due to the voluntary introduction of highly efficient abatement measures in most of the plants in operation at that time. Emissions remained nearly constant until 2010, and then increased sharply (Figure 1). Several plants constructed in China after 2010 are missing abatement equipment and some of the older ones that abated N_2O in the past are no longer doing so[5-11]. Of the two plants in the U.S., one abates over 95% of its emissions, and the other has had a variable history of abatement, with large increases in emissions since 2010[9,10,12].

Similarly to N_2O from adipic acid production, N_2O emissions from nitric acid production are projected to increase by 17% between 2015 and 2030 if no further abatement technology is employed[5], due to growing demand for synthetic N fertilizers and industrial explosives. Of the approximately 580 nitric acid production plants worldwide, about 100 abate N_2O emissions[14]. The nations with the largest emissions in 2020 were the United States, Russia, China, and Australia (Table 1).

Emissions of N_2O from fossil fuel combustion are larger than nitric and adipic acid emissions (Table 1), and future emissions will depend upon how quickly fossil fuel use is curtailed. Electricity production, manufacturing, transportation, and heating buildings contribute to 29%, 15%, 39%, and 17% of N_2O emissions from fossil fuel combustion, respectively, with China, United States, and India the largest emitters. Total fossil fuel emissions of N_2O increased modestly from the 1980s to the 2010s[3].

Abatement opportunities

The two main technologies for currently abating adipic and nitric acid emissions are thermal destruction and catalytic decomposition (Table 2). Both convert N_2O into dinitrogen (N_2) and oxygen (O_2), with efficiency as high as 99%, though 90-95% efficiency is more typical[5]. Estimates of marginal abatement costs for the industrial sector using these existing technologies indicate that abatement is economically feasible. The U.S. Environmental Protection Agency estimates that about 80% of the N_2O abatement potential in adipic acid and nitric acid production is achievable at break-even prices between $0 and $20 per ton of CO_2-equivalent[5]. Other estimates are at the lower end of that range[8,14,15]. Complete (100%) abatement of N_2O emissions from production of glyoxal was achieved by identifying an alternative production path that does not require nitrogen (Table 2). A similar opportunity is currently being pursued with research and development for nitrogen-free adipic acid production[16].

In contrast to voluntary cooperation among the relatively small number of adipic acid producers that opened the way to implement N_2O emission controls in adipic acid production in the 1990s[17], abatement of N_2O in the more numerous nitric acid plants globally is seldom deployed without regulations or incentives. In the United States, N_2O is abated as a side benefit of regulation of nitrogen oxide (NO_x) emissions, which is currently required only for those nitric acid plants located in regions that do not meet federal air quality standards for NO_x or tropospheric ozone. Hence, only about half of U.S. nitric acid plants are currently equipped with NO_x and N_2O abatement[13,14]. In contrast, the European Union's emissions trading program, established in 2007, has financed N_2O abatement for all adipic acid, nitric acid, and glyoxal plants[8]. However, minor emission sources from the production of caprolactam or niacin are still not covered, such as a single niacin plant in Switzerland that contributes 1% of Swiss GHG emissions[18].

Emissions of N_2O from fossil fuel combustion generally occur at temperatures below 1200K, which includes the majority of a large number of distributed sources, such as electricity generation, many manufacturing processes, the internal combustion engine for transportation, and boilers for heating buildings. The technological options for reducing N_2O emissions from fossil fuel combustion sources include several selective catalytic reduction techniques, which can remove up to 80% of emissions. Assuming 60% adoption of the most effective catalytic reduction technologies by 2050, N_2O emission factors from fossil fuel combustion could be cut by half[19]. Measures needed to mitigate fossil fuel CO_2 and CH_4 emissions, such as shifting fuel from coal and oil to natural gas or renewables, would also lower N_2O emissions. However, the co-benefit abatement of N_2O emissions that accompany fuel switching are modest and seldom included in calculations of payback for investments in renewable energy.

Policy options

Policy approaches include multilateral and bilateral intergovernmental agreements, national initiatives, and private sector and consumer-driven efforts. Because N_2O is not a toxin directly affecting human health, it has received less attention for regulation than have other forms of health-related nitrogen pollution, such as nitrate, NO_x, and particulate matter (PM2.5). In some countries, abatement of N_2O is incentivized to contribute to broad societal goals of mitigating climate change and stratospheric ozone depletion, but it is not obligatory. For example, a 3% global reduction in anthropogenic N_2O emissions, averaged over 2023–2070, would increase global stratospheric ozone by about 0.5 Dobson Units and decrease radiative forcing by about 0.40 W m^{-2} averaged over 2023–2100[2].

Three multilateral processes are relevant to N_2O abatement. First, signatories to the United National Framework Convention on Climate Change (UNFCCC) must report their N_2O emissions, and they may include N_2O abatement as part of their Nationally Determined Contributions to the Paris Climate Accord. However, few countries have chosen to do so, focusing instead primarily on CO_2 and CH_4 emissions. Second, because of its role in stratospheric ozone depletion, the Montreal Protocol (MP) of the Vienna Convention could also focus on reducing N_2O emissions[20]. While generally recognized as an environmental policy success story, the MP has targeted only man-made chemicals, whereas significant natural sources of N_2O also occur. With the exception of the fumigant methyl bromide, the MP has not targeted agricultural sector emissions. A focus on only industrial emissions of N_2O could be possible for the MP, but would still require amending the treaty or adopting and ratifying a new protocol, which takes several years to achieve. Third, the United Nations Environment Assembly Resolution (UNEA 5.2) on managing nitrogen wastes, enacted in February 2022, calls on countries to develop and share national action plans to reduce nitrogen wastes. These waste reduction strategies may include N_2O emissions from industrial and energy sectors. Multilateral financing and coordination to assist with developing and implementing national action plans could prioritize the cost-effective abatement of industrial N_2O, especially from nitric acid plants located in several developing countries.

In addition to multilateral initiatives, bilateral efforts can impact N_2O emissions from the industrial sectors of developing countries. The German government's Nitric Acid Climate Action Group (NACAG) provides assistance for lowering industrial N_2O emissions in developing countries, with statements of understanding with Tunisia, Zimbabwe, Georgia, Mexico, Uzbekistan, Thailand, Argentina, Peru, Jordan, and Colombia to help finance and install N_2O abatement technology in their nitric acid plants[14]. Another bilateral effort could follow from the pledges made by representatives of the United States and China at the UNFCCC Conference of the Parties in 2022 for bilateral cooperation on reducing greenhouse gas emissions. Given those two countries' high N_2O emissions from adipic and nitric acid production (Table 1), this could be a fruitful area of cooperation. As more countries take actions through multilateral or bilateral initiatives to reduce industrial and energy sector emissions of N_2O, they could add to the small but growing list of countries that include N_2O in their Nationally Determined Contributions to the Paris Climate Accord.

Consumer-driven preferences could also become an effective means of encouraging adoption of N_2O abatement technologies by the private sector. For example, 65% of the N_2O emissions embodied in nylon products globally are used in passenger cars and light vehicles[10]. Automobile manufacturers could require their supply chains to source nylon exclusively from plants that deploy efficient N_2O abatement technology. The average cost of replacing nylon with N_2O-abated nylon is estimated at only $0.40 per vehicle[10], thus providing a cost-effective means of appealing to growing consumer consciousness of purchasing climate-friendly automobiles. Rather than a consumer-driven, voluntary approach, imported nylon and other products with embedded industrial N_2O could also be regulated through import tariffs, such as those imposed by the European Union's Carbon Border Adjustment Mechanism.

Well-demonstrated and economically-viable technologies clearly already exist to abate N_2O emissions from the industrial sector, especially from adipic acid and nitric acid production plants. Progress was made in the 1990s, but N_2O emissions from adipic acid production are again on the rise, and emissions from nitric acid production remain substantial. Although a modest fraction of total anthropogenic N_2O emissions, abatement of industrial emissions could be achieved quickly and cost-effectively through a variety of policy options, including multilateral and bilateral intergovernmental processes, individual country-level initiatives, and private-sector sourcing of N_2O-abated nylon and other products. It is perplexing why these effective, low-cost options to abate industrial N_2O emissions are not already universal. We speculate that lack of awareness of the existing opportunities for near-term, cost-effective climate mitigation on the part of governments and consumers, as well as lack of incentives for the industry, are responsible for failures to eliminate these industrial sources of N_2O. Given the urgency of climate change mitigation, there is no longer an excuse for inaction.

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Author contributions

E.A.D. conceived of the manuscript, W.W. conducted the model analysis, both authors wrote and edited the manuscript.

Competing interests

The authors declare no competing interests.

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Table 1. Nitrous oxide emissions (kton N_2O/yr) in 2020 for the countries that include the top ten emitters in each sector, based on the Greenhouse Gas—Air Pollution Interactions and Synergies (GAINS) model[8].

Country	Adipic Acid	Nitric Acid	Fossil Fuels	Agriculture	Waste-water	Total
China	310.6	13.9	195	906	144	1598
India		1.2	72	750	141	972
Other Africa countries		0.2	51	740	94	903
USA	11.1	38.8	134	606	28	837
Brazil	1.3	1.7	28	482	22	540
Russia		16.7	21	232	13	285
Mid-East countries		5.7	35	156	35	240
Indonesia		<0.1	14	175	28	219
Pakistan			10	166	21	201
South Africa		6.3	14	114	23	161
Mexico		1.0	11	128	13	154
France	0.9	0.8	7	122	7	141
Canada		0.7	25	109	3	138
Northern Africa countries		1.5	10	99	21	136
Central Asian countries		8.8	5	111	7	134
Germany	1.1	0.9	17	97	8	129
Australia		10.6	8	96	2	119
Ukraine		8.2	3	76	4	92
Japan	1.7	0.4	22	39	4	68
Italy	0.2	0.1	6	36	6	51
Belarus		4.3	1	34	1	41
Republic of Korea	2.2	2.4	8	19	5	39
All others		12.3	125	1312	142	1638
World	329	136	824	6604	772	8837

Table 2: Abatement options for N_2O emissions from industry and fossil fuel combustion

Production product or process	Mechanism of production	Characteristics	N_2O abatement (end-of-the-pipe)	Process change	Policy options
Adipic acid, glyoxal, and niacin	Oxidation with nitric acid	Reaction products of nitric acid oxidation contain a large amount of N_2O which is released at very high concentrations	Catalytic destruction at very high efficiency (99%)	An alternative formation pathway has been identified for glyoxal, and is under investigation for adipic acid	When emission compensation was available (as CDM for developing countries), revenues were part of the business model. Few incentives exist to use different processes or to install existing abatement technologies, but such incentives could be introduced.
Nitric acid and caprolactam	Catalytic oxidation of ammonia	As an oxidation byproduct, high concentrations of N_2O are formed	Catalytic destruction at high efficiency (94%)	Products contains nitrogen; an alternative may not be easily identified	Efficient emission reductions for nitric acid plants (in the EU) once emission certificate allowances have been set to allow profitable abatement, without excessive profits. Bilateral assistance for developing countries to install abatement technologies
Power plants, manufacturing, heating, and internal combustion engines	Combustion of fossil fuels	Combustion at elevated temperatures (800 - 1200K) lead to N_2O formation, from N_2 and O_2, whereas at higher temperatures primarily NO is formed (depending on reaction conditions)	Flue gas concentrations are low; hence options are limited. Catalytic and non-catalytic reduction techniques are more efficient for NO_x and may even trigger some N_2O formation	Switching fuels from coal and oil to natural gas and to renewables would significantly reduce emissions from these sectors	N_2O normally not considered, as typical emissions of CO_2 are several orders of magnitude larger (in CO_2-equivalents), but co-benefit of N_2O abatement could be included in cost-benefit analyses

Figure 1. Progress on abating N_2O emissions from the industrial sector has been uneven. Global emissions of nitrous oxide from adipic acid production (squares with dotted line) declined substantially in the early 1990s due to adoption of abatement technologies, remained mostly flat until 2010, and then increased as several plants in China and one in the U.S. operated without full abatement. Global emissions from nitric acid production (circles with solid line) have declined gradually since 2005. Estimates are based on the Greenhouse Gas—Air Pollution Interactions and Synergies (GAINS) model[8].