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Assessing Nitrous Oxide Emissions from Product Use

A Study on N_2O Applications, Alternatives, and Policies

Berlin, March 2025

Authors

Emmanuella Asomani Asante
Hochschule Weihenstephan Triesdorf (HSWT)

With contributions by:
Wolfram Jörß
Öko-Institut e.V.

Contact
info@oeko.de
www.oeko.de

Head Office Freiburg
P. O. Box 17 71
79017 Freiburg

Street address
Merzhauser Straße 173
79100 Freiburg
Phone +49 761 45295-0

Office Berlin
Borkumstraße 2
13189 Berlin
Phone +49 30 405085-0

Office Darmstadt
Rheinstraße 95
64295 Darmstadt
Phone +49 6151 8191-0

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List of Abbreviations

ASS	Atomic Absorption Spectroscopy
AR4	Forth Assessment Report
AR5	Fifth Assessment Report
AR6	Sixth Assessment Report
AsiaIGA	Asia Industrial Gas Association
CDUs	Central Destruction Units
CFCs	Chlorofluorocarbons
CGA	Compressed Gas Association
CH_4	Methane
CLP	Classification, Labelling, and Packaging
CO_2	Carbon dioxide
CVD	Chemical vapor deposition
EIGA	European Industrial Gases Association
ECHA	European Chemicals Agency
EMCDDA	European Monitoring Centre for Drugs and Drug Addiction
EU	European Union
FDA	Food and Drugs Authority
GHG	Greenhouse Gas
GRAS	Generally Recognized as Safe
GWP	Global Warming Potential
HCFCs	Hydrochlorofluorocarbons
HFCs	Hydrofluorocarbons

IGV	Industriegaseverband (German industrial gases association)
IPCC	Intergovernmental Panel on Climate Change
JIMGA	Japan Industrial and Medical Gaes Association
LAN	Liquid Ammonium Nitrate
MDUs	Mobile Destruction Units
N_2O	Nitrous Oxide
NASCAR	National Association for stock Car Auto Racing
NO_x	Nitrogen oxides
NOS	Nitrous Oxide System
NIRs	National Inventory Report(s)
ODP	Ozone Depletion Potential
ODS	Ozone Depletion Substance
RAC	Risk Assessment Committee
SAN	Solid Ammonium Nitrate
SO_2	sulphur dioxide
OLED	Organic Light-Emitting Diode
UNFCCC	United Nations Framework Convention on Climate Change
UK	United Kingdom
USA	United States of America

Abstract

This report presents an analysis of nitrous oxide (N_2O) emissions from product use, particularly focusing on its applications in the medical and food industries, as well as other product uses. The study leverages data from National Inventory Reports (NIRs) submitted by Annex I parties under the United Nations Framework Convention on Climate Change (UNFCCC). It examines the deliberate use of N_2O due to its unique properties and the associated emissions, which have significant environmental consequences, including global warming and ozone depletion. Through data compilation, stakeholder interviews, the report identifies key sources of N_2O emissions by application, N_2O alternative uses under medical and food industry, classify and analyse N_2O emission statistics according to regional categorization from 1990-2021 of the UNFCCC Annex 1 parties and implemented and ongoing policies and regulation. The findings underscore the need for enhanced regulatory frameworks and improved data quality to inform future mitigation policies, particularly the European Union (EU) and other industrialized nations.

1 GENERAL INTRODUCTION

Nitrous oxide (N_2O) is a transparent, colourless, oxidizing liquid gas with a mild sweet odour, utilized in a wide variety of specialized product uses and applications (US EPA, OAR, Climate Change Division). (USA 2023). Next to carbon dioxide (CO_2) and methane (CH_4), it ranks as the third most prevalent well mixed greenhouse gas (GHG) in the earth's atmosphere. Although it constitutes to a smaller proportion of overall GHG emissions, having atmospheric retention of about 114 years renders it a key factor in long-term global warming (Shankman 2019). N_2O has a global warming potential (GWP) approximately 273 times higher than that of carbon dioxide (CO_2) over a century according to the Sixth Assessment Report of the IPCC(AR6) (GHG Protocol 2024).

Beyond its GWP, N_2O is also currently the most significant ozone-depleting substance being emitted and it is projected to remain so throughout the 21st century (UNEP/FAO-UN 2024b). Nitrous oxide (N_2O) is released at the Earth's surface and goes to the stratosphere, where it adds to the depletion of the ozone layer. Total N_2O emissions have the highest ozone-depleting potential with the weighted emissions surpassing the combined total of all ozone-depleting substances regulated under the Montreal Protocol (UNEP/FAO-UN 2024a).[1]

The bulk of N_2O emissions is generated as byproducts of agricultural, industrial or combustion processes. However, N_2O is also deliberately used in various applications due to its unique properties. These uses span several sectors, including the medical, food, automotive, recreation and chemical industries, where N_2O serves as an anaesthetic, propellant, and oxidizing agent. In the medical industry, N_2O is widely employed as an anaesthetic and analgesic, particularly in dental practices and surgeries, because of its rapid onset and safety profile (WHO 2023). The food industry utilizes N_2O as a propellant in aerosolized products like whipped cream, enhancing texture, preventing oxidation, and extending shelf life. Other industries, N_2O is used as an oxidizing agent in rocket propulsion, engine enhancement and semiconductor manufacturing, further indicating its versatility (Stockman 2017).

Despite its beneficial applications, the intentional use of N_2O in some of the sectors results in direct emissions into the atmosphere, making product use emissions an important category in national greenhouse gas inventories. The amount of N_2O that is emitted depends upon the specific product use or application. Nitrous oxide emissions from product use primarily come from its application in the medical and food industry. In the medical field, N_2O is widely used as an aesthetic and analgesic, contributing to emissions during and after its use. In the food industry, it's a common propellant in whipped cream dispensers and other aerosolized food products. These applications collectively contribute to N_2O emissions, making them an important area of focus for emission reduction strategies, especially since N_2O is a potent greenhouse gas with a global warming potential significantly higher than that of carbon dioxide (IPCC 2006). These emissions are also closely monitored and reported under the United Nations Framework Convention on Climate Change (UNFCCC) to ensure accurate reporting and to support global mitigation efforts.

This project report focuses on the analysis of N_2O emissions from product use, using data from the National Inventory Reports (NIRs) of Annex I countries. The study includes extensive data compilation, interviews with industry stakeholders, and data verification to provide a detailed overview of N_2O emissions from product use. The findings aim to enhance the accuracy of national inventories and inform strategies for reducing N_2O emissions, thereby contributing to both climate and ozone protection goals.

[1] See section 6.3; The Montreal Protocol on Substances that Deplete the Ozone Layer for more information.

1.1 Research Objectives

The following are the research objectives for this report.

- Identify key applications of N_2O product use.
- Review technical alternatives to N_2O for various applications.
- Exploring existing and planned mitigation policies
- Assess next steps required for effective regulations and reduction of N_2O emissions in Germany, the EU, and Industrialized countries globally.

1.2 Scope and Methodology

This report investigates nitrous oxide (N_2O) emissions from product use across various industrial sectors, with a focus on sustainable alternatives and policy strategies. The methodological approach is multifaceted, incorporating both qualitative and quantitative data sources to provide a comprehensive assessment of N_2O emissions and innovative alternatives reduction (or technologies). The report draws inferences, statistical data, and methodologies from the Intergovernmental Panel on Climate Change (IPCC) guidelines and Annex I countries' National Inventory Reports (NIRs) of the UNFCCC to quantify and analyse N_2O emissions. These reports offer baseline data and internationally recognized frameworks for calculating emissions, which will be fundamental in assessing historical and current emission levels from product use. While the report references IPCC guidelines and Annex I countries' data to build a global framework, the primary focus will be on markets where N_2O reduction alternatives (or technologies) are being piloted or adopted, specifically in the EU and North America.

This report thoroughly examines the two primary uses of N_2O: in the food industry, specifically in whipped cream dispensers, and in the medical sector for anaesthesia purposes. The report focuses on these sectors due to their substantial share in N_2O usage, emissions, and the availability of emerging alternatives that can potentially reduce emissions. Furthermore, the project also evaluates into detail, alternative technologies that can replace or reduce and destroy N_2O usage, particularly through close collaboration with some companies and planned policies regarding legitimate use of N_2O. The scope includes an assessment of these alternatives.

2 IDENTIFICATION OF N_2O APPLICATIONS

This chapter provides an in-depth examination of the various applications of nitrous oxide (N_2O) across different industries. Nitrous oxide is a versatile compound with significant industrial applications widely used across various sectors such as medical industry for its anaesthetic properties, in the food industry as a propellant, and in several other industrial processes (automotive and chemical industries) as outlined in this chapter. By identifying and analysing these key applications, this chapter aims to establish a comprehensive understanding of how N_2O is utilized. This understanding is crucial for assessing the sources of N_2O emissions and sets the stage for evaluating potential alternatives in the following chapter.

2.1 Medical Industry

History

In 1772, English chemist Joseph Priestley originally synthesized nitrous oxide by assembling the gas generated from sprinkling nitric acid over iron filings. The first significant use of nitrous oxide was facilitated by Thomas Beddoes and James Watt, who authored the book “Considerations on the Medical Use and on the Production of Factitious Airs (1794)”. Watt developed an innovative device for generating "factitious airs" (nitrous oxide) and a respiratory equipment for inhaling the gas. The book introduced innovative medical theories by Beddoes, which claims tuberculosis and other lung diseases might be addressed through the inhalation of "Factitious Airs". Humphry Davy, a young man, designated the name "laughing gas" for nitrous oxide after identifying its analgesic effect. However, it took 44 years before practitioners sought to employ nitrous oxide for anaesthesia. Nitrous oxide was originally used as an anaesthetic by dentist Horace Wells, who demonstrated its analgesic symptoms (“insensitivity to pain”) during a dental extraction in 1844. Gardner Quincy Colton, assisted by Colton and John Mankey Riggs, gave nitrous oxide to more than 25,000 patients. Currently, nitrous oxide is employed in dentistry as an anxiolytic and a supplementary agent to local anaesthetics. Nitrous oxide was determined to be insufficient as an aesthetic for major surgical procedures in hospital settings. In 1876, Joseph Thomas Clover devised the "gas-ether inhaler," which commenced anaesthesia with nitrous oxide and progressively intensified it with ether or chloroform. This practice persisted in numerous hospitals into the 1930s (Wikipedia 2024a).

Uses

In the healthcare sector, N_2O is used as an anaesthetic, analgesic, veterinary and as an anti-depression agent. In some research, nitrous oxide has been proven to be an effective and reliable medication for alcohol withdrawal (Wikipedia 2024b). However, this has been used mostly for anaesthesia and analgesia since 1844. In anaesthesia, it is used for surgical procedures. For analgesic, it is used to alleviate pain during dental procedures, childbirth, and when changing dressings for burn patients (IPCC 2006). It is conducted through a mask that covers the nose and mouth, and it produces a sense of relaxation and euphoria. Nitrous oxide is deemed safe when utilised correctly and is frequently administered alongside other anaesthetics to augment their effects. (NexAir, LLC 2024a). It is used as a supplementary gas for volatile fluorinated hydrocarbon anaesthetics such as isoflurane, sevoflurane and desflurane[2]. It is also mixed with pure oxygen, to produce an active gas mixture consisting of 70 % nitrous oxide and 30 % oxygen (Germany 2023). In instances of severe pain, this medication is frequently one of the initial treatments provided, usually in a 50% oxygen mixture

[2] For more information on these gases, see section 3.1.1.

(Polaris Market Research 2023).The anaesthetic effect of N_2O is additive to that of the fluorinated hydrocarbon agents (IPCC 2006). In addition to its anaesthetic properties, nitrous oxide is also used as a bronchodilator to treat respiratory conditions such as asthma and chronic obstructive pulmonary disease (COPD). It works by relaxing the smooth muscles in the airways, which allows for easier breathing (NexAir, LLC 2024b). The purity levels for Medical-grade N_2O necessitates a minimum purity threshold of 99.9%. Medical-grade N_2O adheres to more stringent purity standards because of its direct application in patient care (Redballoxygen 2024). The primary use of N_2O is for anaesthesia, where it is assumed that the gas is not metabolized by the body. This means that all the administered N_2O is released back into the atmosphere unchanged, justifying an emission factor of 1.0 (Canada 2023). However, some countries like Sweden, Netherlands, the UK have adopted N_2O destruction technologies to minimize and destruct N_2O emissions from the health sector. (Lundh 2024)

2.2 Food Industry

N_2O is also used as a propellant in aerosol products in food industry. The standard application involves the production of whipped cream, utilising cartridges filled with N_2O to aerate the cream into foam. (Greece 2023). It serves as a rapid propellant in whipped cream dispensers, facilitating the quick and efficient production of light and fluffy cream (Rotass 2024b; ; AIGA). N_2O gives these products a fluffy texture and delicate flavour. Using nitrous oxide to make whipped cream results in a volume four times greater than the original liquid, compared to just double the volume when using air. Nitrous oxide also prevents the butterfat from going rancid, unlike air. Carbon dioxide isn't suitable for whipped cream because its acidity in water would cause the cream to curdle and give it a fizzy texture (Wikipedia 2024a).

Nitrous oxide is also used for food packaging in a protective atmosphere, thereby extending shelf life and maintaining freshness. (Rotass 2024a). N_2O replaces oxygen in packaging, thereby preventing oxidation and spoilage, particularly in products such as meat and baked goods (AIGA).

For frozen food manufacturing, nitrous oxide flash freezing offers a rapid and efficient technique in order to preserve food quality, reducing damage to cell structures, and enhancing nutrient retention (Rotass 2024c). The rapid freezing properties of N_2O are applicable for the surface sterilisation of food products, especially meat, seafood, and baked goods (Rotass 2024c).

N_2O is employed in multiple fermentation and maturation processes. It establishes an inert atmosphere for dough, enhancing yeast activity and expediting dough rise. Nitrous oxide affects the formation of preferred flavour profiles in specific cheeses and wines (Rotass 2024c). Nitrous oxide is utilised to improve flavour and texture in a range of food products. Its use as an additive in carbonated beverages is gaining popularity (Rotass 2024b).

The use of N_2O in food applications necessitates high-purity, food-grade nitrous oxide to guarantee food safety and quality (Airproducts 2024). The purity levels for food-grade nitrous oxide (N_2O) must reach a minimum purity threshold of 99.5%. This generally varies from 99.5% to 99.999% (Rotass 2024c). The gas should be authorized by the Food and Drugs Authority (FDA) as Generally Recognized as Safe (GRAS) when used in accordance with good manufacturing practices (AIGA).

Table 1 Summary N_2O uses in the food industry

Uses	Details
Propellant in Aerosol Products	Used in whipped cream dispensers to aerate cream, producing a light and fluffy texture. Increases the volume of cream four times compared to air
Preservation in Food Packaging	Replaces oxygen in packaging to prevent oxidation and spoilage, extending shelf life, particularly for meat and baked goods
Surface Sterilization	Rapid freezing properties are used for surface sterilization of meat, seafood, and baked goods.
Fermentation and Maturation	Creates an inert atmosphere to enhance yeast activity in dough, aids in cheese and wine flavour profile development
Flash Freezing in Frozen Foods	Used for rapid freezing to preserve food quality, reduce cell structure damage, and retain nutrients
Carbonated Beverages Additive	Gaining popularity as an additive to improve flavour and texture in carbonated drinks

Source; (Rotass 2024a, 2024b, 2024c)

Nitrous oxide use as a propellant in food products is the second-largest category of end use, with only emissions coming from N_2O used in whipped cream being considered as significant. None of the N_2O is reacted during propellant processes hence all nitrous oxide used is emitted to the atmosphere (Canada 2023).

2.3 Chemical and Electronic Industry

Nitrous oxide has several significant applications in semiconductor manufacturing and others within the chemical industry. N_2O is used as a reagent or intermediate in various chemical processes. It also serves as a mild oxidizer in certain chemical reactions.

Semiconductor Manufacturing

N_2O serves as a crucial oxidizing agent in the semiconductor industry, particularly in chemical vapor deposition (CVD) processes. It is used as an oxygen source for depositing silicon oxy-nitride and silicon dioxide films. The gas is often used in conjunction with silane (SiH_4) to produce high-quality oxide films, which are essential electrical insulators in microelectronic transistors. Some of the key applications in semiconductor manufacturing include a. Controlling oxygen content in thin films, b. reducing side oxidation reactions, and c. selective etching of semiconductor thin films. The current electronics market for N_2O is approximately 10 000 metric tonnes per year and is increasing, driven by new high-definition display technologies like ultra-high definition and organic light-emitting diode (OLED)screens (Stockman 2017).

All N_2O used during semiconductor/liquid crystal manufacturing is assumed to be destroyed in the process and no N_2O is assumed to escape into the atmosphere, hence no emission factor has been set (Japan 2023a). This is also classified as destructive product use.

Emissions Control

In some industrial processes, N_2O is used in integrated systems to control nitrogen oxide (NO_x) emissions, such as in the semiconductor industry where it can be part of scrubber systems for emissions reduction (Stockman 2017).

Atomic Absorption Spectrometry

N_2O is commonly used with acetylene in atomic absorption spectrometry. In atomic absorption spectroscopy (AAS), N_2O is used as an oxidant alongside acetylene fuel. This combination is particularly effective when a high-temperature flame (up to 2600-2800°C) is used to atomize the sample. The use of N_2O in AAS allows for precise measurement of metallic element concentrations in various materials as aluminium, silicon, and titanium (CONCOA 2024).

Production of Sodium Azide

N_2O plays a crucial role in the continuous production of sodium azide, which is widely used to inflate automobile airbags. The process involves reacting sodium amide with nitrous oxide on a support material consisting of sodium azide and sodium hydroxide The reaction occurs at temperatures between 200°C and 270°C, resulting in higher space-time yields of sodium azide compared to conventional methods Sodium azide rapidly decomposes to produce nitrogen gas, which inflates the airbag in milliseconds during a collision hence no N_2O is emitted (Romania 2023) .

Jewellers' Blowtorches

N_2O serves as an oxidizing agent in blowtorches used by jewellers and other professionals. When combined with other gases like propane or hydrogen, N_2O produces a hot flame suitable for melting precious metals. The controllable nature of N_2O-based flames allows jewellers to perform delicate soldering and shaping operations (Wikipedia 2024a)

Refrigerant

Nitrous oxide has been used historically as a refrigerant in certain applications, especially before the widespread adoption of synthetic refrigerants like chlorofluorocarbons (CFCs), hydrofluorocarbons (HFCs) and hydrochlorofluorocarbons (HCFCs). While its use as a refrigerant is less common today, N_2O has some properties that made it suitable for its role. N_2O can be used as a refrigerant in specialized cooling systems due to its endothermic expansion properties (Wikipedia 2024a).

Leak testing agent

N_2O is sometimes used to detect leaks in pressurized systems due to its inert nature and ease of detection (Airgas 2016).

2.4 Automotive Industry

N_2O is commonly used to enhance engine power, particularly in racing and high-performance vehicles. This process enables engines to generate increased power by enhancing the air/fuel mixture that enters the engine, applicable to both rockets and race cars (Stockman 2017). N_2O has the potential to enhance engine power from 1 hp to several hundred, contingent upon vehicle performance and modifications (Indy Auto Man 2022). The utilisation of N_2O in engines entails the storage of liquid N_2O in a tank and its subsequent injection into the engine's intake manifold upon activation (NexAir, LLC 2024c). N_2O decomposes at elevated temperatures, approximately 300°C, releasing oxygen upon entering the engine (Hasbollah 2022). The additional oxygen facilitates increased fuel combustion, resulting in a larger combustion event and enhanced power output (NexAir, LLC 2024c).

While N_2O offers significant performance benefits, it requires careful management and is often reserved for racing or controlled performance applications rather than everyday driving. Unfortunately, only a few motorsports sanctioning bodies worldwide allow their racers to use nitrous systems in their vehicles. For instance, Formula Drift and some drag racing events allow for the use of nitrous oxide systems in its cars. However, other mainstream motorsports like Formula 1 and NASCAR do not allow race teams to modify their vehicles with NOS (Nitrous Oxide System) systems. A few reasons why nitrous oxide application have some setbacks in everyday driving use are; It is very expensive which requires a lot of investment, and in some car manufacturing countries, nitrous oxide is either illegal, banned or there are a lot of legal restrictions with its uses (Hasbollah 2022). Another major issue with using nitrous oxide in a reciprocating engine is the risk of excessive power, which can damage or destroy the engine if it is not properly reinforced. When enhancing petrol engines with nitrous oxide, it is crucial to maintain even operating temperatures and fuel levels to avoid pre-ignition, also known as detonation or spark knock. However, the main problem with nitrous oxide isn't the power itself but the excessive pressure it creates, leading to a denser charge in the cylinder. This increased pressure and temperature can cause the piston, valve, and cylinder head to melt, crack, or warp.

Additionally, this process is destructive because the N_2O used is not released into the atmosphere, creating a cycle of continuous use and destruction. Automotive-grade liquid nitrous oxide is slightly different from medical-grade, as it contains a small amount of sulphur dioxide (SO_2) to prevent substance abuse (Wikipedia 2024a).

2.5 Recreational use of Nitrous Oxide

The recreational use of nitrous oxide, commonly known as "laughing gas," has emerged as a significant public health concern in Europe over the past decade. Initially utilized in medical and culinary applications, its misuse for recreational purposes has escalated, particularly among young people and adolescents. Since around 2010, there has been a marked increase in the recreational use of nitrous oxide across various European countries. A survey conducted by the European Monitoring Centre for drugs and drug addiction (EMCDDA) revealed that recreational use of N_2O is very popular among teenagers and young adult with its use reported at festivals, music events and private parties. The reports indicate that this trend has intensified since 2017, coinciding with the introduction of larger gas cylinders specifically marketed online and social media for recreational use. These larger cylinders have made nitrous oxide more affordable and accessible, contributing to a rise in both the frequency and volume of use among individuals. The growing prevalence of nitrous oxide use has been accompanied by an increase in health-related incidents. The report identifies both acute and chronic health risks from nitrous oxide use. While the overall number of poisonings remains relatively low, cases of neurotoxicity have been reported, often linked to more frequent or heavy use. Additionally, the use of larger cylinders poses risks of severe burns and lung injuries. There have also been reports of increased car accidents especially in the Netherlands about 80% increase associated with nitrous oxide consumption, highlighting the broader implications for public safety The social consequence of nitrous oxide use includes public nuisance from noise and litter from discarded cartridges and balloons in public places. The environmental impact includes increased waste from discarded steel canisters and rubber balloons which can harm wildlife (EMCDDA 2022).

Recently, there has been some policy discussion surrounding the use and regulation of nitrous oxide products, focusing on balancing legitimate uses with preventing misuse. See **chapter 6.1** for further information.

Figure 2-1 Laughing gas capsules dumped by the side of a road in Amsterdam

Source: Dutch News n.d.

Figure 2-2 Street sign indicating ban of nitrous oxide use in Groningen

Source: Wikipedia n.d.

3 REVIEW OF TECHNICAL ALTERNATIVES FOR N_2O IN THE MEDICAL AND FOOD INDUSTRY

Following the identification of N_2O's major applications, this chapter focuses on reviewing the technical alternatives to N_2O specifically within the medical and food industries. Given the environmental challenges posed by N_2O emissions, exploring viable substitutes is essential. This chapter evaluates various alternatives to N_2O used in anaesthesia and food packaging, assessing their effectiveness, feasibility, and environmental impact. The aim is to provide a thorough review of these alternatives to support the transition toward more sustainable practices in these sectors.

3.1 Alternative substances and technology use

3.1.1 Medical alternatives

Since 1990, the use of nitrous oxide emissions for anaesthesia has been a prevalent source of emissions. Over the years, various effective alternatives to nitrous oxide for anaesthesia have been employed. This have offered several benefits in terms of safety, efficacy, and environmental impact. This trend is expected to continue. Although nitrous oxide remains widely used, these alternatives offer effective options for anaesthesia in some medical situations, enabling healthcare providers to tailor their approach based on patient needs, procedure requirements, and environmental considerations. Examples of some alternatives are intravenous anaesthetics, inhalation anaesthetics, local anaesthesia etc.

Intravenous alternatives

Total Intravenous Anaesthesia is the method where aesthetic drug is continuously infused into a vein during the entire surgical procedure. With this alternative, neither N_2O nor the fluorinated hydrocarbon agents are used (IPCC 2006). Examples of some intravenous alternative anaesthetics are Propofol, Fospropofol, Barbiturates, Benzodiazepines, Ketamine, Etomidate, Dexmedetomidine etc. with Propofol as the most administered anaesthetic drug for induction of anaesthesia.

Propofol: Propofol is a popular and widely used intravenous anaesthetic. It is used for both induction and maintenance of anaesthesia. Propofol has been shown to be safe and effective, with no significant differences in safety and efficacy compared to thiopental in stable patients (eEML 2024). Propofol ($C_{12}H_{18}O$) has an overall very low impact on greenhouse gas emissions (Issuu 2024).

Ketamine: Ketamine is particularly useful in certain settings. It is widely used in developing countries due to its minimal effects on the cardiovascular system. Ketamine preserves airway reflexes and does not cause respiratory depression, making it a valuable option in some cases (eEML 2024).

Inhalation alternatives

Inhaled aesthetic agents are now often delivered through breathing systems that recycle the patient's exhaled breath. This breath passes through a canister containing a carbon dioxide absorbent before being redirected back to the patient. By using this method, the flow of carrier gas can be significantly reduced after the initial few minutes of anaesthesia, when the patient's uptake is highest. This approach, known as Low Flow Anaesthesia, offers the benefits of lowering emissions and reducing costs (IPCC 2006). Examples of inhalation alternative anaesthetics are sevoflurane, desflurane, isoflurane, and sevoflurane with sevoflurane as the most suitable alternative for anaesthesia.

Sevoflurane: It has been found to be as effective as nitrous oxide for inhalation sedation in adult anxious dental patients (Allen and Thompson 2014). Sevoflurane offers rapid onset and offset of action with few adverse effects. It may be particularly useful for paediatric patients, though it can cause agitation during recovery in some children. Sevoflurane has shown promise as an effective alternative to not only N_2O but also Desflurane due to its low GWP. (eEML 2024).

In the context of global warming potential (GWP), The IPCC's Fourth Assessment Report (AR4) assigned N_2O a GWP of 298 over a 100-year period, highlighting its significant long-term impact, while also recognizing the high GWPs of fluorinated gases, although with less focus on their medical use. The IPCC's Fifth Assessment Report (AR5) updated the GWP for N_2O to 265 and gave more attention to fluorinated anaesthetics like sevoflurane, desflurane, and isoflurane, emphasizing their high climate impact, especially desflurane. The recent Sixth Assessment Report (AR6) updated these values and underscored the healthcare sector's role in emissions from these gases, advocating for the adoption of low-flow anaesthesia and alternatives to high-GWP substances (GHG Protocol 2024).

Table 2 GWP_{100} of Fluorinated substances used as inhalation anaesthetics

Fluorinated substances used as inhalation anaesthetics	Chemical formular	AR4 (GWP100)	AR5 (GWP100)	AR6 (GWP100)
HFE-347mmz1 (sevoflurane)	$(CF_3)_2CHOCH_2F$	-	216	195
HCFE-235ca2 (enflurane)	CHF_2OCF_2CHFCl	-	583	654
HCFE-235da2 (isoflurane)	$CHF_2OCHClCF_3$	350	491	539
HFE-236ea2 (desflurane)	$CHF_2OCHFCF_3$	989	1,790	2,590
For comparison:				
Nitrous oxide	N_2O	298	265	273

Source: (GHG Protocol 2024)

In Germany, the phase-out of N_2O in the medical industry began at a gradual pace. According to a response from Helios clinics the decision to completely abolish N_2O in anaesthesia was made in March 2022 by their specialist group. This move was facilitated by the recognition that N_2O is medically dispensable and has a particularly detrimental and lasting effect on the atmosphere. Helios noted that many clinics had already ceased using N_2O years prior due to its environmental impact. The position paper by the German Society of Anaesthesiology and Intensive Care Medicine (DGAI) and the Professional Association of German Anaesthetists (BDA)[3] highlighted the ecological burden of anaesthesia, leading to recommendations for action, such as the adoption of low-flow anaesthesia.

[3] Position paper Schuster et al. 2020; https://www.ai-online.info/archiv/2020/0708-2020/positionspapier-mit-konkreten-handlungsempfehlungen-der-dgai-und-des-bda-oekologische-nachhaltigkeit-in-der-anaesthesiologie-und-intensivmedizin.html

The clinics are transitioning away from gases like desflurane, known for its negative ecological balance and high GWP, and are adopting alternatives like sevoflurane and intravenous anaesthesia with propofol**,** alongside other medications such as opiates and relaxants. (Stefan Wirtz 2024).

Local anaesthesia

For minor surgical or dental procedures, local anaesthesia remains an effective alternative to general anaesthesia, providing pain relief without affecting the entire body (Roots Dental 2024).

3.1.2 Food industry alternatives

The food industry has been exploring alternatives to nitrous oxide due to environmental concerns and regulatory changes, particularly its contribution to greenhouse gas emissions. This also received a lot of attention when N_2O emissions accounted for about half of Starbucks' global Scope 1 emissions in 2018 (Starbucks 2018). In response, innovative alternatives utilizing compressed air or nitrogen (N_2) have been developed, aiming to provide a greener and potentially more cost-effective solution. The TLT-Foamer technology, developed by the Cambridge-based tech start-up Triple Line Technology, uses compressed air or nitrogen instead of N_2O to create foams and aerated products. The new system uses curved channels to create very small bubbles (5-40 microns) without relying on high-pressure liquefied gases like N_2O.

Figure 3-1TLT Compressed Gas Siphon

Source: (Triple Line Tech 2024)

TLT Technology has developed a new foaming system designed to replace traditional nitrous oxide (N_2O)-based systems (Triple Line Tech 2024): Currently at a prototype stage (Technology Readiness Level 6-7), the technology has been tested in controlled environments but has not yet been commercialized. It primarily uses gases such as air or nitrogen, which are safer, cheaper, and more environmentally friendly compared to N_2O. Nitrogen is highlighted as the most suitable for commercial operations due to its inert nature (Nicmanis 2024).

According to the manufacturer (Nicmanis 2024), the system has several advantages:

- It eliminates the greenhouse gas impact of N_2O.

- It is cost-effective, using easily available compressed gases.
- It is robust and suitable for high-use environments like coffee shops and fast-food outlets.

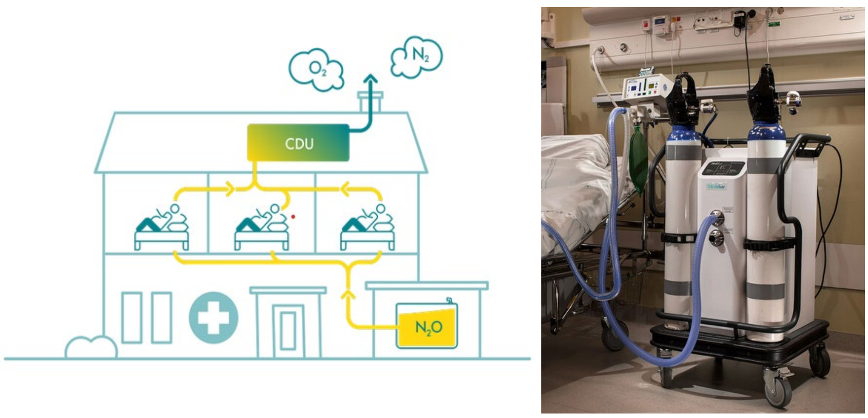
However, there are challenges. Customers are hesitant to commit until the product is fully market-ready, and funding remains an issue. Technical refinements are also needed to ensure long-term durability and compatibility with different liquid types (e.g., cream vs. milk). Despite the challenges, the technology holds significant potential to reduce N_2O emissions, particularly in the food and beverage industry.

3.2 N_2O emission abatement technology

Medical industry abatement technology

The abatement of nitrous oxide emissions is gaining increased attention due to the compound's significant contribution to global warming and ozone depletion. Since 2006, some hospitals have installed N_2O destruction units, and the reductions achieved are reflected in the total emissions (Japan 2023b). An example of such technology is one developed by Medclair. Medclair is a Swedish research and development company founded in 2013, specializing in sustainable solutions for nitrous oxide (N_2O) management in the healthcare industry. Their patented technology addresses the entire lifecycle of N_2O, from distribution to collection and destruction, significantly reducing its environmental impact. Medclair offers both Central Destruction Units (CDUs) and Mobile Destruction Units (MDUs) that can decompose up to 99% of the nitrous oxide, converting it into nitrogen (N_2) and oxygen (O_2). The company's systems can either connect to an Anaesthetic Gas Scavenging System (AGSS) for multiple treatment rooms or work as standalone units, capturing over 99.6% of N_2O emissions. These technologies have been operational for over a decade, with supply and installations in approximately 150 hospitals across 20 countries, predominantly in Sweden, the Netherlands, and the UK[4]. The power consumption of the devices ranges from 44 to 260 Watts, with energy efficiency improving as the N_2O content increases during usage. The adoption abatement technology in hospitals helps meet current work safety regulations and also prepares facilities for future CO_2e requirements.(Medclair 2024).

Figure 3-2 Structure of Medclair's CDU and MDU abatement technology



Source: (Medclair 2025)

[4] Lundh 2024 Personal Communications.

N_2O emission mitigation by collecting & safely disposing of used N_2O canisters.

Veolia has launched the UK's first process lines for the safe treatment of nitrous oxide canisters at their Empire facility in Birmingham. This initiative addresses a growing concern about the environmental impact of discarded N_2O canisters, which are commonly used in medical, food, and recreational applications. The company's approach aims to reduce the greenhouse gas emissions associated with N_2O while ensuring the responsible recycling of canister materials. The new process captures the gas from N_2O canisters and separates it into nitrogen and oxygen components, allowing for safe venting in proportion to atmospheric volumes. The empty canisters are then recycled, addressing both environmental and safety concerns. Some of the key features of the treatment process are to prevent the release of nitrous oxide, to reduce the risk of explosion during waste processing, and to enable the recycling of steel canisters (Veolia UK 2024).

4 N_2O PRODUCTION AND SUPPLY STRUCTURE

4.1 Overview of global production

In 2023, the global nitrous oxide market was valued at USD 1.47 billion and is projected to reach USD 3.19 billion by 2033, reflecting a compound annual growth rate (CAGR) of 8.05% from 2024 to 2033 (Precedence Research 2024). In 2022, the medical segment represented the largest market share, being widely utilised as an anaesthetic agent for various therapeutic indications. About 80-85% of produced N_2O is utilised in hospitals for general anaesthesia. Up to 10% is utilised in dentistry for outpatient clinics. Countries with advanced healthcare systems are the primary consumers (Polaris Market Research 2023). The electronics industry represents a significant sector demonstrating an increasing demand for nitrous oxide. Nitrous oxide is favoured over oxygen because of its reduced reactivity. The electronics sector demands approximately 10 000 metric tonnes of nitrous oxide annually, with expectations for increased demand (Stockman 2017).

Due to sensitivity and confidential concerns, data on the production, supply, and consumption of nitrous oxide (N_2O) are not publicly available in many cases. This limitation significantly impacts the ability to estimate accurate emissions from product use, as much of the information comes from indirect sources or estimates.

4.1.1 N_2O production methods: Thermal Decomposition of Ammonium

Nitrous oxide (N_2O) is predominantly produced through the thermal decomposition of ammonium nitrate, a process widely used for large-scale production in the medical and food industries. This method, initially discovered by Humphry Davy, involves heating ammonium nitrate to a temperature range of approximately 170–240°C, causing it to break down into nitrous oxide and water vapor (Helmenstine 2019). The chemical reaction is as follows:

$$NH_4NO_3 \rightarrow 2H_2O + N_2O$$

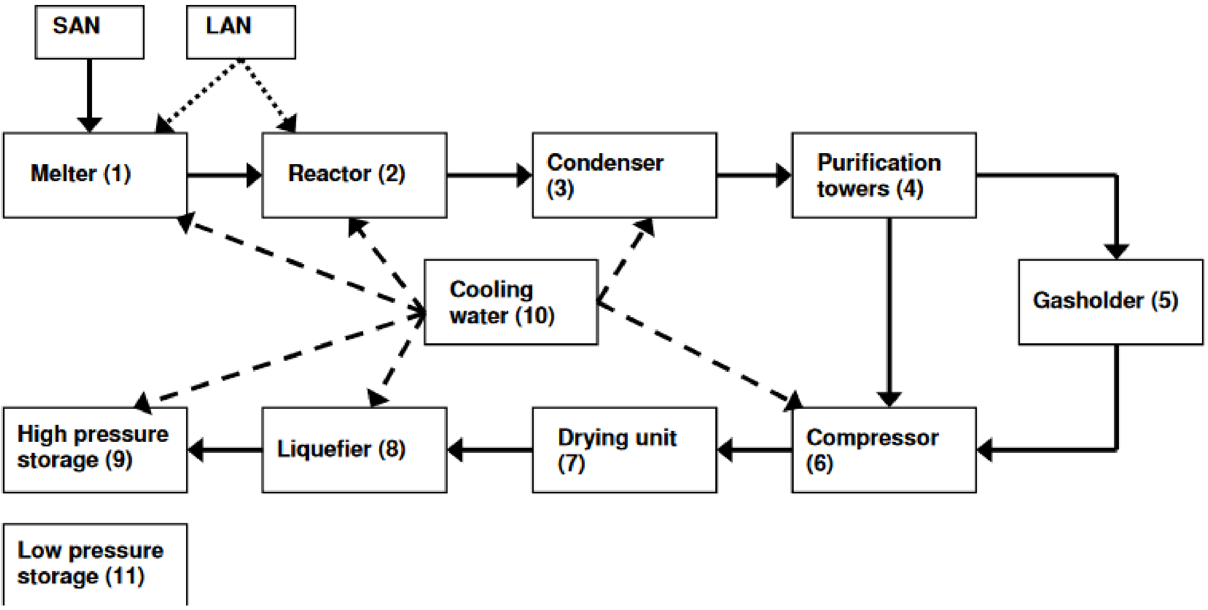
To minimize the risk of explosion during transportation, ammonium nitrate is typically supplied at reduced concentrations, such as a maximum of 93% purity. For industrial use, ammonium nitrate is often provided in liquid form (Liquid Ammonium Nitrate, LAN), which requires specific handling and storage conditions (EIGA 2020).

Production process

1. Storage and Preparation: Liquid Ammonium Nitrate (LAN) is stored in tanks with insulation to prevent cooling and crystallization. If Solid Ammonium Nitrate (SAN) is used instead, it is melted by adding water to create a liquid solution suitable for processing.
2. Thermal Decomposition: The liquid ammonium nitrate is fed into a reactor where it is heated to temperatures between 170°C and 240°C. This heat causes the compound to decompose into nitrous oxide gas and water vapor.
3. Cooling and Water Removal: After decomposition, the gas mixture is cooled in a water-cooled condenser. This step condenses the water vapor, leaving behind a stream of nitrous oxide gas.
4. Purification: The gas is then passed through purification towers to remove any impurities such as nitric acid, ammonia, or nitrogen oxides. This ensures that the nitrous oxide meets the purity standards required for medical and food-grade use.

5. Gas Storage: The purified nitrous oxide is stored in a gas holder, which may either be a water-sealed gasometer or a flexible gas bag. This storage system helps balance production and consumption rates, ensuring a steady supply for further processing.
6. Liquefaction and Final Processing: The gas is compressed to high pressure, dried to remove residual moisture, and then cooled to liquefy it. The liquefied nitrous oxide is stored in specialized tanks and prepared for cylinder filling or bulk transportation (Hi-Tech 2024)

Figure 4-1 Nitrous oxide production mechanism



Source: (AIGA) and (EIGA 2020)

4.2 Geographic distribution

The global nitrous oxide market is dominated by several key players, each contributing to the industry's growth and development. These companies operate in various regions globally, including North America, Europe, Asia Pacific, and other parts of the world. The market is highly competitive and fragmented, with these players contributing to the industry's growth through innovation, strategic partnerships, and expansion of their product range. (Table 3, Table 4)

Table 3 N_2O production and distribution companies

Production Companies	Distribution Companies	Both Production and Distribution	Specialized Equipment/Technology companies
Air Products	SS Gas Lab Asia	Merck KGaA	Promas Engineers Pvt. Ltd.
Air Liquide S.A.	Ellenbarrie Industrial Gases Ltd.	Carbide and Chemicals	Earlbeck Gases & Technologies
Praxair, Inc.	Oxygen and Argon Works Ltd.	Chengdu Taiyu Industrial Gases Co., Ltd	ICO2N GmbH
Linde Group	SOL S.p.A.	Jiangsu Huazhong Gas Co., Ltd	NexAir
Matheson Tri-Gas Inc.	Airgas, Inc.		
Taiyo Nippon Sanso Corporation	American Welding & Gas		
Kanto Denka Kogyo Co., Ltd	Calox		
Showa Denko K.K.	Gulf Cryo		
CryoCarb	Messer Se & Co. Kgaa		
	Nexair		
	Norco Inc		
	Southern Gas Limited		
	Steelman Gases Pvt. Ltd		
	Holston Gases		
	Middlesex Gases & Technologies, Inc.		
	SOS Gases, Inc.		
	Compressed Gas Solutions, Inc.		
	Walsh Gases		

Source: (Insight Ace Analytic 2024)

Table 4 Regional mapping of N_2O product use production hubs

Product use Application	Region
Medical	North America (U.S., Canada)
Electronics	Europe (France, Germany, UK, Italy, Netherlands, Spain, Russia)
Automotive	Asia Pacific (Japan, China, India, Malaysia, Indonesia. South Korea), EU, US
Food & Beverage	Latin America (Brazil, Mexico, Argentina)
	Middle East & Africa (Saudi Arabia, UAE, Israel, South Africa)

Source: (Polaris Market Research 2023)

In summary, in North America, N_2O is widely used in automotive, medical, and food and beverage sectors. In Europe, growth is significant, especially within food and beverage applications. In the Asia Pacific region, demand is significantly influenced by the medical industry and electronics manufacturing, especially in China, Japan, South Korea, and India. N_2O is utilised to produce airbag inflators[5] within the automotive industry, specifically in the EU, U.S., and Japan. The electronics sector in nations such as South Korea, Japan, and the United States employs N_2O in the production of semiconductors. The Food and Beverage Industry exhibits extensive utilisation in food processing and packaging within industrialised nations. Whipped cream propellants are especially prevalent in Western European nations and the United States (Polaris Market Research 2023).

Key Industrial Gas Association.

To ensure safe production, handling, and usage of N_2O, various associations and organizations play a critical role in establishing industry standards and guidelines. These associations establish safety standards, promote best practices, and advocate for regulations related to the production and use of nitrous oxide across different industries globally. (Table 5)

[5] N_2O is used to produce sodium azide, which is used in airbags (see section 2.3).

Table 5 N_2O Gas Associations

Gas Association	Country	Role
European Industrial Gases Association (EIGA)	European and non-European countries	A safety and technically oriented organization producing and distributing industrial, medical, and food gases[6]
Japan Industrial and Medical Gaes Association (JIMGA)	Japan	Merged in 2007 by joining the Japanese Medical Gases Association and Japan Industrial Gases Association. It focuses on improving production, distribution, and use of medical and industrial and gases in Japan[7]
Asia Industrial Gas Association	Asian countries	Established in 2002, AIGA brings together national industrial gases associations in Asia to raise safety and environmental standards in the use and handling of industrial gases[8]
Compressed Gas Association	US and Canada	Dedicated to developing and promoting safety standards in the industrial, medical, and food gases industry in the U.S. and Canada.[9]
IndustrieGaseVerband	Germany	Founded in 1990, the IGV is dedicated to emphasizing the use, application, and significance of gases for individuals, industry, and the environment. IGV functions as networkers and advisors, advocating for the interests of the association's members who produce, fill, and distribute technical and medical gases.[10]

[6] EIGA; https://www.eiga.eu/
[7] JIMGA; https://www.jimga.or.jp/
[8] AsiaIGA; https://www.asiaiga.org/
[9] CGA; https://www.cganet.com/
[10] IGV; https://www.industriegaseverband.de/uber-uns

5 NITROUS OXIDE EMISSION TRENDS

In this chapter, nitrous oxide emissions data for product use of the Annex I parties reported in the national inventory report is analysed. There are 43 Parties to the UNFCCC listed in Annex I of the convention, including the European Union. There are several nitrous oxide emissions data in the national inventory report, but nitrous oxide product use is the subject of interest for this report. N_2O product use is classified under the category 2G3 in the national inventory reporting framework. Under the 2G3 category, there are subcategories, category 2G3a the medical use, and 2G3b other use (2G3b(i)propellant aerosols product use and 2G3b(ii)others). Some Annex 1 parties also reported both subcategories (i.e., the medical and other product use) under one category, with no differentiation. Only Japan reported 2G3b as semi-conductor manufacturing use.

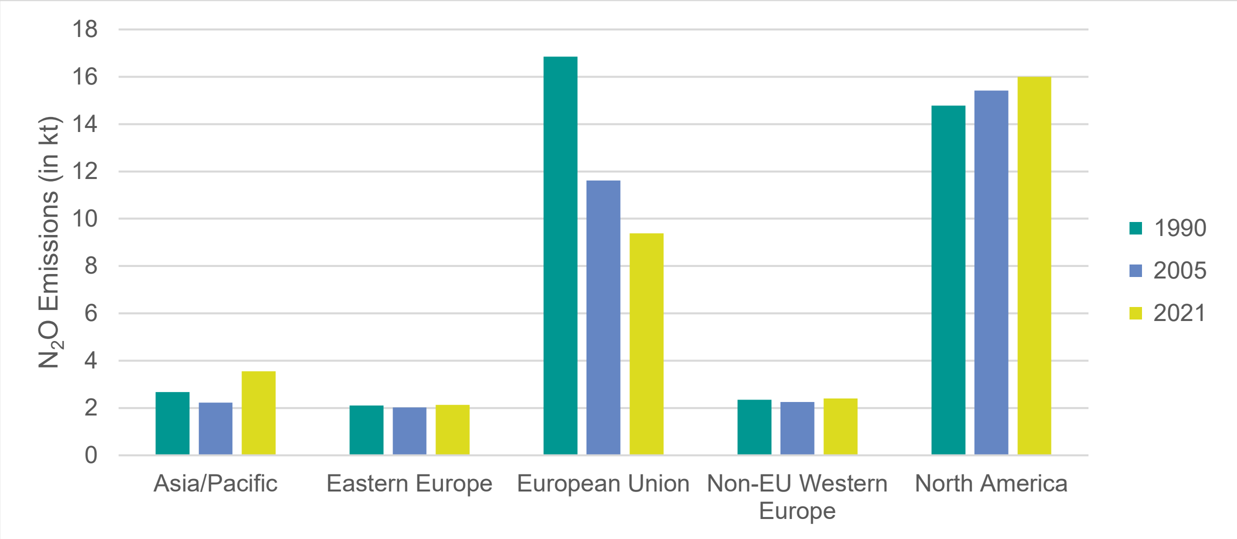
For Non-Annex 1 parties to the UNFCCC, there are approximately 150 non-Annex I parties with 53 parties reporting on GHG emissions in category 2G (other industrial processes and product use) (UNFCCC 2024a). Egypt and Indonesia were the only countries to report on N_2O in category 2G, both for the early 1990s, only. However, an explicit association of those reported emissions to the N_2O product use emissions subject to the present study is not available. The other 51 countries reported on other greenhouse gases from that category.

5.1 N_2O product use emissions trends analysis.

Nitrous oxide product use emissions from the Annex 1 parties were categorize into five regions, namely European Union, Eastern Europe, Non-EU Western Europe, North America, and Asia/Pacific[11]. Among those, the European Union recorded the largest figures in N_2O emissions. No nitrous oxide product use emissions data was reported for Turkey. For Australia, emissions of N_2O from medical use and propellant and aerosol products (classified under 2.G.3) are estimated but remain confidential. These emissions are reported under the Nitric acid production category. (Australia 2023). For this report, estimates were calculated using a methodology developed from a paper by (Jörß et al. 2023)[12]: The average of per capita emissions in the USA and New Zealand multiplied by Australia's population was used to approximate Australia's total N_2O product use emissions.

[11] UNFCC Annex 1 parties according to above chart categories are.
European Union: Bulgaria, Croatia, Hungary, Poland, Romania, Slovakia, Czech Republic, Germany, Belgium, Netherlands, Austria, France, Luxembourg, Ireland, Denmark, Estonia, Latvia, Lithuania, Sweden, Finland, Greece, Italy, Portugal, Spain, Malta, Slovenia.
Eastern Europe: Belarus, Ukraine, Russia.
Non-EU Western Europe: Monaco, UK, Liechtenstein, Switzerland, Norway, Iceland
North America: United States, Canada
Asia/Pacific: Australia, Japan, New Zealand.
[12] Jörß et al. 2023 Mitigation potentials for emissions of nitrous oxide from chemical industry in industrialised countries world-wide.

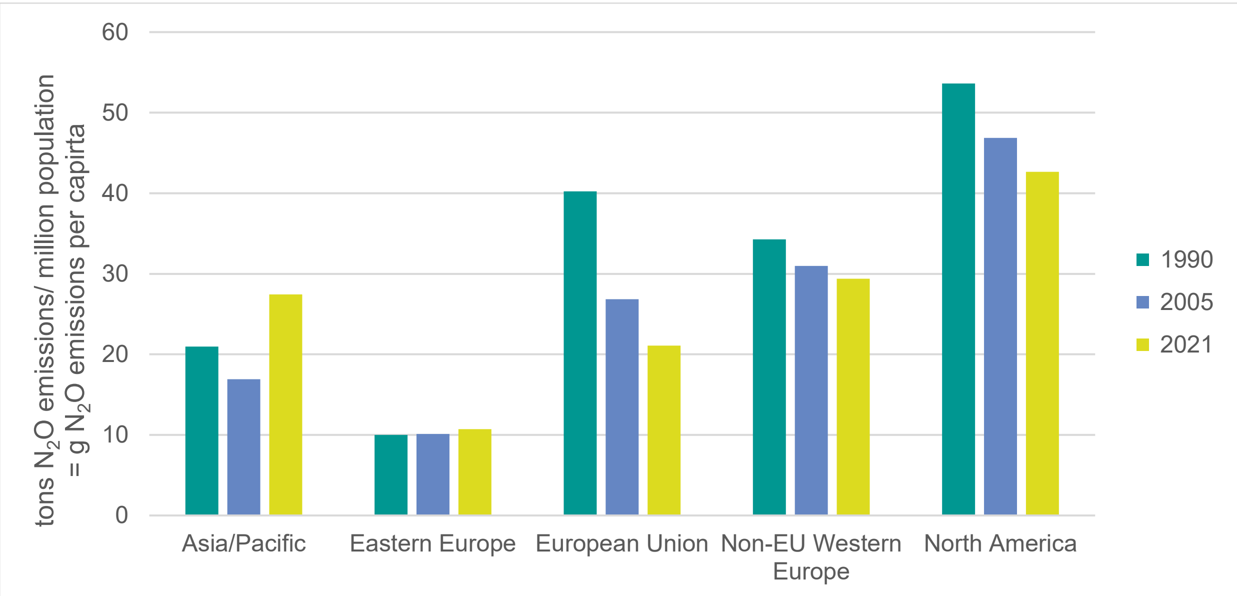
Figure 5-1 N_2O product use emission by UNFCCC Annex I parties.



Source: (UNFCCC 2024b; Macrotrends 2025), own calculations

Based on the data given, several patterns emerge in the evolution of N_2O product use emissions from medical and other (propellant and aerosols use and others) applications over time. Most European Union countries show a massive decrease in N2O product use emissions over the years. A significant drop happened over two decades, between the year 1990 to 2010. Eastern European countries show stable and slightly increasing and decreasing emissions over time. Asia and Pacific display a mixed trend, with some decreases in emissions. North America shows a gradual increase in N_2O emissions over the years as countries in the Non-EU Western Europe shows a stable and slightly increasing trend.

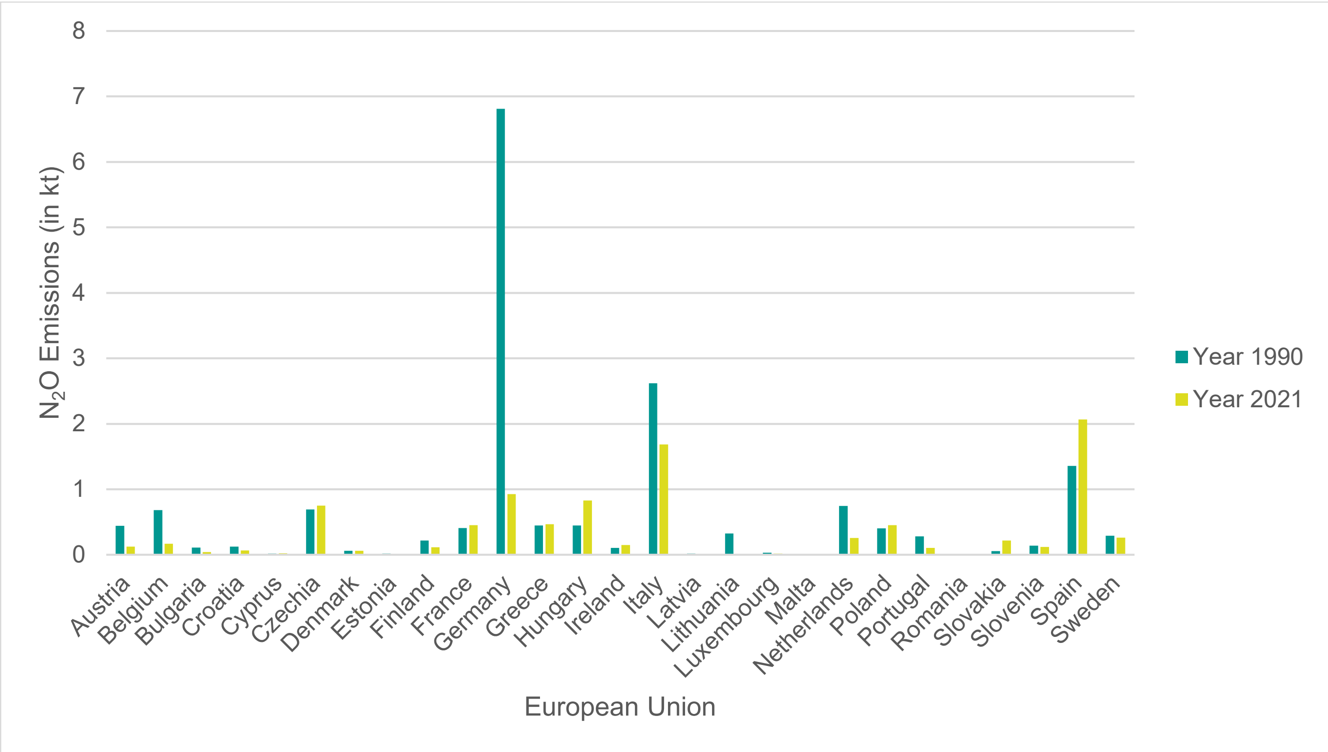
Figure 5-2 N_2O product use emission per capita by UNFCCC Annex



Source: (UNFCCC 2024b; Macrotrends 2025), own calculations

Nitrous oxide emissions per capita measure the average emissions produced by each person in a given population. From the above graph, North America reported high emissions per capita as compared to the other regions. The reason is that North America reports high total emissions and population.

Figure 5-3 Detailed analysis of N_2O product use emission from the European Union



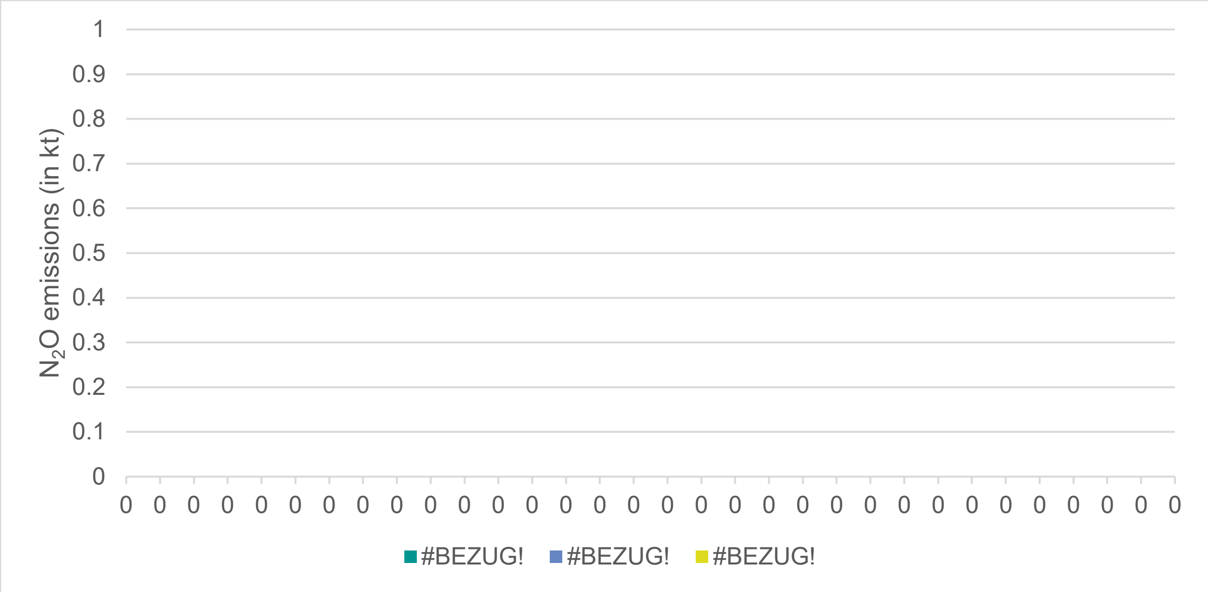
Source: (UNFCCC 2024b)

Many EU countries have seen a decrease in N_2O emissions over the years, especially in like Germany, Italy, Belgium, Austria, and the Netherlands. A detailed analysis showed that Germany's emission declined significantly. Germany, Belgium, and Austria have reported significant reductions in medical N_2O emissions due to the shift and increasing use from N_2O to intravenous anaesthetics like propofol in the medical industry.

5.2 N_2O product use emissions by application

In this subchapter, N_2O product use emissions from 2G3a Medical use and 2G3b(i) propellant and aerosols use are analysed. The analysis compares data and cover regional and global trends in N_2O emissions in each category, as well as highlighting on gaps in nitrous oxide product use emissions reporting.

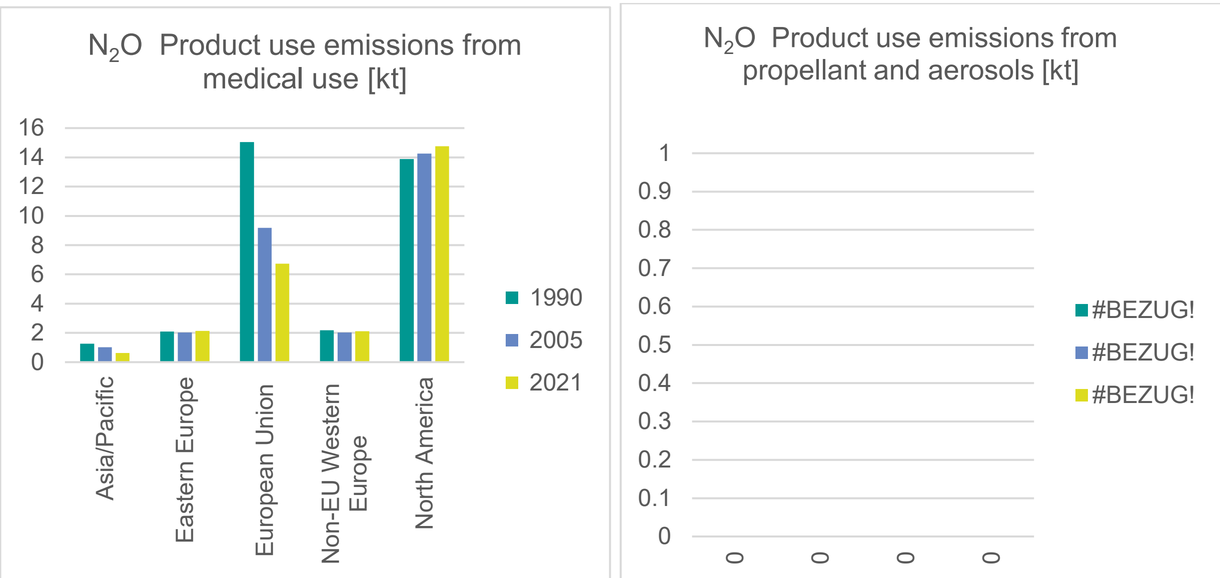
Figure 5-4 UNFCCC Annex I parties' N_2O product use emissions by application overview



Source: (UNFCCC 2024b; Macrotrends 2025), own calculations

From the chart, medical application under category 2G3a reports the largest emissions figures. This category is slowly declining, while 2G3b (i) and (ii) reports less emissions, but a gradual increase in the number of emissions.

Figure 5-5 UNFCCC Annex I parties' N_2O product use emissions by medical and propellant application



Source: (UNFCCC 2024b; Macrotrends 2025), own calculations

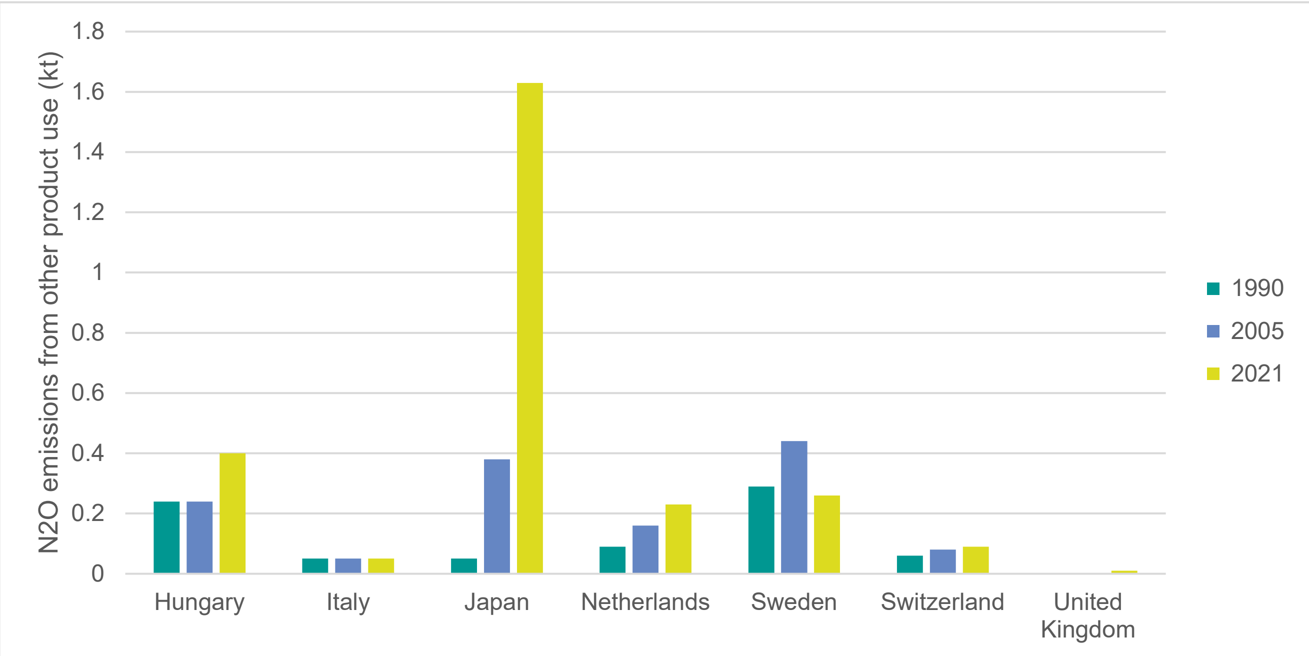
From the graph, N_2O product use from medical use and propellant and aerosol product uses. Not all countries reported under these subcategories. For instance, there are no emissions data reported for Asia and Pacific region for propellant and aerosols product use category. For Medical Use in Asia/Pacific, there is an increase in N_2O product use emissions from 1990 to 2021, indicating a growing dependence on N_2O for medical purposes in this region. In Eastern Europe, medical use emissions remained low with a slight decrease across the years while propellants and Aerosols emissions are consistently low, with no significant change, mirroring the trend in medical use. For the European Union, medical use emissions saw a notable and continuous decrease from 1990 to 2021 indicating efforts to reduce emissions remain efficient and effective in contrast emissions from propellants and Aerosols shows a slight increase in emissions over time, showing less aggressive reduction compared to medical use. With Non-EU Western Europe countries, medical use shows a steady decline in emissions indicating effective reduction measures however propellants and Aerosols product use emissions saw minor fluctuations with a slight increase by 2021, showing a more stable trend compared to medical use. In North America, medical use shows a steady increase in emissions reflecting the exact trend in the overall emission totals whereas propellants and Aerosols emissions projects the same outcome following a trend like medical use but on a smaller scale.

Generally, emissions from medical use are higher than those from propellants and aerosols, reflecting the broader application of N_2O in healthcare setting. From the chart, although medical use application records high emission numbers, they are on a decline while propellant and aerosols use are less but increasing. Efforts to reduce N_2O emissions have been more prominent in the medical sector compared to propellants and aerosols, especially in regions like the European Union.

5.3 Other product use

Other products are found in the category 2G3b(ii). This includes nitrous oxide product use emissions that are not from medical use or propellant use. Below is a detailed analysis.

Figure 5-6 Emissions from other product use of category 2G3b (ii) N_2O Product use



Source: (UNFCCC 2024b)

N_2O Product use emission from 2G3b(ii) vary by country. Italy reported N_2O emissions from explosives under the "other product use" category (2G3bii) (Italy 2023). In Japan, semiconductor and liquid crystal manufacturing was reported under the 2G3b category (Japan 2023a). The Netherlands reported emission from aerosol cans with domestic sales of cream in aerosol cans increasing between 1990 and 2021, leading to a significant rise in N_2O emissions from food aerosol cans (Netherlands 2023). Switzerland's category 2G3b "Other" includes N_2O emissions from whipped-cream makers with gas capsules for private households and restaurants (Switzerland 2023). For United Kingdom, the "other product use" category (2G3b(ii)) reported recreational use emissions. Hungary and Sweden did not provide specific details.

5.4 Data sources and methodology

Data Sources

The estimation of nitrous oxide (N_2O) emissions from product use relies heavily on data from National Inventory Reports (NIRs) submitted by Annex I countries under the United Nations Framework Convention on Climate Change (UNFCCC). These reports provide a comprehensive account of greenhouse gas emissions, including N_2O, from various sectors.

Data for N_2O emissions from product use are drawn from different sources within each country:

- Medical Sector: Sales data of medical-grade N_2O, often provided by pharmaceutical companies, health ministry's etc.
- Food Industry: Sales or production data of N_2O used as a propellant in aerosol products, typically collected from food industry associations or through surveys of manufacturers and distributors.
- Other product use industries (chemical, automotive etc): Data from industries using N_2O for processes such as semiconductor manufacturing or as an oxidizing agent.

Methodology

The methodology for estimating N_2O emissions from product use varies between countries, reflecting differences in available data and reporting practices. Generally, the methodology follows the guidelines provided by the Intergovernmental Panel on Climate Change (IPCC).

- Emission Factors: The IPCC 2006 Guidelines recommend using default emission factors, typically assuming that a significant proportion of the N_2O used in products is eventually emitted into the atmosphere. For medical and food uses, the emission factor is often set at 1.0, indicating that all the N_2O used is released.
- Activity Data: This includes the total amount of N_2O used in different applications, such as the number of aerosol cans produced or the volume of N_2O sold for medical use. Countries used direct data collection from manufacturers or importers or rely on indirect methods such as population-based estimates.
- Country-Specific Methods: Some countries develop specific methodologies tailored to their national circumstances. For instance, the use of hospital bed data to estimate medical N_2O emissions or the application of average per capita consumption to estimate emissions from aerosol propellants.

- Uncertainty and Quality Control: Given the variations in data sources and methods, the quality of emissions estimates differ significantly between countries.

The estimation of N_2O emissions from product use are inherently complex due to the diverse applications and varying data availability across countries. While the methodologies are generally consistent with IPCC guidelines, the quality of data and methodological approaches can differ, leading to varying levels of accuracy and reliability in the reported emissions. These discrepancies highlight the need for improved data collection and standardized reporting practices to enhance the overall quality of emissions data and support more effective mitigation strategies.

6 MITIGATION AND ADAPTATION POLICY INSTRUMENTS AND RESPONSES TO NITROUS OXIDE USE ABUSE

There has been an alarming increase in the recreational use and abuse of N_2O since 2017 especially in some parts of Europe amongst the youth. This is particularly noticeable in some countries in the EU (Netherlands, France, etc) and the UK, which have prompted regulatory authorities to reassess the substance's classification and availability and restrictions on the use of Nitrous oxide.

6.1 Legitimate use regulations and bans

According to the report on nitrous oxide usage and its associated risks (EMCDDA 2022), various European countries have implemented or are planning targeted policy instruments to address the challenges posed by N_2O. These policies aim to mitigate the environmental impacts of N_2O emissions and adapt to the growing public health concerns related to its recreational misuse. This subchapter delves into the specific mitigation and adaptation strategies adopted or proposed in countries like the Netherlands, France, Denmark, Lithuania, Ireland, Portugal, and the United Kingdom.

In the ***Netherlands***, nitrous oxide's recreational use was originally regulated under medicines legislation, which limited its sale and distribution. However, a significant increase in usage led to policy changes. In 2019, nitrous oxide was subjected to the Commodities Act, following a ruling that recreational use did not qualify it as a medicinal product. Municipalities implemented local bylaws restricting sales and use, leading to a decentralized approach where local governments assess and prioritize nitrous oxide problems. This strategy included targeted educational and prevention activities and legal restrictions at the local level. A greater proportion of the Dutch municipalities had employed restrictions on the sale and/or use of nitrous oxide by the end of March 2021 (EMCDDA 2022) .

France observed a notable increase in nitrous oxide use from the 2000s, especially among young people at parties and festivals. The French government responded by passing laws in 2019 and 2021 that prohibited the sale of nitrous oxide to minors and restricted its sale in certain venues like nightclubs and bars. A proposal legislation which aims to ban all sales of nitrous oxide in any form of packaging was introduced in March, 2022 (EMCDDA 2022).

In ***Denmark***, the legislation introduced in June 2020 aimed to prevent nitrous oxide abuse among youth by restricting its sale and possession. The law banned sales to those under 18, limited personal purchases, and prohibited sales in relation to alcohol or tobacco. Despite these measures, enforcement challenges remain, particularly with illicit online sales. Although a new legislation was proposed in early 2022 with some specific action to address these issues, the law has not been passed due to the general elections in November 2022 (EMCDDA 2022).

Lithuania saw a surge in public and business interest in nitrous oxide for recreational use around 2019-2020. In response, the government classified nitrous oxide as a controlled substance, restricting its sale to medical and industrial purposes only. This move was supported by data indicating minimal industrial demand, leading to prohibitions on recreational distribution. Further modifications were done on 25 December 2020. This permitted to use nitrous oxide when marketed, used and/or consumed as a food additive (E942) as defined in Regulation (EC) No 1333/2008 of the European Parliament and of the Council of 16 December 2008 on food additives[13]. No permits or authorizations are needed for this exemption. (EMCDDA 2022).

[13] EU 2008 https://eur-lex.europa.eu/eli/reg/2008/1333/oj/eng

In ***Ireland***, nitrous oxide is not classified as a controlled substance under Irish drug laws, though its sale for psychoactive purposes is prohibited. Recent surveys indicate low but notable use among adults after Covid-19 pandemic, prompting targeted local education and prevention efforts, as well as some seizures by law enforcement to curb illegal distribution. (EMCDDA 2022).

Portugal has been monitoring nitrous oxide usage, noting its distribution in various settings, including parties and social media. In 2021, several seizures were reported, reflecting growing concerns over its recreational use. The General Directorate for Intervention on Addictive Behaviours and Dependencies (SICAD) introduced a proposal to the Ministry of Health to regulate the sale and consumption of nitrous oxide. The proposal was approved and since 8th September 2022, nitrous oxide is classified as a prohibited psychoactive substance. This has been added to the NPS list under Order No 232/2022 dated 7 September 2022 (update to the Decree-Law No 54/2013 of 17 April) (EMCDDA 2022).

The ***United Kingdom***, with a longer history of nitrous oxide use among youth, has implemented various control measures, including public awareness campaigns and law enforcement actions to mitigate its misuse. These efforts have focused on reducing harms associated with its recreational use (EMCDDA 2022). Preceding to November 8, 2023, nitrous oxide was regulated under the Psychoactive Substances Act 2016, making it illegal to produce, supply, import, or export the substance for psychoactive effects in the UK. However, possession was not an offense unless in a custodial setting (GOV.UK 2025). From November 8, 2023, nitrous oxide is classified as a Class C drug under the Misuse of Drugs Act 1971, making possession illegal if it is intended for wrongful inhalation, defined as non-medical or non-dental use (Circular 006/2023: Control of nitrous oxide under the Misuse of Drugs Act 1971 2023). Offenders face penalties including fines, community punishment, or imprisonment. The penalties for supply or production have increased to up to 14 years in prison, an unlimited fine, or both. Medical, dental, veterinary, industrial, and model rocketry uses remain lawful, with strict requirements on suppliers to prevent recreational misuse (GOV.UK 2025).

6.2 Controlled substance classification

European Union

The recent consideration of classifying nitrous oxide as a category 1B reproductive toxicant in the European Union stems from growing concerns about its abuse and potential risk (Zdechovsky 2024). The Committee for Risk Assessment (RAC) of the European Chemicals Agency (ECHA) reviewed the Classification, Labelling, and Packaging (CLP) proposal and gave their opinion on March 16, 2023 (Sinkevičius 2024). You can find this opinion on the ECHA website under "Registry of CLH intentions until outcome"[14]. In the EU, if a substance is classified as toxic for reproduction in category 1A or 1B, it usually means it can't be sold to the general public. For this to happen, the substance must be listed in Annexes V or VI to Annex XVII of the REACH Regulation. The Commission is looking into whether certain legitimate uses should be exempted in Annex 11. The European Commission has included the RAC's opinion in the draft of the next amending regulation (ATP) of the CLP Regulation. The decision to add this to Annex VI of CLP and make it legally binding in the EU is now[15] with the European Commission. This document is currently still being discussed in the relevant committees. After, the final decision will be made after votes by the Council of the European Union and Parliament (ECHA 2023).

[14] ECHA 2025 https://echa.europa.eu/registry-of-clh-intentions-until-outcome
[15] December 2024

6.3 The Montreal Protocol on substances that deplete the ozone layer.

One of the major environmental issues in the 20th Century was the depletion of the stratospheric ozone layer by human-made chemicals. This is known as the Ozone-Depleting Substance. The Montreal Protocol, which emerged from the Vienna Convention for the Protection of the Ozone Layer, was very successful in reducing the emissions and concentrations of chlorine- and bromine-containing halocarbons, the main ODSs. This has helped limit ozone depletion and start the recovery of the ozone layer. The impact of different ODSs on ozone depletion is measured by their ozone depletion potential (ODP), which compares the amount of ozone destroyed by a chemical to that destroyed by chlorofluorocarbon 11 (CFC-11). ODPs are useful for policymaking because they simplify the comparison of ozone-destroying capabilities of various compounds. The primary source of stratospheric NOx is surface emissions of nitrous oxide (N_2O). Although N_2O is mainly a natural atmospheric component, its changes have been studied for their long-term effects on ozone concentrations.

Nitrous Oxide is an Ozone-Depleting Substance. In spite of its shared similarities with CFCs, a previous dominant ODSs, N_2O is not recognised as an ODS under the Montreal Protocol. Its ozone depletion potential (ODP), a metric for the potency of a unit mass emission on ozone relative to that of CFC-11, has been calculated to be 0.017 (Ravishankara et al. 2009; UNEP/FAO-UN 2024a). Although this absolute ODP value is small compared to CFCs (CFC-11 and CFC-12 are 1), the ODP-weighted emission of anthropogenic nitrous oxide is 179.0kt/yr. This is approximately equal to the sum of all other controlled substances under the Montreal Protocol that is being phased out (UNEP/FAO-UN 2024a). Although N_2O is not recognised under the Montreal Protocol despite its high ODP weighted emission, discussions have started to possibly cover N_2O under the Montreal Protocol (EU 2024).

7 CONCLUSION

7.1 Summary of key findings

The analysis revealed that the medical and food industries are primary contributors to N_2O emissions from product use. In the medical sector, N_2O is commonly used as an anaesthetic, whereas in the food industry, it functions as a propellant in products like whipped cream. The data showed a general trend of emissions reduction in the European Union regions due to the adoption of alternative practices such as low-flow anaesthesia and N_2O 50-50 mixture with oxygen, nitrous oxide destruction units, and nitrous oxide abatement technology. However, in other areas, emissions remain substantial due to continued reliance on N_2O. The report also highlighted significant gaps in data accuracy and reporting, underscoring the need for more robust and consistent monitoring frameworks across countries. Some policies in the European region on N_2O use abuse bans and ongoing controlled substance classification were identified and highlighted.

7.2 Recommendations for Germany and the EU

To ensure effective reduction N_2O emissions, it is recommended that N_2O be included in the scope of the EU Ozone Depleting Substances (ODS) Regulation. Currently, N_2O is not covered under the Montreal Protocol's reduction obligations although there are ongoing discussions. Hence, by incorporating N_2O into the ODS reporting requirements, the EU could enhance data quality and lay the groundwork for future mitigation measures. This approach would ensure that the production, import, and export of N_2O are systematically monitored, creating a more comprehensive database that could support the formulation of targeted policies. Such inclusion would not only improve emission tracking but also serve as a critical step toward developing regulatory instruments aimed at reducing N_2O emissions from product use across various sectors.

7.3 Future research and policy development

Future research should prioritize the exploration of new technologies for N_2O replacement and capture and abatement, particularly in the medical and food industries. Investigating the feasibility and effectiveness of alternative substances that could replace N_2O without compromising functionality is crucial. Policy development should focus on integrating N_2O into broader climate change mitigation strategies and ozone protection initiatives. This includes promoting international cooperation to establish global standards for N_2O emission reduction. Further studies should also assess the economic implications of phasing out N_2O, ensuring that the transition to sustainable alternatives is economically viable and does not disproportionately affect certain industries or regions. Emphasizing the importance of public awareness and industry engagement will be key to the successful implementation of these policies.

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Annex

Annex I. Detailed data sources and methodology for Annex I parties as reported.[16]

Countries	Data sources and methodology
Australia	-No Data given
Austria	-2G3a: Data from industry/importers inquiries -2G3b; Market data from supermarkets and wholesale sources extrapolated for retail market shares.
Belarus	2G3; Emissions estimated using IPCC 2006 Guidelines Tier 1 approach 2021 by the Ministry of Health in Belarus.
Belgium	-2G3a: Medical N_2O emissions based on hospital beds (from 1990-1995 using the average consumption of anaesthetics per bed (10,3 kg N_2O/bed/year)), extrapolation (an interpolation was done between 1995 to 2005) and sales data. -2G3b: Data from DETIC (Belgian-Luxembourg Association). Aerosol emissions estimated using EU averages and updated with emission factors from 2017
Bulgaria	-2G3; Medical data from the sole N_2O manufacturer until 2012, import data collected from licensed companies afterward. -2G3b; Propellant use based on import data and population-based emission factors
Canada	-2G3; Statistics are obtained from domestic sales and imports. N_2O emission estimates is based on a consumption approach which assumes the domestic sales and imports equal domestic consumption.
Croatia	-2G3; Data collected from major hospitals. -2G3; Ministry of Economy and Sustainable Development for food industry for (2009-2017) emissions.
Cyprus	-2G3a; Emissions calculated using population and EU emission factors per capita. The Emission factor of 0.00001532 t N2O per capita. -2G3b; Population-based emission factor of 0.00000995 t N_2O/capita
Czechia	-2G3; Data is derived from imports production
Denmark	-2G3a; Sales data from 2005–2012 used to estimate N_2O emissions. Earlier and later years estimated based on averages. -2G3b; No detailed data available, though cream consumption statistics exist
Estonia	-2G3a; Sales data from companies importing N_2O (1992-2021).

[16] Copies of all National Inventory reports of 2023 for the Annex 1 parties; https://unfccc.int/ghg-inventories-annex-i-parties/2023

	-2G3a; For 1992-2004 surrogate data was created using average consumption of whipped cream in 2005-2019 per capita and multiplying this number with population in 1992-2004. Imported aerosol cans tracked since 2007.
Finland	-2G3 Emissions are calculated using production or import.
France	2G3a: Data from the European market is estimated.
Germany	-2G3; Data primarily based on sales from main suppliers. Since 2005, Industriegaseverband (IGV) industrial-gas association has carried out surveys of N_2O sales for all applications
Greece	-2G3 Based on population and emission factors from other European countries like Italy, Spain, Austria, and the Netherlands.
Hungary	-2G3; Extrapolated emissions based on historical trends and N_2O production data and domestic sales data.
Ice land	-2G3; Emissions estimated using IPCC 2006 Guidelines Tier 1 approach from sales data from importers
Ireland	-2G3a; Estimated using population-based data and standard assumptions from other Annex I parties. -2G3b: Unable to estimate due to lack of consumption data.
Italy	-2G3; Emissions of N2O have been estimated considering information available by industrial associations. For previous years, data have been estimated by the number of surgical beds published by national statistics (ISTAT)
Japan	-2G3a; N_2O shipped by pharmaceutical manufacturers or importers -2G3b; N_2O shipment amounts for semiconductor/liquid crystal manufacturing given by Japan Industrial and Medical Gases Association
Kazakhstan	No data given
Latvia	-2G3; Since 2007, emissions data on N_2O sales in Latvia have been available, provided by the State Agency of Medicines of Latvia. From 1990-2006, to create a comparable time series, 2007 is used as the base year. Emissions for these years are calculated proportionally based on the number of inhabitants, as provided by the Central Statistical Bureau (CSB).
Liechtenstein	-2G3; To estimate emissions for Liechtenstein, the specific emissions per inhabitant in Switzerland are used as a proxy.
Lithuania	-2G3a; From 2005, data was provided by the State Medicines Control Agency, which collected data from the wholesale companies. Emissions for 1990-2004 were extrapolated. -2G3b; N2O emissions from aerosol cans in Lithuania was estimated based on Belgium data.

Luxembourg	-2G3; From 2003 to 2021, the use of N2O in hospitals for anaesthesia was directly obtained from the “Entente des hôpitaux luxembourgeois”. Prior years, N2O emissions from anaesthesia usage were estimated by combining reported emissions in Germany with the relative population in Luxembourg.
Malta	-2G3; Emissions data is obtained from institutions and import data of medical grade nitrous oxide.
Monaco	2G3; Data from three major health facilities
Netherlands	-2G3a; the N2O emissions in this source category are from non-key sources. -2G3b; the Dutch Association of Aerosol Producers (Nederlandse Aerosol Vereniging, NAV) reports sales of N_2O-containing spray cans. Emission factor: 7.6 g/can.
New Zealand	-2G3; Import data from New Zealand Customs Service and Stats NZ, although some classification errors are noted.
Norway	-2G3a; Data from major producers and importers. Prior to 1998, annual consumption is estimated using 1998 sales figures and hospital data (number of births and bed nights). -2G3b; No local production; imports since 1993. Emissions assumed to be fully released upon use.
Poland	-2G3a; Emissions estimated at 0.4 kt annually based on a 2001 national study. -2Gb; Emissions calculated for whipped cream use, ranging from 0 kt N_2O in 1988 to 0.05 kt N_2O in 2021.
Portugal	-2G3; The IPCC Guidelines was used to estimate N_2O emissions from data of quantity of N_2O supplied from manufacturers and distributors of N_2O products
Romania	-2G3a; Data from hospital economic operators collected via questionnaires. -2G3b; Limited data from importers; 6 g of N_2O per can used for estimation.
Russian Federation	-2G3a;1990-1996 estimated from surgical operations performed. 1997 onwards from medical institutions
Slovakia	-2G3a; Uses Distributors’ data. -2G3b; Based on direct information from gas distributors.
Slovenia	-2G3a; N_2O is estimated based on consumption from Statistical Office of Republic of Slovenia (SORS)
Spain	-2G3a: Emission are extrapolated from sales data provided by medical companies. -2G3b: Data from imports only supplied by FEIQUE
Sweden	-2G3a: N_2O sales data from gas companies and the Swedish Chemicals Agency.

	-2G3b: Data aggregated with medical use due to confidentiality concerns
Switzerland	2G3a; Data primarily based on sales from main suppliers. -2G3b; For both categories a Tier 2 method based on country-specific emission factors for the production/consumption of N_2O is used
Turkey	No data given
UK	-2G3a; Estimates from hospital beds -2G3b; Estimate is done using the Danish GHG Inventory
Ukraine	-2G3: Estimated using national emission factors from the Ministry of Health.
Ukraine	-2G3a: Medical N_2O emissions estimated for the first time from 1990-2021 using national emission factors. The new method developed is based on statistics from the 81 health facilities of Ukraine
United Kingdom	-2G3: Emissions calculated from hospital bed-days -2G3: Follows the Danish methodology, assuming 1% of cream consumption involves whipped cream sprays, though exact market share is unknown. minimal data on N_2O use in whipped cream.
USA	-2G3; The 1996 share of N_2O usage by subcategory was obtained from SRI Consulting's report. For 1990-1995, the share was assumed to be the same as in 1996. The 1997-2001 share was obtained through communication with an industry expert. The 2002 and 2003 shares were provided by CGA. The emission factor for the food processing propellant industry was obtained from SRI Consulting and confirmed by an industry expert. Due to a lack of data, the 2004-2021 shares were assumed to be the same as in 2003.

Annex II. Emissions from N_2O product use per capita (in grams N_2O per capita)

ANNEX 1 PARTIES	1990	2005	2021
Australia	79.23	41.92	50.29
Austria	14.24	10.73	4.38
Belarus	173.72	172.70	174.92
Belgium	69.48	65.80	64.59
Bulgaria	51.01	50.34	120.47
Canada	20.84	39.32	48.41
Croatia	82.93	96.90	111.47
Cyprus	4.16	7.33	4.88
Czechia	5.34	27.10	20.64
Denmark	11.39	10.10	10.36
Estonia	11.64	16.80	6.79
Finland	43.39	30.85	20.59
France	0.29	0.23	0.20
Germany	4.06	2.85	0.15
Greece	28.25	39.61	24.75
Hungary	11.85	10.56	6.56
Iceland	79.16	39.63	16.32
Ireland	4.26	4.56	4.58
Italy	7.88	8.30	7.86
Japan	7.89	9.66	15.70
Latvia	974.23	1189.48	898.12
Liechtenstein	3984.81	2616.52	1317.30
Lithuania	2.34	2.44	2.51
Luxembourg	729.62	423.15	161.06
Malta	383.15	340.66	221.87
Monaco	49.78	25.79	13.04
Netherlands	90.81	131.37	117.97

New Zealand	101.19	36.17	58.58
Norway	82.29	38.20	19.64
Poland	11.59	6.51	3.20
Portugal	67.87	32.96	16.18
Romania	17.95	20.52	23.45
Russian Federation	0.35	0.63	2.42
Slovakia	1294.25	295.78	170.13
Slovenia	52.96	61.86	70.94
Spain	0.81	0.38	0.39
Sweden	87.53	32.55	24.55
Switzerland	0.01	0.10	0.10
Ukraine	4.65	4.75	2.28
United Kingdom of Great Britain and Northern Ireland	32.55	32.68	33.30
United States of America	57.26	47.68	41.99

Source: (UNFCCC 2024b; Macrotrends 2025), own calculations

Annex III. Comparative analysis of N_2O emissions based on hospital beds.

Three countries UK, Italy, and Belgium of the Annex I parties reported emissions using hospital bed counts to calculate N_2O emissions for specific years. Specifically, Belgium used this method from 1990-1995, Italy from 1990-1993, and the UK in 2011. A standard emission factor of 10.3 kg N_2O/bed/year, derived from the EU GHG inventory, was used to estimate emissions for these countries.

In this section, a recalculation was performed using the same methodology to assess the reliability of the 10.3 kg N_2O/bed/year assumption for estimating N_2O emissions in the absence of production or consumption data for these specific years.

Table 6 Reported N_2O Emission and calculated N_2O Emission per hospital bed for Belgium

Hospital beds data use (years)	**Belgium**		
	Emissions (tonnes) based on 'per hospital bed' emission factor of 10.3 kg/bed & year	Emissions (tonnes) as reported in the inventory for medical use	implied emission factor kg of 'medical use N2O emissions' per hospital bed & year"
1990	821	635	8.0
1991	813	629	8.0
1992	794	625	8.1
1993	797	621	8.0
1994	788	609	8.0
1995	0	597	0

Source: (UNFCCC 2024b; UK 2023; Italy 2023; Belgium 2023)

Table 7 Reported N_2O Emission and calculated N_2O Emission per hospital bed for Italy and the UK

Hospital beds data use (years)	Italy		
	Emissions (tonnes) based on 'per hospital bed' emission factor of 10.3 kg/bed & year	Emissions (tonnes) as reported in the inventory for medical use	implied emission factor kg of 'medical use N2O emissions' per hospital bed & year"
1990	4 209	2 392	6
1991	3 978	2 250	6
1992	4 039	2 271	6
1993	3 925	2 219	6
For UK only			
2011	1890	1939	11

Source: Source: (UNFCCC 2024b; UK 2023; Italy 2023)

The calculated emissions (using 10.3 kg/bed/year emission factor) are higher than the reported emissions from national inventory reports for Italy, and Belgium although UK shows the opposite.

For UK, a higher IEF of 11 kg/bed/year is calculated. This may be on the assumption that UK hospitals may be using more N_2O per bed than expected. This signals that the 10.3 kg/bed/year proxy factor is low for the UK and too high for Belgium and Italy

The duration of hospital stays following surgical procedures can vary significantly, ranging from less than a day to several days or even weeks. As a result, estimates of the number of anaesthetics administered based on surgical bed occupancy are likely to be inaccurate. Additionally, since nitrous oxide (N_2O) is used in only a portion of anaesthetics, its usage cannot be reliably estimated from the total number of anaesthetics administered. This variability and partial usage make it challenging to accurately calculate N_2O emissions using hospital bed data alone (IPCC 2006).