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Mitigation potentials for emissions of nitrous oxide from chemical industry in industrialised countries world-wide

Study for the Nitric Acid Climate Action Group (NACAG)
on behalf of the
Federal Ministry for Economic Affairs and Climate Action (BMWK)

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List of Abbreviations

ACCU	Australian Carbon Credit Units
AR4	4th IPCC assessment report
AR5	5th IPCC assessment report
BAT	Best available technique
BR	Biennial Report
BREF	BAT reference document
BUR	Biennial Update Report
CDM	Clean Development Mechanism
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
CRF	Common Reporting Framework
CSR	Corporate Social Responsibility
EF	Emission factor
ELV	Emission limit values
ERF	Emissions Reductions Fund
ERU	Emission Reduction Unit
ETS	Emissions Trading System
EU	European Union
GHG	Greenhouse gas
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH
GWP	Global warming potential
IPCC	Intergovernmental Panel on Climate Change
JI	Joint Implementation
K-ETS	Korean Emissions Trading Scheme
KCU	Korean Credit Unit
METI	Ministry for Economy, Trade and Industry

NACAG	Nitric Acid Action Group
N_2O	Nitrous Oxide
NC	National Communication
NIR	National Inventory Report
NO	Nitrogen monoxide
NO_2	Nitrogen dioxide
NO_X	Nitrogen Oxides (summary term for air pollutants NO and NO_2, not including the greenhouse gas N_2O)
NSCR	Non-selective Catalytic Reduction
OECD	Organisation for Economic Co-operation and Development
ODA	Official development assistance
PDD	Project Design Document
PGCD	Process-gas catalytic decomposition
SCR	Selective Catalytic Reduction (for the abatement of NO_x emissions)
SNCR	Selective non-catalytic Reduction
tpd	tonnes per day
UAE	United Arab Emirates
UK	United Kingdom of Great Britain and Northern Ireland
UNFCCC	United nations Framework Convention on Climate Change
USA	United States of America

Summary

This study investigates mitigation potentials in industrialised countries for emissions of the greenhouse gas nitrous oxide (N_2O) from chemical industry, in particular from the production processes for nitric acid, adipic acid and caprolactam. For the purpose of this study, ‘industrialised countries’ are the countries not identified by the OECD as eligible for official development assistance (ODA). Based on that criterion, the covered countries and regions are Australia, Canada, Chile, the European Union, Israel, Japan, the Republic of Korea, Norway, Russia, Saudi-Arabia, Singapore, Trinidad and Tobago, United Arab Emirates, United Kingdom, United States of America but do not include ‘emerging economies’ like China.

For the study, information was collected in 15 country briefs covering the size of the respective industries, current regulatory framework conditions affecting N_2O emissions, N_2O abatement in place, and estimates of current N_2O emissions, emission intensities and mitigation potentials.

In total, 2020 process emissions of N_2O from chemical industry in industrialised countries world-wide are estimated at 47.4 Mt CO_2e (GWP AR5), thereof 76 % (36.1 Mt CO_2e) from nitric acid production, 17 % (8.0 Mt CO_2e) from adipic acid production and 7 % (3.3 Mt CO_2e) from caprolactam production. The investigated countries and regions contributing most to N_2O emissions are Russia, the USA, the EU, Australia and Trinidad and Tobago for nitric acid production, the USA for adipic acid production, and the EU, the USA and Russia for caprolactam production.

Climate policies affecting N_2O emissions from chemical industry for the key contributors are missing in particular for Russia, the USA and Trinidad & Tobago. The European Union, while covering N_2O from nitric and adipic acid production under the EU-ETS, employs no policies effectively addressing N_2O emissions from caprolactam production.

For ***nitric acid production***, average emission intensities per country range from very high 8-9 kg N_2O/t HNO_3 (Trinidad and Tobago, Russia) to low 0.5 kg/t and less for Western European countries and Korea. While a comparison of national average emission intensities provides a benchmark-based top-down indication of N_2O mitigation potentials for ambitious climate policies, ‘low-hanging fruit’ mitigation potentials in presently unabated nitric acid plants were additionally estimated: These sum up to 63 % of total N_2O emissions from nitric acid production estimated for 2020 (22.5 Mt CO_2e mitigation potential out of 36.1 Mt CO_2e 2020 emissions). Such mitigation potentials are primarily allocated to Russia, the USA and Trinidad & Tobago. Single further nitric acid plants without abatement were identified for Australia and Japan. For Australia, however, a retrofit is reported to be underway.

Adipic acid production is taking place in only six of the industrialised countries studied, i.e. the USA, Japan, Korea and the EU Member States France, Germany and Italy. Emission intensities range from very high 40 kg N_2O/t adipic acid (USA) to as low as 2-4 kg/t and below for the EU and Korea. While ambitious mitigation is taking place in Japan, Korea and the EU, the mitigation efforts in the USA are insufficient, as available mitigation equipment appears to be operated poorly.

Caprolactam production is taking place in 10 of the industrialised countries studied, i.e. the USA, Russia, Japan, Korea and the six EU Member States Belgium, Czechia, Germany, Netherlands, Poland and Spain. Emission intensities range from very high 9 kg N_2O/t caprolactam (USA and Russia) to as low as 2 kg/t for Japan and Korea. Even lower emission rates were reported for EU Member States Poland (0.6 kg N_2O/t) and Germany (nearly complete elimination). While ambitious mitigation is taking place in Japan, Korea and some EU Member States, the mitigation efforts are

insufficient in the USA, Russia and other EU Member States. Unlike nitric acid and adipic acid production, N_2O emissions from caprolactam production are not covered by the EU-ETS.

1 Introduction

This study investigates mitigation potentials in industrialised countries for emissions of the greenhouse gas nitrous oxide (N_2O) from chemical industry, in particular from the production processes for nitric acid, adipic acid and caprolactam.

The study was launched by the Secretariat of the Nitric Acid Climate Action Group (NACAG[1]), a global climate change initiative launched by the German Government with the objective to globally support the mitigation of N_2O emissions from nitric acid production in developing countries. The secretariat of NACAG initiative is implemented by the German Technical Cooperation (GIZ).

The geographic scope of the study covers industrialised countries world-wide where nitric acid production, adipic acid production and/or caprolactam production takes place. For the purpose of this study, 'industrialised countries' are the countries not identified by the OECD as eligible for official development assistance (ODA). Based on that criterion, the list of covered countries as spelled out in Table 1 does not include 'emerging economies' like China, India, South Africa, Mexico or Brazil.

Table 1: Countries included in the analysis

	Present and / or historic production activities		
	Nitric acid	**Adipic acid**	**Caprolactam**
Australia	✓		
Canada	✓	✓	
Chile	✓		
European Union (1), (2), (3)	✓ (1)	✓ (2)	✓ (3)
Israel	✓		
Japan	✓	✓	✓
Republic of Korea	✓	✓	✓
Norway	✓		
Russia	✓		✓
Saudi-Arabia	✓		
Singapore	✓	✓	
Trinidad and Tobago	✓		
United Arab Emirates	✓ (?)		
United Kingdom	✓		
United States of America	✓	✓	✓

(1) EU Member states with nitric acid production: Austria, Belgium, Bulgaria, Croatia, Czech Republic, Finland, France, Germany, Greece, Hungary, Italy, Lithuania, Netherlands, Poland, Portugal, Romania, Slovakia, Spain, Sweden
(2) EU Member states with adipic acid production: France, Germany, Italy
(3) EU Member states with caprolactam production: Belgium, Czech Republic, Germany, Netherlands, Poland, Spain
Source: data collected in the study

[1] www.nitricacidaction.org

Our investigation results related to the situation of N_2O emissions and mitigation potentials are presented in section 2 in the form of 15 country briefs for industrialised countries and regions around the globe. These profiles contain information on the size of the respective industry, technical information related to N_2O emissions as well as the current regulatory framework conditions for operators of nitric acid, adipic acid and caprolactam production facilities.

The quantification of N_2O mitigation potentials in the country briefs is based on the comparison of available country-specific information on specific N_2O emissions per ton of nitric acid, adipic acid or caprolactam against benchmarks for emission intensities which are proven to be achievable by means of ambitious policy instruments encouraging the employment of effective N_2O abatement techniques. The development of these benchmarks on national or EU level is documented in the Annex.

We acknowledge that the realisation of such benchmark-based mitigation potentials might possibly involve high-cost technological upgrades of abatement technology in facilities already equipped with secondary or tertiary abatement technology. We'd like to stress that the desk-based, remote analysis performed in the present study cannot replace in-depth plant-specific assessments for a sound assessment of mitigation potential and related cost. Where available plant-specific information appears sufficient, the 'national emission intensity benchmark'-based quantification approach discussed above is amended by an estimate of rather easily realisable, 'low-hanging fruit' mitigation potentials focussing on plants where no secondary or tertiary N_2O abatement technologies are being used so far.

In section 3, we summarise the results of our research and provide cross-country overviews, separately for nitric acid production, adipic acid production and caprolactam.

Given the lack of detailed information, any quantifications in our study, in particular for N_2O mitigation potentials, should be understood as rough estimates based on desk research rather than detailed technical potential analyses which would need to consider more plant-specific information than available for our study.

The Russian invasion into Ukraine of February 2022 and the subsequent war and international sanctions are likely to have immense consequences on international energy markets and energy prices. Those are likely to affect fuel and feedstock supplies and competitiveness of the chemical production facilities discussed in this study in different manners throughout the world. The present study does not attempt to assess potential consequences of these events on production patterns and related N_2O emissions or emission mitigation potentials.

2 Country Briefs

2.1 Australia

2.1.1 Australia summary

In Australia, approximately 1.8 million tonnes of nitric acid were produced in 2020. Key N_2O mitigation policies include a voluntary carbon credit scheme linked to an obligation to keep plant emissions below a business-as usual baseline. Secondary catalysts are partly being employed, latest upgrades involve tertiary catalysts. Average specific N_2O emissions in 2020 were at about 3 kg per tonne of nitric acid. Compared to emission intensity benchmarks achievable by ambitious mitigation policies as the EU ETS, Australian N_2O mitigation potentials are estimated at 80-90 %. An easy-to-achieve mitigation potential in so far unabated plants, however, amounts to ~1.1 Mt CO_2/a, or ~20 % of Australia's present emissions from nitric acid production.

Table 2: Country Profile Australia

	Nitric Acid	Adipic Acid	Caprolactam
Number of facilities	12 lines / 6 locations	-	-
Relevant climate policies	Emissions Reductions Fund (ERF): voluntary carbon credit scheme; ERF safeguard mechanism: obligation for large emitters to keep GHG emissions below individual baseline, use of carbon credits for compliance is possible		
N_2O Abatement Technologies in Place	Secondary / tertiary catalysts installed in ~ 80 % of HNO_3 production capacity	Not applicable	Not applicable
Annual Production (2020)	1.8 Mt [100% HNO_3]	-	-
Annual N_2O emissions (2020)	5.2 kt N_2O / 1.4 Mt CO_2e	-	-
N_2O emissions uncertainty estimate	± 15 %		
Specific N_2O emissions (2020)	2.9 kg N_2O/t		
N_2O mitigation potential	Gap to emission intensity benchmark of ambitious mitigation policy: ~80-90 % ~ 4.5 kt N_2O / a ~1.2 Mt CO_2e / a 'Low-hanging fruit' potential in unabated plants: ~20 % ~ 1.1 kt N_2O / a ~0.3 Mt CO_2e / a		

Note: N_2O amounts converted into CO_2 equivalents using the GWP of 265 as set out in the 5th IPCC Assessment Report (AR5)
Sources: Australia 2019; 2022a; 2022b; Klimadock 2020; Clean Energy Regulator 2022a; 2022b; Orica 2022, own calculations of Öko-Institut

2.1.2 Presence of N_2O-emitting chemical industries

In Australia, the production of nitric acid takes place, usually linked to the production of fertilisers or explosives. Production of adipic acid and caprolactam, however, does not occur. Nitric acid production levels have been on the rise in the last decades. Nitric acid production amounts reported for 2020 are at about 1.8 million tonnes, which is approximately 40 % above 2010 levels (1.3 Mt) or 240 % above 2000 levels (0.5 Mt) (Australia 2022a), see Table 4.

In the Australian National GHG inventory report under the UNFCCC (NIR) (Australia 2022b), three companies producing nitric acid are mentioned: Wesfarmers, Orica and Queensland Nitrates. Research in the industry, however, concluded in five companies (including joint ventures) operating twelve production lines at six sites in Australia (Klimadock 2020):

Table 3: Nitric acid production sites in Australia

Company	Location	Year of construction	Capacity [t 100% HNO_3]	N_2O abatement	Comments
CSBP / Wesfarmers	Kwinana, Western Australia	1996		yes	Abatement installed since 2012, abatement rates ≥ 80 % Upgrade of abatement technology by 2030 announced in decarbonisation roadmap. (Wesfarmers 2022)
		2007		yes	
		2014		yes	
		total CSBP Kwinana	**720,000**		
Incitec Pivot Limited / Dyno Nobel	Moranbah, Queensland	2012	265,000	yes	Secondary abatement with 50-60% abatement rate to be upgraded to tertiary abatement, resulting in 99 % abatement. Completion expected for 2024 (Incitec Pivot 2022)
ORICA Limited	Kooragang, New South Wales			yes	Upgrade to tertiary N_2O abatement announced in 2021 for 2022 N_2O abatement rate to be upgraded from ~ 92% to ~96%, expected emissions reduction 48% (Orica 2021)
				yes	
				yes	
		total ORICA Kooragang	**330,000**		
ORICA Limited	Yarwun, Queensland		105,000	Under development	ERF project registered; final investment decision pending, awaiting Australian carbon market reform (Orica 2022) 2020 GHG emissions reported at ~0.3 Mt CO_2e (Clean Energy Regulator 2022a)
			103,500		
			231,000		
		total ORICA Yarwun	**409,500**		
YARA Pilbara	Karratha, Western Australia	2003	264,000	yes	Joint Venture YARA / ORICA
QNP / Queensland Nitrates	Moura, Queensland		173,250	Information not available	525 tpd / 405 tpd [100%]/; Joint venture DYNO Nobel (Incitec Pivot) / CSBP (Wesfarmers)

Sources: (Klimadock 2020; Orica 2021; Yara 2022; Incitec Pivot 2022; Wesfarmers 2022; Orica 2022; Thyssenkrupp 2023; Clean Energy Regulator 2022a), Öko-Institut calculations

2.1.3 Policies affecting N_2O emission levels

The key policy instrument affecting N_2O emissions from Australian nitric acid plants is the Emission Reduction Fund (ERF)[2] in combination with the ERF safeguard mechanism[3]:

The ERF is basically a voluntary baseline & credit scheme. Under the ERF, eligible plant operators, including nitric acid plants, can register emission reduction projects where emission reductions are estimated using methods[4] approved[5] under the ERF. The ERF purchases abatement contributions through reverse auctions, following which the Government contracts with successful bidders for the delivery of abatement. The scheme involves the issuance of ACCUs (Australian Carbon Credit Units). An Australian Carbon Exchange is under development and is intended to make ACCU trade simpler (Australia 2019; Clean Energy Regulator 2022b). Beyond the crediting and purchasing element, the ERF is complemented by a safeguard mechanism which incentivise large emitters (above 100 kt CO_2e/year) to keep their GHG emissions below their business-as-usual baselines. For compliance with the safeguard mechanism, companies can either limit their emissions, or purchase ACCUs (Clean Energy Regulator 2019).

The methodology applicable to quantify ERF N_2O emission reductions from nitric acid production is the 'facility method'[6]. The Australian nitric acid producer Orica reports that their decarbonisation project for the Kooragang site (see Table 3) was approved to generate ACCUs under that method (Orica 2021). Furthermore, the ERF safeguard mechanism applies to Australian nitric acid producers, several nitric acid plants covered by the safeguard mechanism report respective baselines covering N_2O process emissions and other direct GHG emissions (Clean Energy Regulator 2022c). No information is publicly available, however, summarising the extent to which Australian nitric acid producers comply by limiting their own N_2O emissions or by means of purchasing ACCUs. Anecdotic information confirms, however, that at least Orica needs to rely on purchased ACCUs for their Yarwun site (Orica 2022).

2.1.4 N_2O abatement in place

Compared to Europe, Australian nitric acid industry had a rather slow history of deploying N_2O abatement before 2011 (EnerGreen Consulting 2011). This was linked to the Australian government's decision not to host JI projects in the first implementation period of the Kyoto protocol, 2008-2012 (Australia 2009).

By 2022, most Australian nitric acid plants have been equipped with N_2O abatement as spelled out in detail in Table 3. One production site, however, covering almost 20 % of Australia's nitric acid production capacity, is not yet equipped with N_2O abatement. Abatement rates of existing N_2O abatement facilities is reported in the range of 80 % to 92 %. Upgrades in abatement technology in order to reach 96%-99 % abatement rates are underway or planned for some installations (see Table 3).

[2] https://www.cleanenergyregulator.gov.au/ERF/About-the-Emissions-Reduction-Fund
[3] https://www.cleanenergyregulator.gov.au/ERF/About-the-Emissions-Reduction-Fund/the-safeguard-mechanism
[4] https://www.cleanenergyregulator.gov.au/ERF/Pages/Method-development.aspx
[5] https://www.cleanenergyregulator.gov.au/ERF/method-development/developing-methods
[6] https://www.cleanenergyregulator.gov.au/ERF/Choosing-a-project-type/Opportunities-for-industry/facility-methods/facilities-method

2.1.5 N_2O emissions

In the Australian GHG inventory submission to the UNFCCC (CRF Tables in Australia (2022a)), N_2O emissions from nitric acid production, which were calculated based on facility-specific monitoring data, have been merged with N_2O emissions from the 'other N_2O product use' category[7], in order to protect the confidentiality of N_2O product use data (Australia 2022b).

The data reported in the Australian inventory thus do not allow to conclude directly on N_2O from nitric acid production. In order to estimate Australian N_2O emissions from nitric acid production, we have estimated Australian N_2O product use emissions on a per-capita basis, taking as the basis the average of New Zealand and USA per capita emissions for N_2O from 'other product use'. Using that approach we estimate that approx. 20 % of 2020 N_2O emissions reported by Australia for the joint ***nitric acid production*** and ***other product use*** categories can be attributed to 'other product use'.

Both the Australian reporting data and our estimates for the allocation of data to nitric acid production and other product use are given in Table 4. The average N_2O emission factor for nitric acid production excluding N_2O product use estimated by Öko-Institut is 2.8 kg/t and varies in the time series between 2.3 and 9.4 kg/t. That Öko-Institute estimate is reconfirmed by information on specific N_2O emissions from nitric acid production quoted in the Australian inventory report as 0.0028 t N_2O/ t nitric acid for 2020 and a range of 0.002 – 0.01 t/t for the time series.

Table 4: N_2O emissions from Australian nitric acid production

	nitric acid production million tonnes (100% nitric acid)	**N_2O emissions nitric acid production, including 'other N_2O product use'**		**N_2O emissions from 'other product use'**	**N_2O emissions nitric acid production, excluding 'other N_2O product use'**	
		kt N_2O	kg N_2O / t nitric acid	kt N_2O	kt N_2O	kg N_2O / t nitric acid
	reported by Australia to UNFCCC			Öko-Institut estimate		
2000	0.54	5.8	10.9	1.0	4.8	8.9
2005	0.86	8.9	10.4	0.8	8.1	9.4
2010	1.29	10.5	8.2	1.0	9.6	7.4
2015	1.55	5.2	3.4	1.1	4.1	2.7
2016	1.63	4.7	2.9	1.0	3.7	2.3
2017	1.63	5.1	3.1	1.1	4.0	2.5
2018	1.71	6.1	3.6	1.3	4.8	2.8
2019	1.70	7.5	4.4	1.3	6.2	3.6
2020	1.82	6.5	3.6	1.4	5.1	2.8

Sources: Australia 2022a United States of America 2022a New Zealand 2022, United Nations 2022, Öko-Institut calculations

The uncertainty of N_2O Emissions reported by Australia in CRF category 2.B Chemical Industry was estimated by Australia at ± 5.8 % (95% confidence limits assuming normal distribution) in the NIR (Australia 2022b). For the Öko-Institute estimate of Australia's N_2O emissions from nitric acid production excluding emissions from 'other N_2O product use' (Table 4) we estimate an uncertainty of ± 15 %.

[7] The 'other N_2O product use' category covers N_2O emissions from use as anaesthetic or as propellant for whipped cream etc.

2.1.6 N_2O mitigation potentials

Australian specific emissions of ~ 3 kg N_2O / t nitric acid are very high compared to European levels.

Benchmarks for emission intensities achievable by ambitious mitigation policies can be derived from the EU-ETS in the range of 0.43 kg/t as EU-ETS average, 0.26 kg/t as average of the top half of EU-ETS or 0.6 kg/t for the bottom half of EU-ETS participants (see Annex I).

These EU-ETS benchmarks for emission intensities are at ~10-20% of present Australian emission intensities. Benchmark-based top-down mitigation potentials for N_2O from Australia's nitric acid production add up to ~4.5 kt N_2O/a or ~ 1.2 Mt CO_2e / a (GWP AR5).

In a bottom-up perspective focussing on plants without any present N_2O abatement we consider a ~95 % reduction of unabated N_2O emissions at the Orica Yarwun site and thus estimate a low-cost mitigation potential at approximately 1.1 kt N_2O/a or 0.3 Mt CO_2e / a (i.e. approximately 20 % of Australia's 2020 N_2O emissions from nitric acid production).

2.2 Canada

2.2.1 Canada summary

In Canada, approximately 0.8 million tonnes of nitric acid were produced in 2020. Key N_2O mitigation policies include a carbon tax. All plants are equipped with abatement technologies. Average specific N_2O emissions were at about 0.8 kg/ tonne of nitric acid. Compared to emission intensity benchmarks achievable by ambitious mitigation policies as the EU ETS, Canadian N_2O mitigation potentials are estimated at 20-65 %. A 2022 retrofit of existing abatement in one plant achieved a reduction of 25 % compared to 2020 emissions.

Table 5: Country Profile Canada

	Nitric Acid	Adipic Acid	Caprolactam
Number of facilities	8	-	-
Relevant climate policies	Canadian Environmental Protection Act Greenhouse Gas Pollution Pricing Act		
N_2O Abatement Technologies in Place	All plants are equipped with abatement technologies	-	-
Annual Production (2020)	0.8 Mt HNO_3	None since 2009	-
Annual N_2O emissions (2020)	0.6 kt N_2O / 0.2 Mt CO2e	-	-
N_2O emissions uncertainty estimate	~1 %	-	-
Specific N_2O emissions (2020)	0.8 kg N_2O/t		
N_2O mitigation potential	Gap to emission intensity benchmark of ambitious mitigation policy: ~20-65% 0.15-0.4 kt N_2O/a ~0.05-0.1 Mt CO_2e/a Achieved mitigation by 2022 (upgrade of existing abatement technology): ~25 % 0.15 kt N_2O/a ~0.04 Mt CO_2e/a	-	-

Note: N_2O amounts converted into CO_2 equivalents using the GWP of 265 as set out in the 5th IPCC Assessment Report (AR5)
Sources: Canada 2022, Environment and Climate Change Canada 2022, own calculations of Öko-Institut

2.2.2 Presence of N_2O-emitting chemical industries

In Canada, nitric acid production is taking place at five locations with a total of eight production lines (Environment and Climate Change Canada 2022): Out of those eight facilities, seven are operating with a high-pressure technology design, one uses a dual pressure production process.

Six out of seven high-pressure production lines are equipped with tertiary NSCR abatement technology (Environment and Climate Change Canada 2022). Until 2022, the two remaining lines, one high-pressure, one dual pressure, both operated by Orica Canada Inc. used process-gas catalytic reduction (PGCD). PGCD is a secondary abatement measure that consist of catalysts installed underneath the ammonia burner that catalyse the N_2O formed during the ammonia oxidation reaction. According to Orica (2022), one of those facilities was revamped with tertiary N_2O abatement in 2022, however, the report does not indicate which production line was retrofitted.

Table 6 provides a list on current and decommissioned nitric acid facilities in Canada, including their process type, abatement technology and operation years between 1990 and 2020.

Table 6: Overview on current and decommissioned nitric acid facilities in Canada

Company	Production Lines	Process Type	Abatement Technology	Start of Operation	End of Operation
Agrium Inc.	1	HP	NSCR	Before 1990	-
Cominco Inc.	*1*	*DP*	*None*	*Before 1990*	*1994*
Cyanamid Canada	*1*	*HP*	*NSCR*	*Before 1990*	*1990*
Dyno Nobel Nitrogen Inc.	*3*	*HP*	*NSCR*	*Before 1990*	*2010*
Koch Fertilizer Canada, ULC	3	HP	NSCR	1)Before 1990 2)1994 3)1997	-
Orica Canada Inc. (Carseland, AB)	2	1) DP 2) HP	1) PGCD since 2008 2) PGCD since 2012[a]	1) Before 1990 2) 1998	-
Orica Canada Inc. (Beloeil, QC)	*1*	*HP*	*NSCR*	*Before 1990*	*1999*
Terra International (Canada) Inc.	1	HP	NSCR	Before 1990	-
Yara Belle Plaine Inc.	1	HP	NSCR	2004	-

Notes: HP: High Pressure, DP: Dual Pressure, NSCR: Non-selective catalytic reduction, PGCD: Process-gas catalytic decomposition
Facilities in italics are no longer in operation.
[a]: According to Orica (2022), one of the lines at Carseland was retrofitted with tertiary N_2O abatement in 2022. The report does not indicate which line was retrofitted.
Source: Own representation after Environment and Climate Change Canada 2022; Orica 2022

There is one adipic acid facility in Ontario, but the plant has not produced adipic acid since the spring of 2009. No caprolactam production is taking place in Canada (Environment and Climate Change Canada 2022).

2.2.3 Policies affecting N_2O emission levels

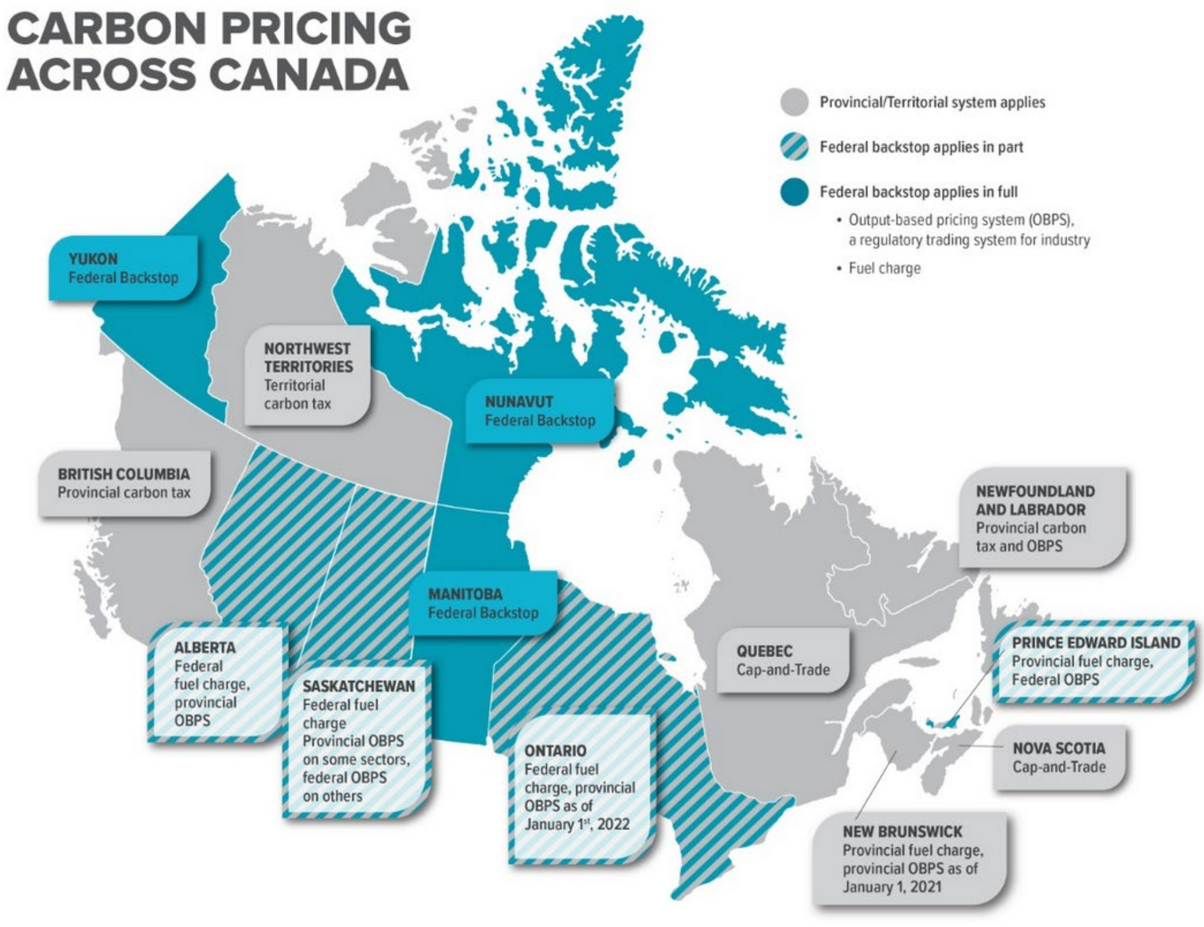
N_2O emissions were first targeted in Canada by the Canadian Environmental Protection Act, from 1999[8], where N_2O is included in the list of toxic substances whose release should be controlled.

The Greenhouse Gas Pollution Pricing Act, from 2018[9], has two parts: a fuel pricing system, and an output-based pricing system. The latter is targeting greenhouse gas emissions from the industry and is explicitly formulated to cover greenhouse gases in CO_2e. The exact implementation is differing

[8] last amended in 2021, https://laws-lois.justice.gc.ca/PDF/C-15.31.pdf
[9] last amended in 2022, https://laws-lois.justice.gc.ca/PDF/G-11.55.pdf

among Canadian provinces and territories, but the act implies that the federal policies apply if no regional policy is in place. Nitrous oxide is covered under most schemes (Sawyer et al. 2021).

Figure 1: GHG emission pricing in Canada



Source: Canadian Government https://www.canada.ca/en/environment-climate-change/services/climate-change/pricing-pollution-how-it-will-work.html

2.2.4 N_2O abatement in place

All eight currently operating nitric acid producing lines in Canada are equipped with abatement technologies. As Table 6 shows, six plants with a high-pressure design have a NSCR abatement technology in place. One high pressure plant uses a secondary process-gas catalytic decomposition (PGCD) abatement process, which has a higher N_2O emission factor than the NSCR technology, installed in 2012. One nitric acid plant in Canada has a dual pressure design and uses a PGCD abatement system for N_2O. This abatement system was installed in 2008 (Environment and Climate Change Canada 2022). According to company information (Orica 2022), one of the plants with a PGCD abatement system was upgraded to tertiary abatement in 2022, now achieving abatement rates of 95% compared to no abatement. The available information does not indicate, however, whether the upgraded facility was the high pressure or the dual-pressure plant.

2.2.5 N_2O emissions

Emissions from nitric acid production in Canada have seen a strong decline between 2000 and the early 2010 years. In 2008 and 2012, respectively, two lines were equipped with process-gas catalytic decomposition abatement technologies, effectively reducing the amounts of N_2O emissions (Environment and Climate Change Canada 2022). One of those lines was additionally retrofitted with tertiary NSCR abatement in 2022. Furthermore, one plant was decommissioned at the end of 2010, leading to a reduction of production and consequently emissions.

Table 7: N_2O emissions from Canadian nitric acid production

	nitric acid production	N_2O emissions of nitric acid production	
	million tonnes (100% nitric acid)	kt N_2O	kg N_2O / t nitric acid
	reported by Canada to UNFCCC		
2000	1.09	4.0	3.6
2005	1.18	4.0	3.4
2010	0.89	1.6	1.8
2015	0.90	0.8	0.8
2016	0.93	0.9	0.9
2017	0.86	0.8	1.0
2018	0.97	0.9	0.9
2019	0.97	0.8	0.9
2020	0.81	0.6	0.8

Source: Canada (2022), own calculations of Öko-Institut

According to Environment and Climate Change Canada (2022), for the period of 2010-2020, mostly facility-level production data was used together with plant-specific emission factors or data from emission monitoring systems (Tier 3). Only for shorter time periods where a Tier 3 method could not be applied due to lack of data, technology-specific emission factors were applied. The uncertainty of N_2O emissions from nitric acid production in the Canadian Inventory is indicated with 0.8 % to 1 % for the period of 2012-2020 where the emission factors were the largest contributors to the uncertainty, while available information on production is considered to be of high data quality (Environment and Climate Change Canada 2022).

2.2.6 N_2O mitigation potentials

Canadian specific emissions in 2020 of ~ 0.8 kg N_2O/t nitric acid are in the range of European levels, albeit at the higher end.

Benchmarks for emission intensities achievable by ambitious mitigation policies can be derived from the EU-ETS in the range of 0.43 kg/t as EU-ETS average, 0.26 kg/t as average of the top half of EU-ETS or 0.6 kg/t for the bottom half of EU-ETS participants (see Annex I).

These EU-ETS benchmarks for emission intensities are at ~20-65% of present Canadian emission intensities. Benchmark-based top-down mitigation potentials for N_2O from Canada's nitric acid production add up to ~0.1 – 0.4 kt N_2O/a or ~ 0.05-0.1 Mt CO_2e/a (GWP AR5).

In a bottom-up perspective focussing on plants without any present N_2O abatement, however, there would be no additional mitigation potential as all plants are equipped with either secondary or tertiary N_2O abatement.

Nevertheless, there are two facilities which, according to Environment and Climate Change Canada (2022), were not equipped with NSCR abatement technologies in 2020 and thus the most probable candidates for further emission reductions. According to company communication (Orica 2022), one of those plants was retrofitted with a tertiary abatement in 2022, achieving emission reduction levels of 95 % compared to no abatement. We estimate the achieved additional emission reduction at ~0.15 kt N_2O/a or 0.04 Mt CO_2e/a or about 25 % of current Canadian N_2O emissions from nitric acid production.

There is thus only one nitric acid production line in Canada which is not equipped with tertiary N_2O abatement. However, this plant nonetheless has secondary PGCD, and the additional mitigation potential of retrofitting also that plant with tertiary abatement could possibly lead to additional emission reductions of approximately 0.1 kt N_2O/a or 0.03 Mt CO_2e/a or about 15 % of current Canadian N_2O emissions from nitric acid production.

2.3 Chile

2.3.1 Chile summary

In Chile, approximately 0.3 million tonnes of nitric acid were produced in 2020. No mitigation policies targeted at N_2O emissions from Chemical industry were identified for Chile. Secondary catalysts are partly installed at two out of three nitric acid facilities. Average specific N_2O emissions were at about 1.0 kg/tonne of nitric acid. Additional N_2O mitigation potentials are estimated at ~55 %.

Table 8: Country Profile Chile

	Nitric Acid	Adipic Acid	Caprolactam
Number of facilities	3 lines / 1 location	-	-
Relevant climate policies	No active policies targeting N_2O from the chemical industry. Carbon tax targets NO_x on stationary sources		
N_2O Abatement Technologies in Place	Secondary catalysts partly installed, partly unclear	Not applicable	Not applicable
Annual Production (2020)	~0.3 Mt	-	-
Annual N_2O emissions (2020)	0.3 kt N_2O 0.1 Mt CO_2e	-	-
N_2O emissions uncertainty estimate	~3 %	-	-
Specific N_2O emissions (2020)	1.0 kg N_2O/t		
N_2O mitigation potential	Gap to emission intensity benchmark of ambitious mitigation policy ~40-75% 0.1-0.2 kt N_2O/a ~0.05 Mt CO_2e/a 'Low-hanging-fruit' potential in unabated plants[10]: ~0.3 kt N_2O/a ~0.9 Mt CO_2e/a		

Note: N_2O amounts converted into CO_2 equivalents using the GWP of 265 as set out in the 5th IPCC Assessment Report (AR5)
Source: Ministerio del Medio Ambiente (2022), Enaex (2022), New Climate Institute (2022)

2.3.2 Presence of N_2O-emitting chemical industries

In Chile, the production of nitric acid takes place, mostly linked to the production of explosives for the mining industry and fertilizers. Production of adipic acid and caprolactam, however, does not occur. While data for nitric acid production are not publicly available for Chile, numbers for emissions from nitric acid production in the 5th Chilean Biennial Update Report (Ministerio del Medio Ambiente 2022) show rising values until about 2009, which are sinking and remaining on a fairly constant level after that. These numbers suggest that production levels have been increasing, before consolidating

[10] The potential determined here is for the installation of a tertiary abatement system at the Panna 1 facility of ENAEX. However, according to Enaex (2022), this facility was not in operation in 2021.

while abatement measures have been put in place. Information from UNFCCCs CDM registry[11] also supports these assumptions.

Available information from the company ENAEX S.A (Enaex 2022). lists plants at one location, with a total of three production lines[12]. Two facilities, *Panna 3* and *Panna 4* at the *Prillex* plant, have abatement mechanisms in place which are registered as CDM projects (Republic of Chile 2014; CDM Executive Board 2014). Table 9 lists installed nitric acid production capacities for the three facilities of the Prillex plant. Another CDM project for catalytic N_2O destruction at the Panna 1 plant is listed in the CDM database. However, the report by the company only lists Panna 3 and 4 as facilities with an abatement mechanism and information in Ministerio del Medio Ambiente (2020) supports this information.

Table 9: Yearly nitric acid production capacities for the ENAEX Prillex Plant

	Installed Production Capacity [kt HNO_3 per year]
Panna 1	47
Panna 3	338
Panna 4	328
Sum	713

Source: CDM Executive Board (2006), CDM Executive Board (2014), Republic of Chile (2014)

2.3.3 Policies affecting N_2O emission levels

Chile has introduced a carbon tax in 2014[13]. This tax targets CO_2 emissions as well as local contaminants (PM, SO_2 and NO_x) on stationary sources and NO_x on new cars.

Chile however has no policies in place explicitly targeting N_2O emissions and according to official documents, none are currently planned[14].

Private companies are nonetheless investing in climate friendly production facilities to participate for example in initiatives like the Dow Sustainability index. (Enaex 2022)

CDM measures are implemented at two facilities of one nitric acid production plant in Chile. (Source CDM database).

2.3.4 N_2O abatement in place

At the facilities Panna 3 and Panna 4 at the Prillex Location of the company ENAEX, there are N_2O abatement systems (secondary catalytic N_2O destruction) in place, which have been supported by CDM measures (Source: CDM database, Enaex (2022)). These abatement systems reduce, on

11 https://cdm.unfccc.int/Registry/index.html

12 The company lists more locations and facilities; however, the report does not explicitly detail the type of the facilities and their production types. For this report, they are thus not included in the list of nitric acid production sites.

13 https://icapcarbonaction.com/en/news/chile-publishes-climate-change-framework-law-paving-way-market-based-policy

14 Sources: New Climate Institute (2022), Ministerio del Medio Ambiente (2022), Ministerio del Medio Ambiente (2021), IEA - International Energy Agency (2018), Republic of Chile (2014), OECD Publishing (2018))

average, 90% of the potential emissions. Another CDM project for catalytic N_2O destruction at the Panna 1 plant is listed in the CDM database[15]. However, the report by the company only lists Panna 3 and 4 as facilities with an abatement mechanism and information in Ministerio del Medio Ambiente (2020) also supports the assumption that only two out of three production lines are equipped with abatement technologies.

2.3.5 N_2O emissions

Table 10 provides an overview on emissions from nitric acid production in Chile from different sources, mainly Ministerio del Medio Ambiente (2020) and Enaex (2022).

The most reliable data and the longest available time series on emissions from nitric acid production in Chile is provided in the Chilean GHG inventory in the 5th Biennial Report to the UNFCCC (Ministerio del Medio Ambiente 2022) and the National Inventory Report (Chile 2020; Ministerio del Medio Ambiente 2020). The emissions are provided in kt N_2O. The National Inventory Report lists Tier 3 as method for determination of emissions in CRF category 2.B.2. for projects under CDM (and thus starting in 2008) and use of a country specific emission factor for years without continuous monitoring and for the fraction of production not under CDM required monitoring. This means that the information on a substantial part of the nitric acid production after 2008 is of good quality. Ministerio del Medio Ambiente (2020) indicates that the uncertainty of N_2O emissions from nitric acid production in the Chilean Inventory is of ~3 % for this period.

The company ENAEX, which produces nitric acid in Chile, provides a GHG report (Enaex 2022) and lists emissions in CO_2e (based on AR4 GWP) for both direct and indirect emissions from their plants as well as information about emission reductions from N_2O abatement technologies. The report is certified by an independent auditor, providing a reasonable level of confidence about the data contained within. Unfortunately, the report does not give detailed information on the different types of direct emissions from the different facilities (not all of which actually produce nitric acid), so the exact level of emissions from nitric acid productions cannot be derived from the data. Furthermore, the company describes on their website[16] that the emissions intensity rate for nitric acid production has been decreasing from 4.3 t CO_2e/t nitric acid in 1982 (~14.4 kg N_2O / t HNO_3[17]) to about 0.3 t CO_2e/t nitric acid in 2020 (~1.0 kg N_2O / t HNO_3), due to the installation of abatement technologies and energy efficiency gains. These values are in line with those given in Ministerio del Medio Ambiente (2020).

Table 10: N_2O emissions from Chilean nitric acid production

	N_2O emissions from nitric acid production				Nitric acid production in Chile
	Reported by Chile to UNFCCC		Reported by ENAEX		Reported in Ministerio del Medio Ambiente (2020)
	kt N_2O	kg N_2O / t HNO_3	kt N_2O	kg N_2O / t HNO_3	Mt HNO_3 (100%)
2000	1.7	n.a.	n.a.	n.a.	0.2
2005	2.8	n.a.	n.a.	n.a.	0.3
2010	0.5	1.52	n.a.	n.a.	0.5
2015	0.9	1.48	n.a.	n.a.	0.6

15 The crediting period under the CDM for this project has expired. (CDM Executive Board 2006).
16 https://www.enaex.com/cl/us/environment/
17 Recalculation by Öko-Institut, assuming the GWP AR4 of 298, also used by ENAEX in Enaex (2022).

2016	0.6	1.10	n.a.	n.a.	0.6
2017	0.8	1.40	0.8	n.a.	0.5
2018	0.3	0.46	0.6	n.a.	0.6
2019	n.a.	n.a.	2.7	n.a.	n.a.
2020	n.a.	n.a.	0.3	1.0	0.3[18]

Notes: n.a.: not available; N_2O emissions were partly recalculated from CO_2e [GWP AR4] by Öko-Institut.
Sources: Ministerio del Medio Ambiente (2022), Enaex (2022), own calculations of Öko-Institut

2.3.6 N_2O mitigation potentials

Benchmark

Chilean specific emissions of ~ 1.0 kg N_2O/t nitric acid are close to the range of European levels, albeit at the higher end. Benchmarks derived from the EU-ETS countries would be 0.43 kg/t as EU-ETS average, 0.26 kg/t as average of the top half of EU-ETS or 0.6 kg/t for the bottom half of EU-ETS participants (see Annex I).

These EU-ETS benchmarks are at ~40-75% of present Chilean emission intensities. Respective mitigation potentials for N_2O from Chile's nitric acid production add up to ~0.1 – 0.2 kt N_2O/a or ~ 0.03-0.0.06 Mt CO_2e/a (GWP AR5).

Specific analysis

From information in Ministerio del Medio Ambiente (2020) and Enaex (2022), it can be concluded, that the Panna 1 facility of the ENEAX Prillex nitric acid plant is the only one not using abatement technology for N_2O emissions. Under the CDM, a project description for an abatement system for this facility is listed (CDM Executive Board 2006). From the information in the CDM database, the planning and implementation status of this project remains unclear. Since, however, calculations and planning have already been established for this facility, the installation of an abatement system can be considered as having a low inhibition threshold. From CDM Executive Board (2006), the yearly emission reduction potential for the installation of a tertiary NSCR abatement at the Panna 1 facility is of 76 489 t CO_2e or about 0.3 kt N_2O. It has to be noted that, according to Enaex (2022), there was no nitric acid production at Panna 1 in 2021. From the available data, it cannot be concluded if this facility will be operating in the future, and under which conditions this operation will take place.

[18]Calculated based on emissions and emission factors in Enaex (2022).

2.4 European Union

2.4.1 European Union summary

After the United Kingdom's withdrawal from the European Union in 2020, the EU consists of 27 Member States: Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain and Sweden.

Production of nitric acid, adipic acid and caprolactam takes place in the EU. Key N_2O mitigation policies include the cap-and -trade EU emissions trading scheme (EU-ETS) for both nitric and adipic acid production. No effective EU-wide mitigation policy applies to caprolactam production.

Approximately 18 million tonnes of ***nitric acid*** were produced in 2020. The use of N_2O abatement is widespread. Average specific N_2O emissions were at about 0.5 kg/ tonne of nitric acid. Additional N_2O mitigation potentials are estimated at ~30 %.

Approximately 0.25 million tonnes of ***adipic acid*** were produced in 2020. The use of N_2O abatement is widespread. Average specific N_2O emissions are available only for Italy at about 4 kg/ tonne of adipic acid. Given very high reductions already achieved, no additional N_2O mitigation potential is estimated for EU adipic acid production. Approximately 1 million tonnes of ***caprolactam*** were produced in 2020. The use of N_2O abatement differs strongly in type and effectiveness between plants. Average specific N_2O emissions are available only for Belgian and Polish plants at about 4 kg/ tonne of caprolactam. Additional N_2O mitigation potentials are at ~50%.

Table 11: Country Profile European Union

	Nitric Acid	Adipic Acid	Caprolactam
Number of facilities	~60 facilities in 19 Member States	5	~10
Relevant climate policies	Inclusion in EU ETS		None
N_2O Abatement Technologies in Place	Widespread application of secondary and/or tertiary abatement measures		Partial application of primary or tertiary abatement measures
Annual Production (2020)	~18 Mt [100% HNO_3]	~0.25 Mt	~1 Mt
Annual N_2O emissions (2020)	9.4 kt N_2O / 2.5 Mt CO_2e	0.9 kt N_2O / 0.25 Mt CO_2e	4.5 kt N_2O / 1.2 Mt CO_2e
N_2O emissions uncertainty estimate	~9 %		
Specific N_2O emissions (2020)	~0.5 kg N_2O/t	Not available for EU27 ~ 4 kg N_2O /t (Italy)	Not available for EU27 ~ 4 kg N_2O/t (Belgium/Poland)
N_2O mitigation potential	~15-50% / ~ 1.5-4.5- kt N_2O/a ~0.4-1.2 Mt CO_2e/a	none	~20-80% / ~ 0.9-4.0- kt N_2O/a ~0.25-1 Mt CO_2e/a

Note: N_2O amounts converted into CO_2 equivalents using the GWP of 265 as set out in the 5th IPCC Assessment Report (AR5)
Sources: European Union 2022a; 2022b, EU Member States' 2022 National Inventory Reports and Common Reporting Format Inventory Tables, FutureCamp Climate GmbH 2022, Öko-Institut calculations

2.4.2 Presence of N_2O-emitting chemical industries

Production of nitric acid takes place in 19 EU Member States, adipic acid is produced in three Member States, Caprolactam in 6 Member States. In total, approximately 60 nitric acid plants, 5 adipic acid plant and 10 caprolactam plants are being operated in the EU (Table 12).

Table 12: Presence of N_2O-emitting chemical industries in EU Member States (2020)

	Nitric Acid Production	Adipic Acid Production	Caprolactam Production
Austria	3 units in 1 plant	-	-
Belgium	8 units in 2 plants	-	1 plant
Bulgaria	2 plants	-	-
Croatia	3 units in 2 plants	-	-
Cyprus	-	-	-
Czech Republic	4 units	-	1 plant
Denmark	-	-	-
Estonia	-	-	-
Finland	3 plants	-	-
France	9 plants	1 plant	-
Germany	9 plants	3 plants	2 plants
Greece	1 unit	-	-
Hungary	2 plants	-	-
Ireland	-	-	-
Italy	2 plants	1 plant	-
Latvia	-	-	-
Lithuania	3 units	-	-
Luxembourg	-	-	-
Malta	-	-	-
Netherlands	5 plants	-	1 plant
Poland	5 plants	-	several units
Portugal	3 plants	-	-
Romania	4 units in 2 plants	-	-
Slovakia	3 plants	-	-
Slovenia	-	-	-
Spain	4 plants	-	1 plant
Sweden	1 plant	-	-

Sources: Austria 2022b; Belgium 2022b; Bulgaria 2022b; Croatia 2022b; Cyprus 2022; Czechia 2022b; Denmark 2022b; Estonia 2022; Finland 2022b; France 2022b; Germany 2022b; Greece 2022b; Hungary 2022b; Ireland 2022b; Italy 2022b; Latvia 2022; Lithuania 2022b; Luxembourg 2022; Malta 2022; Netherlands 2022; Poland 2022b; Portugal 2022; Romania 2022; Slovakia 2023; Slovenia 2022b; Spain 2022b; Sweden 2022b

Note that information provided in the EU Member States' National Inventory Reports as summarised in Table 12 appears to provide a more complete picture than the Union Registry under the EU-ETS: For the EU-ETS only 34 operators in 12 EU Member States are registered in the 'nitric acid production' activity under the EU-ETS (European Commission 2021). It can be concluded that a large share of EU nitric acid installations is probably covered under other EU-ETS activities which may plausibly be the case if nitric acid production facilities are operated under a joint environmental permit with other production facilities.

Nitric acid production levels in the EU Member States have remained rather constant since 1990 (see Table 13). For ***adipic acid*** and ***caprolactam,*** production statistics at EU level are not available.

2.4.3 Policies affecting N_2O emission levels

The EU's major instrument to limit N_2O emissions from ***nitric acid production*** and ***adipic acid production*** is the EU emissions trading scheme (ETS) where these emissions are included since 2013. In the years 2008 – 2012, emission reduction units (ERU) generated in N_2O abatement project under the UNFCCC Joint implementation (JI) scheme had been eligible to be converted into ETS emission certificates. For details related to the functioning of the EU-ETS, including monitoring, reporting and verification (MRV) of emissions and benchmarks for free allocation in order to prevent carbon leakage, see FutureCamp Climate GmbH (2022).

The inclusion in the EU-ETS featured a strong economic incentive for operators to deploy effective N_2O abatement, resulting in a steep decline of emissions, as visible in the GHG emission inventories (see Table 13 below).

N_2O emissions from ***caprolactam production*** are not covered by the EU-ETS.

Prior to the EU-ETS, the EU had implemented different legislation affecting all three chemical sectors by means of setting standards for plant licensing: Since 1996 ‚best available techniques' (BAT) have been determined under the IPPC (integrated pollution, prevention and control) Directive which was replaced by the IED Industrial Emissions Directive) in 2010. BAT have been collected in sector-specific BAT reference documents (BREFs). BAT conclusions are to be considered by EU Member States' licensing authorities for operational permits.

However, the BREF exercise had little impact on N_2O emissions in chemical industry, as an assessment in FutureCamp Climate GmbH (2022) concludes:

> *"It is obvious that the adipic acid and caprolactam chapters of the BREFs don't put much importance on N_2O emissions. For adipic acid, this is partly explained by the fact that abatement technologies were already in place at that time. In the case of caprolactam, it seems that production techniques and processes and the resulting N_2O emission levels are so heterogenous that no common sense on adequate BAT was achievable.*
>
> *In the case of nitric acid plants, the IPPC's effectiveness with respect to N_2O abatement seemed limited, too. One of the main reasons was that even the October 2007 deadline for existing installations to comply with BAT N_2O emission levels was in many cases not enforced, partly due to late implementation by member states. It turned out that JI [*Joint Implementation*] and (the expectation of the) inclusion into the EU ETS outpaced the IPPC regulation on the way to N_2O abatement." (FutureCamp Climate GmbH 2022)*.

2.4.4 N_2O abatement in place

Both in ***nitric acid production*** and in ***adipic acid production***, the use of effective catalytic secondary and/or tertiary abatement is wide-spread in the EU.

For ***caprolactam production***, little information related to employed N_2O abatement measures is available from EU Member States GHG inventories. While Belgium reports primary measures taken and Germany reports on highly effective thermal waste gas treatment, no information is available for plants in Czech Republic, Poland, Netherlands and Spain.

2.4.5 N_2O emissions

EU N_2O emissions from ***nitric acid production*** for 1990-2020 are given in Table 13. As nitric acid production amounts are confidential in some of the Member States, specific N_2O emissions per tonne of nitric acid are not available on EU level. However, production data is available for 17 out of 21 relevant Member states, representing 84 % of the EU's 2020 N_2O emissions from nitric acid production. Using that subset as a proxy, it can be concluded that EU specific N_2O emissions have declined by 93 % from 1990 to 2020, with the major reductions taking effect in the period 2005 – 2015. Total 2020 EU nitric acid production level is estimated at approx. 18 million tonnes.

Table 13: N_2O emissions from nitric acid production in EU Member States

	N_2O emissions nitric acid production	**nitric acid production** million tonnes (100% nitric acid)	**N_2O emissions nitric acid production**	
	kt N_2O	million tonnes (100% nitric acid)	kt N_2O	kg N_2O / t nitric acid
	reported by the EU to UNFCCC	reported by 17 out of 21 relevant EU Member States [a] to UNFCCC		
1990	166.6	15.38	114.3	7.4
1995	146.7	14.05	102.0	7.3
2000	154.1	15.10	108.5	7.2
2005	137.0	15.31	97.4	6.4
2010	40.1	14.05	28.8	2.0
2015	14.8	15.11	11.7	0.8
2016	13.2	14.74	10.6	0.7
2017	12.2	15.70	9.8	0.6
2018	11.4	15.00	9.1	0.6
2019	10.5	15.12	8.6	0.6
2020	9.4	15.09	7.9	0.5

Notes:
a) 17 Member States with available production quantities for the 1990-2020 time series: Austria, Belgium, Croatia, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Lithuania, Poland, Slovakia, Slovenia, Spain, Sweden. Missing EU Member States with Nitric acid production: Bulgaria, Romania, Portugal, Netherlands
Sources: Austria 2022a; Belgium 2022a; Croatia 2022a; Czechia 2022a; Denmark 2022a; Finland 2022a; France 2022a; Germany 2022a; Greece 2022a; Hungary 2022a; Ireland 2022a; Italy 2022a; Lithuania 2022a; Poland 2022a; Slovakia 2022; Slovenia 2022a; Spain 2022a; Sweden 2022a; European Union 2022a, Öko-Institut calculations

In The EU's National Inventory Report (European Union 2022b) the uncertainty of aggregated EU N_2O emission estimates is given as 8.7 % the aggregation level the inventory category 2.B "Chemical Industry", thus combining N_2O emissions from nitric acid production, adipic acid production and caprolactam, glyoxal and glyoxylic acid production. Separate estimates for nitric acid, adipic acid and caprolactam production are not available.

EU N_2O emissions from ***adipic acid production*** for 1990-2020 are given in Table 14. Production levels responsible for the majority of EU emissions are not available in the GHG emission inventories due to confidentiality constraints. For Italy, representing about 30 % of EU's present N_2O emissions from adipic acid production, the time series of average N_2O emission factors is given in Annex II.

Today's emission levels are at below 1 % of 1990 levels, with a steep reduction happening between 1995 and 2010. As demonstrated by the Italian data in Annex II, this reduction pattern is likely to be mostly due to improvements in N_2O abatement rather than changes in production levels.

Total 2020 EU adipic acid production level is estimated at roughly 0.25 million tonnes by extrapolating Italian data.

Table 14: N_2O emissions from adipic acid production in the European Union

	adipic acid production million tonnes	**N_2O emissions adipic acid production,**	
		kt N_2O	**kg N_2O / t adipic acid**
	reported by the European Union to UNFCCC		
1990	C	193.1	C
1995	C	182.8	C
2000	C	42.8	C
2005	C	38.0	C
2010	C	5.1	C
2015	C	1.5	C
2016	C	1.2	C
2017	C	3.6	C
2018	C	1.3	C
2019	C	1.0	C
2020	C	0.9	C

Notes: C: confidential
Sources: (European Union 2022a)

EU N_2O emissions from ***caprolactam production*** for 1990-2020 are given in Table 15. Production levels responsible for the majority of EU emissions are not available in the GHG emission inventories due to confidentiality constraints. For Belgium and Poland, jointly representing about 30 % of EU's present N_2O emissions from adipic acid production, the time series of average N_2O emission factors are given in Annex III.

The EU emissions time series shows little systematic movement, emission levels are at the same order of magnitude as 1990 levels. As Germany reports emissions close to zero due to thermal waste gas treatment (Germany 2022b) and specific emissions given for Belgium and Poland in Annex III, it can be concluded that overall EU trends are largely determined by the emission characteristics of plants in Czech Republic, Netherlands and Spain where information on production amounts and abatement measures is not available.

Total 2020 EU caprolactam production level is estimated at roughly 1 million tonnes by extrapolating Belgian and Polish data.

Table 15: N_2O emissions from caprolactam production in the European Union

	caprolactam production million tonnes	N_2O emissions caprolactam production, kt N_2O	kg N_2O / t caprolactam
	reported by the European Union to UNFCCC		
1990	C	5.2	C
1995	C	5.4	C
2000	C	5.9	C
2005	C	6.0	C
2010	C	7.0	C
2015	C	6.5	C
2016	C	6.1	C
2017	C	5.9	C
2018	C	5.5	C
2019	C	5.2	C
2020	C	4.5	C

Notes: C: confidential
Sources: (European Union 2022a)

2.4.6 N_2O mitigation potentials

For ***nitric acid production***, the weighted average emission factor available for the sum of 17 Member States representing 84 % of present EU N_2O emissions from that sector is 0.52 kg N_2O/t, which is approximately 15 % above the benchmark of 0.43 kg/t derived for the average EU-ETS members in Annex I. (The EU-ETS benchmark is lower than the available EU average, as the data for UK and Norwegian plants with particularly low specific emissions were considered for the EU-ETs benchmark, as well.) An alternative benchmark derived from the top 50% of EU-ETS plants is at 0.26 kg/t (see Annex I).

N_2O mitigation potentials for EU nitric acid production can thus be estimated at 15 – 50 %, equivalent to ~1.5 – 4.5 kt N_2O/a or ~0.4 – 1.2 Mt CO_2e/a [GWP AR5].

For ***adipic acid production***, N_2O emissions in the EU were drastically reduced in the past. No additional N_2O mitigation potential can be quantified for the European Union.

For ***caprolactam production***, the N_2O mitigation potential is highly uncertain as present specific emissions are not available for the majority of EU caprolactam production. We estimate the mitigation potential for ambitious secondary or tertiary abatements at approximately 20-80% of present N_2O emissions, i.e. ~0.9 – 4.0 kt N_2O/a or ~0.25-1Mt CO_2e/a [GWP AR5].

2.5 Israel

2.5.1 Israel summary

In Israel, approximately 0.2 million tonnes of nitric acid were produced in 2019. N_2O mitigation policies focus on plant-specific emission limit values for N_2O exhaust concentrations. Secondary catalysts had been installed under the CDM in 2007/2008, information on present use is not available. Average specific N_2O emissions were at about 2.5 kg/ tonne of nitric acid. Compared to emission intensity benchmarks achievable by ambitious mitigation policies as the EU ETS, Israeli N_2O mitigation potentials are estimated at ~85 %.

Table 16: Country Profile Israel

	Nitric Acid	Adipic Acid	Caprolactam
Number of facilities	4 lines / 2 locations	-	-
Relevant climate policies	Limits on N_2O exhaust concentrations as part of environmental permits.		
N_2O Abatement Technologies in Place	N_2O abatement was installed under the CDM before 2010. Present ambition of use of mitigation equipment is unclear.	-	-
Annual Production (2020)	Confidential roughly estimated at 0.18 Mt	-	-
Annual N_2O emissions (2020)	~0.4 kt N_2O / ~ 0.12 Mt CO_2e	-	-
N_2O emissions uncertainty estimate	- 50 % / + 300 %		
Specific N_2O emissions (2020)	~2.5 kg N_2O/t		
N_2O mitigation potential	Gap to emission intensity benchmark of ambitious mitigation policy: ~85% / 0.35 kt N_2O/a ~0.1 Mt CO_2e/a		

Note: N_2O amounts converted into CO_2 equivalents using the GWP of 265 as set out in the 5th IPCC Assessment Report (AR5)
Sources: (Israel Ministry of Environmental Protection 2022; Israel 2021), Öko-Institut calculations

2.5.2 Presence of N_2O-emitting chemical industries

In Israel, two nitric acid factories operate four production units, see plant details in Table 17. Production of adipic acid and caprolactam does not take place.

Table 17: Israel nitric acid plant data

Operator	Dshanim ICL	Haifa Group	Haifa Group	Haifa Group
Location	Kiryat Ata	Mishor Rotem	Mishor Rotem	Mishor Rotem
unit name	**unit 38**	**N3**	**N4**	**N5**
Capacity [tonnes/year]	60 000		147 000	
year of operation	~ 1987	~ 1994	~ 1994	~ 2020
date of permit	2016	2016	2016	2015
stack flow rate [Nm³/h] (limited by permit)	28 000	28 000	18 000	51 000

Note: Previous Haifa Group plants N1 and N2 located in Haifa were closed down and replaced by the N5 facility of Mishor Rotem
Sources: (Israel Ministry of Environmental Protection 2022), (Archipetrol 2022)

2.5.3 Policies affecting N_2O emission levels

The operation of nitric acid plants in Israel is subject to environmental permits to be issued by a centralised authority in the main office of the Israel Ministry of Environmental Protection (Israel Ministry of Environmental Protection 2022). Permits include limitation for the emissions of nitrous oxide (N_2O). The permits are issued individually, and emission limit values are given within the range of emissions limit values from the corresponding European Union reference document on Best Available Techniques (BREF)[19]: in the case of nitric acid the corresponding BREF is LVIC-AAF[20] (Large Volume Inorganic Chemicals – Ammonia, Acids and Fertilisers). Plant-specific technical constraints are being considered for the permits. Emission limit values (ELVs) for N_2O are given as N_2O concentration limit values, expressed as mg N_2O / Nm³, averaged for the primary catalyst[21] lifespan, but no more than 4 months. Such plant-specific ELVs range between 200 mg/Nm³ for the newest pant and 600 mg/Nm³ for the oldest. Some permits include an additional limitation of 800 mg/Nm³ for any half-hour (Israel Ministry of Environmental Protection 2022), furthermore stack flow rates are limited. 2022 N_2O emissions in line with the environmental permits can thus be calculated not to exceed a total of 0.47 kt N_2O (see Table 18) or 0.12 Mt CO_2e (GWP AR5).

[19] For further information on EU policies, see section 2.4.
[20] https://eippcb.jrc.ec.europa.eu/reference/large-volume-inorganic-chemicals-ammonia-acids-and-fertilisers
[21] The primary catalyst used to produce NO as intermediate step in the nitric acid production is referred to for the ELV. There is no formal obligation to deploy a secondary catalyst especially for N_2O mitigation.

Table 18: Israeli plant-specific emission limit values for N_2O from nitric acid production

Operator	Dshanim ICL	Haifa Group	Haifa Group	Haifa Group
Location	Kiryat Ata	Mishor Rotem	Mishor Rotem	Mishor Rotem
unit name	**unit 38**	**N3**	**N4**	**N5**
ELV in force as of 2022 [mg N_2O / Nm^3], average for primary catalyst lifespan (max 4 months)	600	580	580	200
stack flow rate [Nm^3/h] (limited by permit)	28 000	28 000	18 000	51 000
Calculated limit to 2022 annual emissions [t N_2O] (ELV * stack flow rate * 8760 h/a)	147	142	91	89

Source: (Israel Ministry of Environmental Protection 2022), Öko-Institut calculations

Since 2004, Israel actively participated in the Clean Development Mechanism (CDM) under the UNFCCC. The majority of Certified Emission Reductions (CER) issued for Israeli projects were directed to projects that reduce N_2O emissions from nitric acid production. Due to the collapse in international CER prices, coupled with high costs associated with verification of emission reductions and issuance of CERs, the vast majority of Israeli CDM projects are not currently requesting issuance of credits, and CERs issued to Israeli projects pertain almost exclusively to the 2008 – 2012 Kyoto Protocol 1 period (Israel 2015). Since 2004, Israel actively participated in the Clean Development Mechanism (CDM) under the UNFCCC. (Israel 2015)

The latest available National Communication of Israel under the UNFCCC (3rd NC, 2018) does not mention any further policies targeting N_2O emissions from industry (Israel 2018).

2.5.4 N_2O abatement in place

N_2O ELVs in the permits are set based on N_2O exhaust concentration which can be obtained by primary measures, i.e. optimised operation of the main NO catalyst. The ELV oblige operators to exchange the main catalyst every 3-5 months. (Israel Ministry of Environmental Protection 2022)

Under the CDM, however, all Israeli nitric acid plants had been equipped with secondary N_2O catalysts in the 2007- 2013 period (see 2.5.3).

Little information is available to what extent secondary N_2O catalysts are still being used after the collapse of CER prices and after relocation of some of the nitric acid plants from Haifa Bay to Mishor Rotem[22]: According to industry information, however, a refurbishment of two of the Mishor Rotem plants, including secondary catalytic N_2O abatement facilities, was commissioned in 2018 (KBR 2018).

[22] The Haifa Bay plants had participated in the CDM (UNFCCC 2023). However, that plant was closed and replaced by the N5 plant (see Table 7) in Mishor Rotem in Negev desert.

2.5.5 N_2O emissions

Information on actual N_2O emissions from Israeli nitric acid plants is strongly diverging between two different sources, i.e. on one hand the Israeli Greenhouse Gas Emissions Inventory submitted to the UNFCCC (Israel 2021) and on the other hand the Israeli Pollutant Release and Transfer Register (PRTR)[23] data provided by the Israel Ministry of Environmental Protection (Israel Ministry of Environmental Protection 2022):

Respective data is given in Table 19. The Israeli GHG inventory is calculated by the Central Bureau of Statistics (CBS) according to IPCC default emission factors. However, for the Israeli GHG inventory, no documentation of applied estimation methodologies is available[24]. The PRTR database is operated by the Ministry of Environmental Protection. In the context of this study, it has not been possible to fully clarify the diverging data sets and assess potential over- or underestimates in any of these data sources. It appears likely, however, that PRTR data are measurement-based and thus more accurate than the inventory data. Therefore, we base our conclusions in this study primarily on the PRTR data.

Table 19: N_2O emissions from Israeli nitric acid production

	Data source: PRTR kt N_2O	Data source: GHG inventory kt N_2O	Deviation factor: GHG inventory / PRTR
2012	0.51	2.70	5.3
2013	0.46	2.59	5.7
2014	0.46	2.73	5.9
2015	0.45	2.53	5.6
2016	0.55	2.56	4.7
2017	0.20	0.85	4.1
2018	0.42	1.32	3.1
2019	0.42	1.31	3.1
2020	0.44	not available	not applicable

Sources: (Israel Ministry of Environmental Protection 2022; Israel 2021), Öko-Institut calculations

GHG inventory emission estimates since 2012 have been three to six times higher than PRTR estimates. If the emission factors applied by the CBS for the inventory calculation can be assumed to be constant over time, the declining trend in that deviation factor (right-hand column of Table 19) could be interpreted that the average emission intensity of Israeli nitric acid production has almost doubled between 2014 and 2019. This would be a plausible effect of less ambition in the operation of existing N_2O abatement facilities after the collapse of CER prices.

It should be noted that 2018-2020 PRTR emissions data (0.42 – 0.44 kt N_2O/a) are in the order of magnitude to the 2022 N_2O emission limit of the environmental permits (0.47 kt N_2O, see 2.5.3 / Table 18).

23 https://www.gov.il/en/departments/topics/prtr/govil-landing-page

24 The UNFCCC obligation to annually submit standardised GHG inventory datasets (CRF) and inventory reports (NIR) is limited to UNFCCC parties listed in Annex I of the convention. The 2021 Israeli GHG inventory submission (Israel 2021) was made on a voluntary basis.

Given the strongly diverging data source on N_2O emissions from Israel nitric acid production, we estimate the uncertainty of the emission estimate at -50% / + 300 %.

2.5.6 N_2O mitigation potentials

Given the deviating N_2O emission estimates (Table 19) and confidential nitric acid production amounts, mitigation potential can only very roughly be estimated, subject to high uncertainties: Assuming a nitric acid production capacity of approximately 0.2 million tonnes per year (Table 17), a 85% capacity use and N_2O emission estimates based on PRTR (Table 19), 2020 average specific N_2O emissions per ton of nitric acid are estimated at 2.5 kg/t.

Benchmarks for emission intensities achievable by ambitious mitigation policies can be derived from the EU-ETS in the range of 0.43 kg/t as EU-ETS average, 0.26 kg/t as average of the top half of EU-ETS or 0.6 kg/t for the bottom half of EU-ETS participants (see Annex I).

These EU-ETS benchmarks are at ~10-25% of present Israeli emission intensities as estimated above. Respective mitigation potentials for N_2O from Israel's nitric acid production add up to ~0.35 kt N_2O/a or ~ 0.1 Mt CO_2e / a (GWP AR5).

Data is not available to support a bottom-up estimate for N_2O mitigation from presently unabated plants.

2.6 Japan

2.6.1 Japan summary

Japan did achieve high abatement rates for ***adipic acid*** production, its historically most relevant N_2O emission source from chemical industry. N_2O emissions from ***nitric acid*** and ***caprolactam*** production add up to residual emissions from adipic acid production. Both nitric acid and caprolactam production industries appear to be incompletely equipped with N_2O abatement technologies. No specific mitigation policies targeted at N_2O emissions from Chemical industry were identified for Japan. Compared to emission intensity benchmarks achievable by ambitious mitigation policies as the EU ETS, Japanese N_2O mitigation potentials are estimated at 80-90 % for nitric acid and 70% for caprolactam production. Easy-to-achieve mitigation potentials in so far unabated nitric acid and caprolactam plants sum up to about 0.6 kt N_2O/a (~0.15 Mt CO_2/a) equivalent to ~30 % of Japan's 2020 N_2O emissions from chemical industry.

Table 20: Country Profile Japan

	Nitric Acid	Adipic Acid	Caprolactam
Number of facilities	10	1	3 (one of those announced to be closed in October 2022)
Relevant climate policies	No active policies targeting N_2O emissions from chemical industry. Under the "J-credits" baseline & credit scheme, no approved methodology is available for N_2O abatement in chemical industry.		
N_2O Abatement Technologies in Place	Catalytic decomposition units at least partly in use (estimated at 75 % of capacity)	N_2O decomposition unit installed 1999	abatement units at least partly in use (estimated at 80 % of capacity)
Annual Production (2020)	0.23 Mt [100% HNO_3]	not available (~0.17 Mt/a production capacity)	0.2 Mt
Annual N_2O emissions (2020)	0.7 kt N_2O / 0.2 Mt CO_2e	1.1 kt N_2O / 0.3 Mt CO_2e	0.4 kt N_2O / 0.1 Mt CO_2e
N_2O emissions uncertainty estimate	73 %	9 %	99 %
Specific N_2O emissions (2020)	3.0 kg N_2O/t	Not available	2.0 kg N_2O/t
N_2O mitigation potential	Gap to emission intensity benchmark of ambitious mitigation policy: ~80-90% / 0.5-0.6 kt N_2O/a ~0.15 Mt CO_2e/a 'low-hanging fruit' potential in unabated plants: ~50% / 0.35 kt N_2O/a ~0.1 Mt CO_2e/a	Low - (high abatement achieved)	~70% 0.3 kt N_2O/a ~0.07 Mt CO_2e/a

Note: N_2O amounts converted into CO_2 equivalents using the GWP of 265 as set out in the 5th IPCC Assessment Report (AR5)
Sources: (Japan 2022a; 2022b), (Sumitomo Chemical 2022; ICIS 2007; METI 2022a) own calculations of Öko-Institut

2.6.2 Presence of N_2O-emitting chemical industries

In Japan, the production of nitric acid, adipic acid and caprolactam takes place.

Nitric acid production levels in Japan have been declining in the last decades. Nitric acid production amounts reported for 2020 are at about 0.2 million tonnes, which is approximately 40 % below 2015 levels (0.4 Mt), 55 % below 2010 levels (0.5 Mt) or 65 % below 2000 levels (0.7 Mt), see Table 21. Ten nitric acid facilities are operated in Japan. The main processes used in nitric acid production are the New Fauser Process (medium pressure) and Chemico Process (high pressure), both based on the Ostwald chemical process (Japan 2022b).

Also, ***caprolactam production*** in Japan is declining. In 2020, production levels (0.2 million tonnes) were approximately at 50 % of 2010 levels, or at about one third of production levels in 2000 (see Table 23). In 2020, Caprolactam was produced in three facilities. However, Sumitomo have announced to close their Ehime plant in Oct 2022 and exit the business (Sumitomo Chemical 2022).

Japanese production capacities for ***adipic acid*** were reported to be 172 kt/a in 2007 in two plants (170 kt/a and 2 kt/a) (ICIS 2007; IPCC 2000). In 2020, however, only one adipic acid plant existed in Japan (Japan 2022b). Information on actual production levels is not publicly available.

2.6.3 Policies affecting N_2O emission levels

Japan does not deploy policies targeting N_2O emissions from chemical industry.

The Japanese Carbon Tax does not cover N_2O emissions (Gokhale 2021). Also the existing regional ETS schemes in Japan (Tokyo & Saitama) are limited in scope to CO_2 and do not cover N_2O emissions (ICAP 2022).

Among the climate-related policies and measures presented by Japan in its 4th Biennial Report to the UNFCCC (Japan 2019) as affecting N_2O emissions, the promotion “J-credit” scheme is the only one which could possibly apply to N_2O from chemical industry: J-credits are issued since 2013 under a baseline-and-credit scheme for domestic projects and can be sold to the voluntary market and for corporate social responsibility (CSR) activities. However, until January 2022, no specific methodology has been approved which would allow the generation of J-credits for N_2O abatement in chemical industry: approved methodologies in the industry sector have so far been limited to N_2O emission abatement in the anaesthetics sector and to emission abatement of fluorinated greenhouse gases (METI 2022a). The same limitation as to approved methodologies applies to the Japanese Domestic CDM scheme, the J-credits’ predecessor until 2012 (METI 2012).

From 2022, the government is also working on the detailed design for the implementation of the Green Transformation (GX) League, a baseline-and-credit system for companies setting voluntary targets. This new mechanism will likely build upon existing carbon trading systems such as J-Credit scheme (ICAP). In February 2022, GX league basic concept was announced by the Japanese Ministry for Economy, Trade and Industry (METI) (METI 2022b), in April 2022 an endorsement by 440 companies representing 28% of Japan’s emissions (38% of emissions in industrial, business and energy conversion sectors) were announced (METI 2022c). Details will still need to be clarified until full-scale operation which is planned for the 2023 fiscal year. Information relating to future participation of chemical industry with N_2O emissions is not yet publicly available.

2.6.4 N_2O abatement in place

For ***nitric acid production***, *catalytic decomposition units are* reported to be *in operation* in the 2022 NIR (Japan 2022b) without giving details on completeness and the past schedule of deployment of N_2O abatement. The time series of average emission factors reported by Japan in the emissions inventory (see Table 21) shows little change since 1990, thus differing from e.g. EU Member States where the introduction of N_2O abatement is reflected by a steep decline in the emission factors. We thus consider it likely that the Japanese nitric acid industry is not fully equipped with N_2O abatement facilities. Considering the average emission intensity of ~ 3-3.5 kg N_2O/ t HNO_3 (Table 21) and approximated emission factors of 8 kg N_2O/t for unabated high or medium pressure plants and 1.5 kg N_2O/t for abated plants we estimate that approximately 25 % of Japanese nitric production capacities are not yet equipped with secondary or tertiary N_2O abatement technologies.

The single Japanese ***adipic acid production*** plant has been equipped with N_2O decomposition equipment in 1999 (Japan 2022b). Effects are clearly visible in the time series of N_2O emissions given in Table 22.

No information is available related to the use of N_2O abatement in the Japanese **Caprolactam production** facilities. Each of the three plant's emission factors are reported to fluctuate (Japan 2022b). Given the time series of specific N_2O emissions reported by Japan to the UNFCCC (Table 23), however, moving slowly from the IPCC default EF (assuming no N_2O abatement) of 9 kg N_2O / t caprolactam in the 1990s to levels of approximately 2-3 kg/t after 2015 gives rise to the assumption that secondary or tertiary N_2O abatement techniques may have been introduced in at least some of the plants. Considering the average emission intensity of ~ 2-2.5 kg N_2O/ t caprolactam (Table 23) and approximated emission factors of 9 kg N_2O/t for unabated plants and 0.6 kg N_2O/t for abated plants we estimate that approximately 20 % of Japanese caprolactam capacities are not yet equipped with secondary or tertiary N_2O abatement technologies.

2.6.5 N_2O emissions

Table 21 presents data reported by Japan related to N_2O emissions from ***nitric acid*** production. There is no visible trend in specific emissions which would hint to a systematic introduction of N_2O abatement techniques.

Table 21: N_2O emissions from nitric acid production in Japan

	nitric acid production million tonnes (100% nitric acid)	**N_2O emissions nitric acid production,** **kt N_2O**	**kg N_2O / t nitric acid**
	reported by Japan to UNFCCC		
1990	0.71	2.5	3.5
1995	0.70	2.5	3.5
2000	0.66	2.6	3.9
2005	0.60	2.5	4.2
2010	0.51	1.8	3.6
2015	0.39	1.4	3.6
2016	0.36	1.3	3.6
2017	0.36	1.2	3.3
2018	0.33	1.1	3.3
2019	0.31	1.0	3.3
2020	0.23	0.7	3.0

Sources: Japan 2022a

Table 22 presents data on N_2O from ***adipic acid*** production in Japan. As production amounts from the single Japanese adipic acid plant are confidential, no time series on specific emissions is available. However, the time series on N_2O emissions clearly shows the effect of the N_2O abatement equipment installed in 1999.

Table 22: N_2O emissions from adipic acid production in Japan

	adipic acid production million tonnes	**N_2O emissions adipic acid production,** **kt N_2O**	**kg N_2O / t adipic acid**
	reported by Japan to UNFCCC		
1990	C	24.2	C
1995	C	24.0	C
2000	C	12.6	C
2005	C	1.7	C
2010	C	1.7	C
2015	C	0.4	C
2016	C	0.5	C
2017	C	0.3	C
2018	C	0.2	C
2019	C	0.3	C
2020	C	1.1	C

Note: C: confidential; Japanese production capacities were reported to be 172 kt/a in 2007 (ICIS 2007). Assuming the use of the IPCC default emission factor of 300 kg/t (appropriate in case of absence of N_2O mitigation) for the 1990-1995 period, production amounts in those years would have been at approximately 80 kt adipic acid per year.
The N_2O decomposition unit installed in 1999 featured a low availability in the year 2000, leading to rather high emissions in that year.
Sources: Japan 2022a; 2022b; ICIS 2007

Table 23 presents production and N_2O emissions data for caprolactam from Japan. Specific emissions reported for 2020 were at 23 % of specific emissions in the 1990s (which had been based on the IPCC default emission factor, assuming no N_2O abatement).

Table 23: N_2O emissions from caprolactam production in Japan

	caprolactam production million tonnes	**N_2O emissions nitric acid production,**	
		kt N_2O	**kg N_2O / t caprolactam**
	reported by Japan to UNFCCC		
1990	0.52	4.7	9.0
1995	0.55	4.9	9.0
2000	0.58	5.2	9.0
2005	0.46	3.4	7.4
2010	0.41	2.6	6.2
2015	0.24	0.9	3.7
2016	0.22	0.5	2.3
2017	0.22	0.5	2.4
2018	0.21	0.4	2.1
2019	0.19	0.5	2.7
2020	0.20	0.4	2.0

Sources: Japan 2022a;

The uncertainty of N_2O Emissions from Chemical Industry reported to the UNFCCC was estimated by Japan in the 2022 National Inventory Report (Japan 2022b) as follows:

- 73 % for N_2O from nitric acid production.
- 9 % for N_2O emissions from adipic acid production
- 99% for N_2O emissions from caprolactam

The methodology applied by Japan to conclude on the rather high uncertainties for N_2O emissions from nitric acid production and caprolactam production employs a calculation of the standard deviation from the emission factors and production amounts of each plant (Japan 2022b). This fact supports our conclusion that the availability and use of N_2O abatement equipment strongly differs between the single nitric acid and caprolactam production facilities.

2.6.6 N_2O mitigation potentials

Nitric Acid Production

Japanese specific emission of ~ 3 – 3.5 kg N_2O / t nitric acid are very high compared to European levels.

Benchmarks for emission intensities achievable by ambitious mitigation policies can be derived from the EU-ETS in the range of 0.43 kg/t as EU-ETS average, 0.26 kg/t as average of the top half of EU-ETS or 0.6 kg/t for the bottom half of EU-ETS participants (see Annex I).

These EU-ETS benchmarks are at ~10-20% of present Japanese emission intensities. Benchmark-based top-down mitigation potentials for N_2O from Japan's nitric acid production add up to ~0.5 – 0.6 kt N_2O/a or ~ 0.15 Mt CO_2e / a (GWP AR5).

In a bottom-up perspective focussing on plants without any present N_2O abatement (estimated 25 % of Japanese production capacity, see 2.6.4) we estimate a low-cost mitigation potential at approximately 0.3 kt N_2O/a or 0.1 Mt CO_2e/a (i.e. approximately 50 % of Japan's 2020 N_2O emissions from nitric acid production).

Adipic Acid:

Adipic acid production used to be the most relevant N_2O emission source in Japanese Chemical industry. After the equipment of the single Japanese plant with a N_2O decomposition unit, only low mitigation potentials remain.

Caprolactam

In Japanese caprolactam production 75% mitigation has been reached compared to the 1990s, probably by equipping ~80 % of the production capacity with N_2O abatement technologies. Ambitious waste gas treatment in the complete set of Japanese caprolactam production facilities might lead to a ~95% reduction or more, equal to an abatement of approx. 70% of today's emission intensity, or 0.3 kt N_2O/a (0.07 Mt CO_2e [GWP AR5]).

However, as one of the three Japanese plants was announced to be closed in October 2022 (Sumitomo Chemical 2022), the factual mitigation potential may be lower.

2.7 Republic of Korea

2.7.1 Korea summary

Nitric acid, adipic acid and caprolactam production are taking place in the Republic of Korea.

For Korea, approximately 1.3 million tonnes of nitric acid were estimated as production in 2020. N_2O abatement technologies, installed under CDM projects, are in place at several facilities. Key N_2O mitigation policies include coverage under the Korean emissions trading scheme (K-ETS) since 2021. Previously, CDM projects were exempted from the K-ETS but CERs generated under the CDM could be sold to K-ETS participants. Average specific N_2O emissions are roughly estimated at about 0.6 kg N_2O/t of nitric acid, 1.7 kg N_2O/ t of adipic acid and 2.3 kg N_2O/ t of caprolactam. Additional N_2O mitigation potentials are thus very limited.

Table 24: Country Profile Republic of Korea

	Nitric Acid	Adipic Acid	Caprolactam
Number of facilities	6	1	1
Relevant climate policies	N_2O emissions from chemical industry are covered under the Korea Emissions Trading Scheme since the 3rd K-ETS phase starting 2021. In K-ETS phases 1 & 2 (2015-2017 / 2018-2020), exemptions for facilities approved under the CDM applied.		
N_2O Abatement Technologies in Place	Yes	Yes	Yes
Annual Production	1.3 Mt in 2020	0.12-0.14 Mt (in 2012)	0.13 Mt (in 2010)
Annual N_2O emissions (2020)	1.15 kt N_2O / 0.3 Mt CO_2e thereof		
	62 %	16 %	22 %
N_2O emissions uncertainty estimate	Not available		
Specific N_2O emissions	~ 0.6 kg N_2O/ t	~ 1.7 kg N_2O/ t	~ 2.3 kg N_2O/ t
N_2O mitigation potential	limited	limited	limited

Note: N_2O amounts converted into CO_2 equivalents using the GWP of 265 as set out in the 5th IPCC Assessment Report (AR5)
Source: The Government of the Republic of Korea (2021), Korea IT Times (2021), ICAP (2023), Republic of Korea (2013), Republic of Korea (2011), own calculations of Öko-Institut

2.7.2 Presence of N_2O-emitting chemical industries

Nitric acid production is taking place in the Republic of Korea. According to international trade statistics, South Korea is the major exporter of nitric acid in Asia (OEC 2020). Table 25 provides an overview on CDM projects at nitric acid producing facilities in the Republic of Korea. Based on the information given in the PDDs (Republic of Korea 2012; 2020; 2021b; 2021a; 2010), the annual production amount of those facilities is at about 1.3 million tonnes nitric acid. All nitric acid production facilities in the Republic of Korea are equipped with N_2O abatement technologies installed under CDM projects.

According to press releases (Korea IT Times 2021; The Korea Economic Daily 21 Apr 2021), is set to increase, with expansions of about 0.8 kt additionally planned until 2024. 90 % of current nitric acid production is generated by Hu-Chems Co (The Korea Economic Daily 21 Apr 2021).

There is one plant by BASF[25] producing ***adipic acid*** in the Republic of Korea in Onsan (BASF 2021). The plant was originally constructed by Rhodia, which implemented N_2O abatement under a CDM project (Republic of Korea 2013). According to the CDM Project Description document, this facility produced 0.1 Mt adipic acid in the year 2012 (see also Table 25). It is possible that the production capacity was changed after the end of the CDM crediting period, however, no information is available on the current production levels or capacity of adipic acid in the Republic of Korea.

There is one facility (Capro Co) producing ***caprolactam*** in the Republic of Korea, with a current production capacity of 270kt/year[26]. According to the CDM Project design document (Republic of Korea 2011), a nitrous oxide abatement technology was installed at 2 out of 3 plants at the site with a production capacity of 128 kt/year and a proposed reduction of N_2O emissions by >90 % (see also Table 25). It remains unclear, whether the third plant has any N_2O abatement technology installed and whether it is still in operation.

Table 25: Approved CDM Projects for N_2O reduction in the chemical industry in the Republic of Korea

CDM Ref #	Target	Company	Location	CERs issued	Estimated annual production [kt / a]
922	Nitric Acid	Hanwha Corporation	Ulsan	2007-2020	107
765	Nitric Acid	Hu-Chems Fine Chemical Corp	Yeosu (Plant 2,3,4)	2007-2020	701
6637	Nitric Acid	Hu-Chems Fine Chemical Corp	Yeosu (Plant 5)	2013-2020	397
1443	Nitric Acid	Dongbu Hannong Chemicals Ltd	Ulsan	2008-2013	*90**
99	Adipic Acid	Rhodia Energy Korea Co, Ltd	Onsan	2006-2017	121
4665	Caprolactam	Capro Corporation	Ulsan	2011-2020	128

*Note: From the available information, it remains unclear whether the facility by Dongbu Hannong Chemicals Ltd in Ulsan is still in operation at the time of writing.
Source: IGES (2022)

2.7.3 Policies affecting N_2O emission levels

The Korea emissions trading scheme (K-ETS) is in place since 2015 and covers all companies with annual average GHG emissions of 125,000 t CO_2e or more, and individual facilities with annual average GHG emissions of 25,000 t CO_2e or more. Next to other GHGs, N_2O emissions are considered in the K-ETS. The target under this scheme is to reduce Korean GHG emissions in 2030 by at least 35 % compared to 2018 and achieve carbon neutrality in 2050. Under the phases of the K-ETS, domestic and international offsets are allowed under different criteria. Domestic and international credits need to be transformed into Korean Credit Units (KCUs) to be used for

[25] BASF acquired the facility from Solvay Chemicals Korea in 2020 (BASF 2021), which is listed as one of the project participants in Republic of Korea (2013).
[26] http://www.hcccapro.co.kr/en/product/capro_lactam/index.asp

compliance. Under the current phase 3, up to 5 % of each entity's compliance obligation can be offset using credits. (ICAP 2023; IETA 2021)

While N_2O process emissions from nitric acid, adipic acid and caprolactam production would thus have been covered by the K-ETS since 2015 (if companies or facilities exceed the size thresholds), facilities covered under the CDM were exempted from the K-ETS[27]. These exemptions were issued for the 1st and 2nd phases of the K-ETS, extending from 2015 to 2017 and from 2018 to 2020, respectively. As CERs will not be valid under the Paris Agreement after 2020, the K-ETS exemption for CDM projects was lifted for the 3rd K-ETS Phase starting 2021. (KEMCO 2023; KFQ 2020; TÜV Nord 2021).

It can thus be concluded that N_2O emissions from Korean nitric acid, adipic acid and caprolactam production facilities are fully covered by the K-ETS starting 2021.

There are further policies targeting N_2O emissions in the industry sector, however, those are not specifically targeted at nitric acid production (The Government of the Republic of Korea (2021)).

2.7.4 N_2O abatement in place

There are several CDM projects for N_2O abatement for N_2O from nitric acid, adipic acid and caprolactam production in the Republic of Korea.

Nitric Acid

Registered CDM Projects for N_2O abatement from nitric acid production are mostly tertiary catalyst technologies, with an abatement rate of >95 %. Table 26 gives an overview on the different projects as listed in the CDM database. From the available information, it is unclear whether the plant in Ulsan is still in operation today. Plant #6 in Yeosu by Hu-Chems Fine Chemical Corp. was registered under the CDM with the aim to start operation and crediting in 2023.

Table 26: Registered CDM Projects in the Republic of Korea related to nitric acid production

Company	Location	Remaining emissions [kt CO_2e/a]	Estimated annual production [kt / a]	Emission Reduction
Hanwha Corporation	Ulsan	23	107	90%
Hu-Chems Fine Chemical Corp	Yeosu (Plant 2,3,4)	101	701	92%
Hu-Chems Fine Chemical Corp	Yeosu (Plant 5)	33	397	89%
Hu-Chems Fine Chemical Corp	*Yeosu (Plant 6)*	*40**	*440**	*88%*
Dongbu Hannong Chemicals Ltd	*Ulsan*	*60**	*90**	*80%*

*Note: Hu-Chem plant #6 was registered under the CDM with the aim to start operation & crediting in 2023. From the available information, it is unclear whether the plant of Dongbu Hannong in Ulsan is still in operation today
Source: Republic of Korea (2021a) , Republic of Korea (2020), Republic of Korea (2012), Republic of Korea (2021b), Republic of Korea (2010), IGES (2022)

[27] For adipic acid production, however, N_2O emissions were not exempted from the K-ETS and CERs generated were not admitted in the K-ETS. (KEMCO (2023); ICCA (2023).)

One project describes a secondary catalyst with an estimated 80 % abatement efficiency, the other facilities are equipped with tertiary abatement with an efficiency that is given as about 90 % emission reduction.

Adipic Acid

There is one plant by BASF producing adipic acid in the Republic of Korea in Onsan (BASF 2021). The plant was originally constructed by Rhodia, which implemented N_2O abatement under a CDM project (Republic of Korea 2013). From the CDM project description, an emission reduction of 99 % of N_2O emissions is achieved.

Caprolactam

According to the CDM Project design document (PDD) (Republic of Korea 2011), a nitrous oxide abatement technology was installed at the caprolactam producing site of the company Capro Co with a proposed reduction of N_2O emissions by >90 %. However, the PDD only states that N_2O abatement is installed for 2 out of 3 plants. It remains unclear whether the third plant at the site is using N_2O abatement and whether it is operational.

2.7.5 N_2O emissions

N_2O Emissions from the chemical industry (CRF category 2.B.) in the Republic of Korea are shown in Table 27. However, neither Korea's 4th Biennial Report (The Government of the Republic of Korea (2021)) not the National GHG Inventory (The Government of the Republic of Korea 2022) provide a breakdown of emissions for the different subcategories which would facilitate the distinction of emissions from nitric acid, adipic acid and caprolactam production.

Table 27: N_2O emissions from chemical industry (CRF 2.B) in the Republic of Korea

	Reported by the Republic of Korea to UNFCCC
	kt N_2O
2000	22.8
2005	35.8
2010	0.7
2011	1.0
2012	1.4
2013	1.3
2014	1.0
2015	0.9
2016	1.1
2017	1.2
2018	1.2
2019	1.2
2020	1.2

Source: 2000-2018: The Government of the Republic of Korea (2021), 2019-2020: The Government of the Republic of Korea (2022)

Default emission factors from the 2006 IPCC guidelines are applied for the determination of emissions from nitric acid production, whereas for adipic acid and caprolactam, default emission factors from 1996 IPCC guidelines are applied (The Government of the Republic of Korea (2021)). No uncertainty estimate is provided.

From the emission data provided in the CDM Project description documents and The Government of the Republic of Korea (2022), we estimate that 2020 N_2O emissions from chemical industry can be allocated to nitric acid production at 62 %, to adipic acid production at 16 %, and to caprolactam production at 22 %.

2.7.6 N_2O mitigation potentials

A rough estimate of specific N_2O emissions from ***nitric acid production*** is conducted as follows:

Based on the emission split described above and based on a 2020 production estimate of 1.3 Mt nitric acid, we derive specific emissions of approximately 0.6 kg N_2O / t nitric acid. As explained in Annex I, benchmarks for N_2O emissions from nitric acid production derived from the EU-ETS are at ~0.25 – 0.6 kg N_2O/t.

Additional N_2O mitigation potentials for Korean nitric acid production are thus very limited and could only be achieved by improving the abatement percentages shown in Table 26. Abatement of 95 % and above is technically feasible with modern technologies and regular optimal maintenance. Without external incentive, either financial or legal, it might be improbable that these mitigation potentials will currently be realised. However, due to high incentives from the EU-ETS, upgrades of existing abatement technologies are currently being implemented in Europe to reduce emissions as low as possible, with combinations of secondary and tertiary abatement reaching abatement rates of more than 99 %. In the future, similar developments might be possible in Korea.

For ***adipic acid production***, using the method described above for nitric acid, we derive specific emissions of about 1.7 kg N_2O / t adipic acid. This value is below the EU average for adipic acid production, which is at 3.4 kg N_2O / adipic acid. Additional mitigation potentials are thus not available.

For ***caprolactam production***, using the method described above for nitric acid, we derive specific emissions of about 2.3 kg N_2O / t caprolactam. This value is above the specific emissions in Poland (used as a benchmark for the EU) of 0.6 kg N_2O /t caprolactam. According to Republic of Korea (2011), the abatement technology installed reaches an abatement of 89 %. Assuming that abatement rates of more than 95 % could be possible, it would thus be technically feasible to further reduce emissions from caprolactam production in the Republic of Korea. Without any external incentive, either financial or legal, it is however improbable that these mitigation potentials will be realised.

2.8 Norway

2.8.1 Norway summary

In Norway, approximately 2 million tonnes of nitric acid were produced in 2020. Key N_2O mitigation policies include coverage under the EU emissions trading scheme. Secondary catalytic N_2O abatement technologies are in place. Average specific N_2O emissions were at about 0.2 kg/tonne of nitric acid. Given the low emissions level, no additional N_2O mitigation potentials are estimated for Norway.

Table 28: Country Profile Norway

	Nitric Acid	Adipic Acid	Caprolactam
Number of facilities	2	-	-
Relevant climate policies	Inclusion in EU ETS	-	-
N_2O Abatement Technologies in Place	complete application of secondary catalytic abatement measures	-	-
Annual Production (2020)	~2 Mt [100% HNO_3]	-	-
Annual N_2O emissions (2020)	0.3 kt N_2O / 0.1 Mt CO_2e	-	-
N_2O emissions uncertainty estimate	Low ~1-7 %	-	-
Specific N_2O emissions (2020)	0.2 kg N_2O/t		
N_2O mitigation potential	none	-	-

Note: N_2O amounts converted into CO_2 equivalents using the GWP of 265 as set out in the 5th IPCC Assessment Report (AR5)
Sources: Norway 2022a; 2022b

2.8.2 Presence of N_2O-emitting chemical industries

In Norway, production of nitric acid takes place in six production lines in two plants while production of adipic acid and of caprolactam is absent (Norway 2022b).

Production levels have been increasing over the past decades. 2020 production levels (1.95 million tonnes) are 18 % above 2010, 30 % above 2000, and 47 % above 1990. (Norway 2022a)

2.8.3 Policies affecting N_2O emission levels

Despite not being a Member of the European Union, Norway takes part in the EU emissions trading scheme (EU-ETS) which covers N_2O emissions from nitric acid production.

For more details related to the EU-ETS, see section 2.4.2.

2.8.4 N_2O abatement in place

Catalytic secondary abatement is on all production lines in Norway (Norway 2022b).

2.8.5 N_2O emissions

Norwegian N_2O emissions from nitric acid production for 1990-2020 are given in Table 29. Emission intensities were drastically reduced in particular between 2005 and 2010. After 2010, specific emissions slowly continue to decline at very low levels.

Table 29: N_2O emissions from nitric acid production in Norway

	nitric acid production million tonnes (100% nitric acid)	**N_2O emissions nitric acid production,**	
		kt N_2O	**kg N_2O / t nitric acid**
	reported by Norway to UNFCCC		
1990	1.33	6.7	5.0
1995	1.49	5.3	3.5
2000	1.50	5.6	3.7
2005	1.59	6.3	4.0
2010	1.65	1.1	0.7
2015	1.73	0.8	0.5
2016	1.67	0.8	0.5
2017	1.73	0.7	0.4
2018	1.98	0.7	0.3
2019	1.92	0.6	0.3
2020	1.95	0.3	0.2

Sources: Norway 2022a

In its GHG inventory submission, Norway reports uncertainties of the measurement-base emission estimates of 1-7 %.

2.8.6 N_2O mitigation potentials

Norwegian average specific N_2O emissions from nitric acid production are among the lowest reported from countries covered by the EU-ETS (see Annex I). No additional N_2O mitigation potential can be quantified.

2.9 Russia

2.9.1 Russia summary

In the Russian Federation, approximately 10 million tonnes of ***nitric acid*** and 0.36 million tonnes of ***caprolactam*** were produced in 2020. No mitigation policies targeted at N_2O emissions from Chemical industry were identified for Russia. While catalytic NOx abatement is generally applied in Russian nitric acid production, no targeted N_2O abatement takes place. According to recent research and analysis average specific N_2O emissions are assumed to range at about 8 kg/tonne of ***nitric acid***, four times higher than the estimate in the Russian GHG inventory. Respective N_2O mitigation potentials are estimated at ~95 %. For ***caprolactam*** production, a ~95% N_2O mitigation potential is estimated, compared to the IPCC default of 9 kg N_2O/tonne caprolactam, used for the Russian GHG inventory.

Table 30: Country Profile Russia

	Nitric Acid	Adipic Acid	Caprolactam
Number of facilities	64 production lines / 14 operators	-	3 operators
Relevant climate policies	No specific policies targeting N_2O from chemical industry. Framework legislation provides foundation for addressing N_2O emissions. However, lack of ambition of 2030 GHG target implies little probability for additional instruments to be applied.		
N_2O Abatement Technologies in Place	catalytic NO_x abatement in place, no targeted N_2O abatement		no N_2O abatement
Annual Production (2020)	10.2 Mt [100% HNO_3]		0.36 Mt
Annual N_2O emissions (2020)	GHG inventory: 20.3 kt N_2O / 5.4 Mt CO_2e; Own estimate: 81.3 kt N_2O / 21.7 Mt CO_2e		3.3 kt N_2O / 0.9 Mt CO_2e
N_2O emissions uncertainty estimate	Very high, largely diverging estimates	-	40%
Specific N_2O emissions (2020)	GHG inventory: 2 kg N_2O/t; Own estimate: 8.1 kg N_2O/t		9 kg N_2O/t (IPCC default estimate)
N_2O mitigation potential	Gap to emission intensity benchmark of ambitious mitigation policy: ~95% / 75-80 kt N_2O/a ~20-21 Mt CO_2e/a; 'low-hanging fruit' potential in unabated plants: ~70% / ~58 kt N_2O/a ~15 Mt CO_2e/a	-	~93% / 3 kt N_2O/a ~0.8 Mt CO_2e/a

Note: N_2O amounts converted into CO_2 equivalents using the GWP of 265 as set out in the 5th IPCC Assessment Report (AR5)
Sources: BNDT 2019; Gitarskiy 2021; Malyavin 2021; Russian Federation 2022a; 2022b; RCC 2005, own calculations of Öko-Institut

2.9.2 Presence of N_2O-emitting chemical industries

In Russia, the production of nitric acid and caprolactam takes place. According to the Russian GHG emission inventory, production of adipic acid does not take place in the Russian Federation (Russian Federation 2022b).

For ***nitric acid production***, 64 production lines by 14 companies are in operation (BNDT 2019) cumulated capacity is at 12.4 million tonnes per year, split between basically three different types of installations (Malyavin 2021):

- Single pressure / high pressure plants (types “UKL-7” and “AK-500”): ~56 % of capacity
- Dual pressure (high/medium), type “AK-72”: ~32 % of capacity
- Dual pressure (low/medium), type “1/3,5”: ~12 % of capacity

Nitric acid production levels have been strongly increasing over the past decades. Production levels reported for 2020 (10.2 million tonnes), were approximately 140% above 2000 levels and 40% above 2010 levels (see Table 31). Key driver for the development of nitric acid production has been the use of the manufacture of mineral fertilisers, to large extents for export.

In Russia, three producers of ***caprolactam*** are active (RCC 2005): companies Kuybyshevazot, Shekinoazot and Azot (Kemerovo). Caprolactam production levels have. Caprolactam production levels have been rising over the past decades. Production levels reported for 2020 were approximately 50% above 2000 levels (see Table 32).

2.9.3 Policies affecting N_2O emission levels

Russia does not deploy (yet) policies targeting N_2O emissions from chemical industry.

For NO_x emissions, however, regulatory standards apply including ambient air quality standards, emission limits and emission taxes for NO and NO_2. (Gitarskiy 2021)

N_2O emissions, as a part of the Kyoto Protocol Annex A ‘basket of greenhouse gases’ have been included in high-level Russian policy documents, including

- Russia’s 2020 NDC with a 2030 target[28],
- Russia’s 2021 low-carbon strategy until 2050[29],
- Russia’s Federal law #296/2021 on greenhouse gas emission limitation[30] as well as
- the respective Presidential decree #666/2020[31]

As summarised by Gitarskiy (2021) the Federal law #296/2021

- establishes mandatory reporting requirements for all GHG emitters above certain thresholds;

[28] (Russian Federation 2020).
[29] http://publication.pravo.gov.ru/Document/View/0001202111010022
[30] http://publication.pravo.gov.ru/Document/View/0001202107020031
[31] http://www.kremlin.ru/acts/bank/45990

- sets up national registers specifically designed for reporting and accounting of greenhouse gas emissions;
- creates the frameworks for GHG reduction projects and the generation of linked emission reduction units;
- empowers Russian Government to establish emission reduction targets for economy sectors and assess their achievement.

While the 2021 low-carbon strategy until 2050 explicitly mentions N_2O abatement for nitric acid production as one of the measures for the implementation of the strategy, no specific instruments targeted at N_2O emissions have yet been implemented.

Russia's 2030 target set out in its 2020 NDC aims at a 30% GHG reduction compared to 1990 levels, taking into account 'the maximum possible absorptive capacity of forests and other ecosystems' (Russian Federation 2020). It should be noted, however, that Russia's present GHG emission levels are far below that -30 % target, due to the plummeting of GHG emissions in the early 1990s after the break-up of the Soviet Union: Russia's 2020 GHG emissions were at only 48% of 1990 emissions including LULUCF, or at 65% without LULUCF (Russian Federation 2022b).

Given this lack of pressure for GHG abatement to meet Russia's NDC, it appears very uncertain whether Russia will actually deploy specific policy instruments targeting chemical industry's N_2O emissions in the coming years.

2.9.4 N_2O abatement in place

For ***nitric acid production*** in Russia, NO_x emission abatement measures are generally being applied, underpinned by stringent environment and health regulatory restrictions (Gitarskiy 2021). The Russian NIR (Russian Federation 2022b) claims that Russian nitric acid production capacities are fully equipped with NSCR abatement technology (primarily intended to mitigate NO_x emissions, but contributing to N_2O abatement, as well) and supports this with a source dated 2001 (OOO "Azotekon" 2001). However, as analysed by Malyavin 2021, the NO_x abatement of most Russian nitric acid plants has been upgraded to SCR, resulting in the loss of N_2O abatement.

Prior to the year 2010, plans had been developed for JI-financed N_2O abatement projects of seven Russian nitric acid producers, with the view of generating JI emission reduction units (ERUs) by 2008 or 2009. However, none of the projects was finally registered and no ERUs were issued (UNEP 2022). Thus, we estimate present Russian nitric acid production capacities to mostly lack N_2O abatement. For dual pressure (high/medium) plants of type AK-72, application of NSCR can possibly still be assumed (Malyavin 2021).

For Russian caprolactam production, no information on applied N_2O abatement was found. Given that a) the Russian GHG emission inventory uses the IPPC default emission factor implying no N_2O abatement (Russian Federation 2022b) and b) the lack of specific policy instrument addressing N_2O emissions in chemical industry (see 2.9.3) we conclude that no N_2O abatement is in place.

2.9.5 N_2O emissions

In the Russian GHG inventory, N_2O emission from ***nitric acid production*** are calculated using an emission factor of 2 kg N_2O / tonne of nitric acid, as proposed in the 2006 IPCC guidelines (IPCC 2006) for plants employing NSCR (non-specific catalytic reduction) (source: RUS NIR 2022). As discussed in section 2.9.4 above, the choice of that emission factor is likely to be adequate for the 1990s, before NO_x abatement was upgraded to SCR, resulting in the loss of N_2O abatement performance. Default emission factors in the 2006 IPCC guidelines for unabated low-, medium- or high pressure plants, applicable for SCR-equipped facilities in the absence of measurement data, range from 5-9 kg N_2O/t (IPCC 2006, Vol 3, Tab 3.3, p. 3.23).

The 2019 refinement to the 2006 IPCC guidelines, however, present a refined set of emission factors applicable for the N_2O emission calculation from nitric acid production (IPCC 2019, Vol 3, Tab 3.3 (Updated), p 3.9). Using the overview and technical classification of Russian nitric acid plants in BNDT (2019) and the set of emission factors proposed by the 2019 IPCC refinement, a range of alternative emission estimate for Russia has been calculated by Malyavin (2021) which are approximately three to six times higher than the estimate in the Russian GHG inventory. Expressed as specific emissions, the calculation concludes in a weighted average emission factor of 8.1 (range: 6.8 – 13.8).

Table 31 presents both data reported by Russia related to N_2O emissions from ***nitric acid*** production as well as an alternative estimate based on the calculations in Malyavin (2021).

Table 31: N_2O emissions from Russian nitric acid production

	nitric acid production million tonnes (100% nitric acid)	**N_2O emissions nitric acid production**		**N_2O emissions nitric acid production,**	
		kt N_2O	kg N_2O / t nitric acid	kt N_2O	kg N_2O / t nitric acid
	reported by Russia to UNFCCC			Öko-Institut estimate based on Malyavin (2021)	
2000	4.3	8.6	2.0		
2005	5.8	11.7	2.0		
2010	7.4	14.7	2.0		
2015	8.3	16.6	2.0		
2016	8.7	17.4	2.0		
2017	9.1	18.1	2.0		
2018	8.9	17.8	2.0		
2019	9.4	18.8	2.0		
2020	10.2	20.3	2.0	81.9 (69.0 – 140.2)	8.1 (6.8 – 13.8)

Sources: Malyavin 2021; Russian Federation 2022a;Öko-Institut calculations

Table 32 presents production and N_2O emissions data for ***caprolactam production*** in Russia. Emissions were calculated using the IPCC default emission factor of 9 kg N_2O/ tonne caprolactam, assuming no N_2O abatement.

Table 32: N_2O emissions from caprolactam production in Russia

	caprolactam production million tonnes	N_2O emissions nitric acid production, kt N_2O	kg N_2O / t caprolactam
	reported by Russia to UNFCCC		
2000	0.25	2.2	9.0
2005	0.31	2.8	9.0
2010	0.33	3.0	9.0
2015	0.33	2.9	9.0
2016	0.36	3.2	9.0
2017	0.37	3.3	9.0
2018	0.39	3.5	9.0
2019	0.39	3.5	9.0
2020	0.36	3.3	9.0

Sources: Russian Federation 2022a

The uncertainty of N_2O emissions from nitric acid production reported to the UNFCCC was estimated by Russia at 11 % (Russian Federation 2022b): However, considering the alternative calculation by Malyavin (2021) presented above, we estimate the uncertainty of the N_2O emissions estimated for nitric acid production at 300-700%.

The uncertainty of N_2O emissions from caprolactam production reported to the UNFCCC was estimated by Russia at 40 % (Russian Federation 2022b):

2.9.6 N_2O mitigation potentials

Nitric Acid Production

As discussed in 2.9.5, central estimates for specific N_2O emissions from nitric acid production range from 2 kg N_2O / t nitric acid (Russian GHG inventory) to about 8 kg / t (based on Malyavin 2021) which we consider as more realistic. Both estimates are very high compared to European levels. Benchmarks for emission intensities achievable by ambitious mitigation policies can be derived from the EU-ETS in the range of 0.43 kg/t as EU-ETS average, 0.26 kg/t as average of the top half of EU-ETS or 0.6 kg/t for the bottom half of EU-ETS participants (see Annex I).

These EU-ETS benchmarks are at ~3-7% of the higher estimate of present Russian emission intensities, or at ~15-30% considering the estimate in the Russian GHG inventory. Benchmark-based top-down mitigation potentials for N_2O from Russia's nitric acid production add up to ~75 – 80 kt N_2O/a or ~ 20-21 Mt CO_2e / a (GWP AR5) for the higher emission estimate, or to ~3-6 kt N_2O/a or ~ 4-5 Mt CO_2e / a (GWP AR5) considering the Russian GHG inventory estimate.

In a bottom-up perspective focussing on plants without any present N_2O abatement (estimated as ~ two thirds of dual (high/medium) pressure capacities and all high pressure and dual (medium/low) pressure capacities, see 2.9.2) we estimate a low-cost mitigation potential at approximately 58 kt N_2O/a or 15 Mt CO_2e/a (i.e. approximately 70 % of the high estimate of Russia's 2020 N_2O emissions from nitric acid production).

Caprolactam

In Russian caprolactam production no N_2O mitigation has been applied so far. The benchmark for emission intensities achievable by ambitious waste gas treatment is at 0.6 kg N_2O / t caprolactam (see Annex III), i.e. 7% of the IPCC default of 9 kg/t used for Russia. Application of N_2O abatement thus might lead to a 93% reduction, equal to approx. 3 kt N_2O/a (0.8 Mt CO_2e).

2.10 Saudi Arabia

2.10.1 Saudi Arabia summary

For Saudi-Arabia, roughly 0.4 million tonnes of nitric acid were estimated as produced in 2020. No mitigation policies targeted at N_2O emissions from Chemical industry were identified for Saudi-Arabia. However, the single nitric acid plant of Saudi-Arabia is equipped with N_2O abatement. Information on specific N_2O emissions is not available. Therefore, N_2O mitigation potentials could not be estimated for Saudi-Arabia.

Table 33: Country Profile Saudi Arabia

	Nitric Acid	Adipic Acid	Caprolactam
Number of facilities	1	-	-
Relevant climate policies	none		
N_2O Abatement Technologies in Place	Yes. No information on type of system	-	-
Annual Production (2020)	Actual production information not available Production capacity ~0.4 million tonnes	-	-
Annual N_2O emissions	inventory information not available rough estimate ~0.2 – 0-9 kt N_2O / ~0.05 – 0.25 Mt CO_2e	-	-
N_2O emissions uncertainty estimate	High due to limited data availability	-	-
Specific N_2O emissions (2020)	Not available 2019 IPCC refinement defaults: 1.5-2.5 kg N_2O/t		
N_2O mitigation potential	Not available		

Note: N_2O amounts converted into CO_2 equivalents using the GWP of 265 as set out in the 5th IPCC Assessment Report (AR5)
Source: Espindesa (2017), IPCC (2019), own calculations of Öko-Institut

2.10.2 Presence of N_2O-emitting chemical industries

According to information provided by the company Espindesa (Manufacturer of the plant), there is one nitric acid plant in Al-Jubail in Saudi Arabia with a production capacity of 1 200 t per day (Espindesa 2017). The operator of the plant is the company Sadara (DowChemical/Saudi Aramco). The plant was completed in 2017.

InvestSaudi is actively promoting investments into adipic acid production facilities in Saudi Arabia (Invest Saudi 2021). It is thus likely that adipic acid production might be taking place in Saudi Arabia in the future.

2.10.3 Policies affecting N_2O emission levels

Saudi Arabia has no policies in place targeting N_2O emissions and according to official documents, none are currently planned (Sources: New Climate Institute (2021a), Saudi Arabia Designated National Authority (2022)).

- no CDM projects (Source GIZ NACAG[32], CDM Database[33]).

2.10.4 N_2O abatement in place

There are no CDM projects related to N_2O abatement in Saudi Arabia. Nevertheless, the nitric acid plant in Al-Jubail is equipped with a N_2O abatement system (Personal communication from the manufacturer of the nitric acid plant in Saudi Arabia). No information was shared on the type or efficiency of the system in place.

2.10.5 N_2O emissions

The GHG inventory in the Fourth National communication by Saudi Arabia to the UNFCCC (Saudi Arabia Designated National Authority 2022) does not list any N_2O emissions for the industry sector for the year 2016, and there is no information on emissions from Saudi Arabia for more recent years. Since the facility in Al-Jubail was only completed in 2017, emissions from this plant are not yet captured in official GHG inventories by Saudi Arabia.

We roughly estimate annual N_2O emissions 2020 as follows:

Assuming an 80% capacity use, annual production levels would be approx. 0.35 million tonnes per year. IPCC (2019) proposes for modern plants with abatement emission factors of 1.5-2.5 kg N_2O / t nitric acid, resulting in emissions of approx. 0.5-0.9 kt N_2O/a. However, an ambitiously operated abatement system might result in specific emissions of less than 0.5 kg N_2O/t, or ~0.2 kt N_2O/a.

2.10.6 N_2O mitigation potentials

Due to the limited information available, a quantification of the N_2O mitigation potential is not possible.

[32] https://www.nitricacidaction.org/
[33] https://cdm.unfccc.int/Projects/projsearch.html

2.11 Singapore

2.11.1 Singapore summary

For Singapore, little information on nitric acid production is available, the plant capacity is estimated at 0.1 million tonnes of nitric acid per year. No information is available related to present N_2O abatement equipment. However, given the key Singapore mitigation policy N_2O emissions from Chemical industry is the Singapore Carbon Tax since 2019, featuring a rising schedule of taxes per t CO_2e, should incentivise ambitious N_2O abatement within few years.

Table 34: Country Profile Singapore

	Nitric Acid	Adipic Acid	Caprolactam
Number of facilities	1	- (1 plant closed 2012)	-
Relevant climate policies	Since 2019: Singapore carbon tax of 5 S$/ t CO_2e (~ 0.7 EUR / S$) scheduled to rise to 25 S$/ t CO_2e by 2024, 45 S$/ t CO_2e by 2026, and 50-80 S$/ t CO_2e by 2030. No policies targeting industry N_2O emission before 2019.		
N_2O Abatement Technologies in Place	Uncertain 2012 CDM application for tertiary catalytic N_2O destruction was cancelled.	Plant was equipped with N_2O abatement	--
Annual Production (2020)	Uncertain Plant capacity ~ 0.1 Mt HNO_3/a	-	-
Annual N_2O emissions (2020)	Uncertain If unabated, up to approx. 1 kt N_2O/a (0.27 Mt CO_2e)	-	-
N_2O emissions uncertainty estimate	Very high:	-	-
Specific N_2O emissions (2020)	Not available		
N_2O mitigation potential	~98% of unabated emission levels: Up to ~ 1kt N_2O/a / 0.25 Mt CO_2e/a Realisation of mitigation potential expected soon under rising schedule of Singapore Carbon Tax	-	-

Note: N_2O amounts converted into CO_2 equivalents using the GWP of 265 as set out in the 5th IPCC Assessment Report (AR5)
Sources: Invista 2012; Singapore 2020; 2022; NCCS 2023; Chemmanager 2015; Schneider et al. 2010,own calculations of Öko-Institut

2.11.2 Presence of N_2O-emitting chemical industries

In Singapore, one nitric acid plant (a high pressure Weatherley plant) is in operation since 2009, operated by INVISTA; the plant's capacity is 320 tonnes of nitric acid per day (Invista 2012). The plant was built next to INVISTA's adjacent adipic acid plant (production capacity approx. 300 tonnes of adipic acid per day[34]) which, however, was reported to be closed in 2012 (Chemmanager 2015).

[34] Source: Schneider et al. 2010

It appears, however, that the at least temporary presence of nitric and adipic acid production in Singapore[35] may not have been noted by the Singapore National Environment Agency in charge of the GHG inventory:

- In the GHG inventory for ***2018***, published 2022 in the Singapore 5th Biennial Update Report to the UNFCCC (Singapore 2022) both nitric acid production and adipic acid production are reported as 'not occurring'. The same information ('not occurring') was given in the GHG inventory for 2016 in the Singapore 4th Biennial Update Report of 2020 (Singapore 2020).
- Inventory summaries published in Singapore (2020) and Singapore (2022) for the years ***2000, 2010, 2012 and 2014*** are given at the aggregation levels of the inventory category CRF 2 "industrial processes and product use" (IPPU) and do not specify chemical industry. IPPU total N_2O emissions given for those years, however, are in the order of magnitude of 0.1 kt N_2O/a, consistent with 2016 and 2018 N_2O emissions reported for category 2E 'electronics industry' and far below emission levels expected from nitric and adipic acid plants, if operating (see section 2.11.5).

2.11.3 Policies affecting N_2O emission levels

Before 2019, no Singapore policies addressed N_2O emissions from chemical industry.

Since 2019, however, Singapore has implemented a carbon tax, which is applied uniformly to all sectors including energy-intensive and trade-exposed sectors, without exemption (NCCS 2023). The carbon tax level is set for 2019 – 2023 at S$ 5 /t CO_2e (approximately US$ 3.5 / t CO_2e or EUR 3.5 / t CO_2e[36]).

In the 2018 Carbon Pricing Act, the GWP to be used for the conversion of N_2O emissions into CO_2 equivalents is defined as 310, i.e. the GWP of the 2nd IPCC Assessment Report, thus about 15% higher than the GWPs for N_2O according to the 5th IPCC Assessment Report (265)[37]. Recalculated to N_2O emissions, the 2019-2023 carbon tax is thus at S$ 1.55 / kg N_2O (~ USD/EUR 1.1 / kg N_2O)

However, the Singapore carbon tax is scheduled to be raised to $25 /t CO_2e in 2024 and 2025, and $45/t CO_2e in 2026 and 2027, with a view to reaching $50-80/t CO_2e by 2030 (NCCS 2023). Given a stringent enforcement, this will be a strong incentive for Singapore chemical industry to abate N_2O emissions as far as technically possible.

2.11.4 N_2O abatement in place

For the ***nitric acid plant***, a CDM process design document (PDD) was published in 2012 proposing to install a tertiary catalytic N_2O decomposition unit at the plant (Invista 2012). In the PDD it was stated that, prior to the PDD, no N_2O had taken place although NO_x emissions were being abated by SCR in order to comply with Singapore clean air standards. However, the validation of the CDM project was terminated, no CER (certified emission reductions under the CDM) were ever issued

[35] In a global assessment of non-CO_2 GHG emissions in EPA (2019), Singapore ranked as world-wide third largest emitter of N_2O from nitric and adipic acid production after China and the USA. As clarified in US EPA (2023), however, that assessment had primarily been based on 2011 information on Singapore adipic acid production capacities and ignorant of the 2012 plant closure reported in Chemmanager (2015).

[36] In September 2022, one Singapore Dollar was exchanged into approximately 0.7 US Dollars or 0.7 Euros.

[37] Under the 4th IPCC Assessment Report, the GWP_{100} was 298.

(IGES 2022). No information is available, however, whether the nitric acid plant was nevertheless equipped with N_2O abatement technology.

For the ***adipic acid plant***, the 2012 PDD for the nitric acid plant stated that N_2O emissions from the adipic acid plant have been abated since start-up (Invista 2012).

2.11.5 N_2O emissions

N_2O emissions from nitric acid production are estimated as follows: Given a capacity of 320 t/d and about 330 operating days per year (Invista 2012), production levels might reach up to 105 kt nitric acid per year. Given emission factors for an unabated high-pressure plant of 9 kg/t (IPCC default for high pressure) up to 10.56 kg/t (quoted from Stockholm Environment Institute 2010 in Invista 2012) emissions in the case of no N_2O abatement and full capacity use could be at about 0.9 – 1.1 kt N_2O/a.

In case effective N_2O abatement was installed in the Singapore facility despite the cancellation of the attempt to receive CERs under the CDM, emissions could be at 1-5% of those emissions levels, or lower in case of less use of the production capacity.

The uncertainty of the emissions estimate is thus very high.

2.11.6 mitigation potentials

Nitric Acid Production

Singapore emission levels, if confirmed unabated, would be very high at approx. 9-10 kg N_2O / t nitric acid, compared to benchmarks derived from the EU-ETS countries at approx. 0.43 kg/t +/- 50% (see Annex I). Mitigation potentials could be at about 95% - 98% and, at full production capacity use, amount to about 1 kt N_2O/a (+/- 10%) equivalent to approximately 0.25 Mt CO_2e/a.

However, given the strong abatement incentive originating from the tax rate schedule of the Singapore Carbon Tax starting 2019 (see 2.11.3), the Singapore nitric acid plant's full equipment with N_2O abatement should be expected rather soon.

2.12 Trinidad and Tobago

2.12.1 Trinidad and Tobago summary

For Trinidad and Tobago, roughly 0.5 million tonnes of nitric acid were estimated as produced in 2020. No mitigation policies targeted at N_2O emissions from Chemical industry were identified for Trinidad and Tobago. The single nitric acid plant of Trinidad and Tobago is not equipped with N_2O abatement. Average specific N_2O emissions were estimated at about 10 kg/tonne of nitric acid. N_2O mitigation potentials are estimated at ~98%.

Table 35: Country Profile Trinidad and Tobago

	Nitric Acid	Adipic Acid	Caprolactam
Number of facilities	1	-	-
Relevant climate policies	None		
N_2O Abatement Technologies in Place	none	-	-
Annual Production	production amounts not available plant capacity: ~0.5 million t/a	-	-
Annual N_2O emissions (2018)	3.9 kt N_2O ~1 Mt CO_2e	-	-
N_2O emissions uncertainty estimate	High	-	-
Specific N_2O emissions (2020)	Possibly ~ 9 kg N_2O/t for an unabated plant	-	-
N_2O mitigation potential	'Low-hanging-fruit' potential in unabated plants: ~98 % ~ 3.8 kt N_2O/a ~1 Mt CO_2e/a	--	

Note: N_2O amounts converted into CO_2 equivalents using the GWP of 265 as set out in the 5th IPCC Assessment Report (AR5)
Source: Proman (2023), New Climate Institute (2021b), Ministry of Planning and Development (2021), personal communication

2.12.2 Presence of N_2O-emitting chemical industries

In Trinidad and Tobago, there is one facility which produces nitric acid for further transformation into urea ammonium nitrate, a fertilizer. The facility is operated by the company Methanol Holdings (Trinidad) Limited (part of Proman, Switzerland) and situated in Point Lisas (Proman 2023). The plant capacity for the final product is given with 1520 t/day by the plant manufacturing company[38].

2.12.3 Policies affecting N_2O emission levels

Trinidad and Tobago has no policies in place targeting N_2O emissions and according to official documents, none are currently planned (Sources: New Climate Institute (2021b), Ministry of Planning and Development (2021)).

[38] https://www.ferrostaal.com/en/top-references-ferrostaal/construction-of-a-petrochemical-plant-in-trinidad-aum-complex/

There are no CDM projects in Trinidad and Tobago concerning nitric acid production (IGES 2022).

2.12.4 N_2O abatement in place

There are no CDM projects in Trinidad and Tobago. Currently, the MHTL nitric acid plant is not equipped with abatement technologies. However, the operator is planning to retrofit a tertiary catalytic N_2O abatement in the future[39] and is looking for funding.

2.12.5 N_2O emissions

The most reliable data and the longest available time series on emissions from nitric acid production in Trinidad and Tobago is provided in the GHG inventory in the Third National communication by Trinidad and Tobago to the UNFCCC. The emissions are provided in Gg N_2O. BR lists Tier 1 as method for determination of emissions in CRF category 2.B. and use of default emission factors. This means that only a simplified approach is used for the determination of the emissions, introducing an uncertainty about the actual emission levels. Table 36 provides an overview on emissions from nitric acid production in Trinidad and Tobago.

Table 36: N_2O emissions from Trinidad and Tobago nitric acid production

	Reported by Trinidad and Tobago to UNFCCC
	kt N_2O
2000	0
2005	0
2010	3.9
2011	4.2
2012	4.0
2013	3.0
2014	3.7
2015	4.1
2016	3.7
2017	3.8
2018	3.9

Source: Ministry of Planning and Development (2021)

2.12.6 N_2O mitigation potentials

N_2O mitigation potentials are high, since currently there are no N_2O abatement technologies in place in for nitric acid production in Trinidad and Tobago. Available information on the planned tertiary catalyst technology lists N_2O removal rates of 98 % to over 99 %[40]. This would imply an almost complete N_2O mitigation potential of the 2018 emissions of ~ 4 kt N_2O or ~ 1 Mt CO_2e respectively.

[39] Source: Personal Communication from industry sources
[40] Source: Personal Communication from industry sources

2.13 United Arab Emirates

2.13.1 UAE summary

For the United Arab Emirates, little information on nitric acid production is available. Annual production is roughly estimated at levels below 0.15 million tonnes of nitric acid per year. No mitigation policies targeted at N_2O emissions from Chemical industry were identified for the UAE. No information is available related to present N_2O abatement equipment. Information on specific N_2O emissions is not available. Thus, N_2O mitigation potentials could not be estimated for the UAE.

Table 37: Country Profile UAE

	Nitric Acid	Adipic Acid	Caprolactam
Number of facilities	Unclear, possibly 1 or 2	-	-
Relevant climate policies	none		
N_2O Abatement Technologies in Place	No information available	-	-
Annual Production (2020)	Not available possibly in the range 0.04 – 0.15 Mt	-	-
Annual N_2O emissions (2020)	Not available Possibly in the range: ~0.02 - 1.5 kt N_2O / ~0.01 - 0.4 Mt CO_2e	-	-
N_2O emissions uncertainty estimate	Very high		
Specific N_2O emissions (2020)	Not available		
N_2O mitigation potential	Not available		

Note: N_2O amounts converted into CO_2 equivalents using the GWP of 265 as set out in the 5th IPCC Assessment Report (AR5)
Source: own calculations Öko-Institut

UAE nitric acid production capacities are estimated in the range of 100 – 500 t/a, resulting in annual production amounts of 0.03 – 0.15 million tonnes nitric acid per year. Assuming emission factors ranging between 0.5 kg N_2O/t (well maintained N_2O abatement) and 10 kg N_2O/t no abatement, annual N_2O emission from UAE nitric acid production could plausibly range between 0.015 and 1.5 kt N_2O/a or 0.01 – 0.4 Mt CO_2e/a [GWP AR5].

2.13.2 Presence of N_2O-emitting chemical industries

Little information is available related to the production of ***nitric acid*** in the UAE.

In the UAE's 1st National Communication under the UNFCCC (United Arab Emirates 2007), nitric acid production was reported to take place in that country. However, in our desk research no individual production facility could positively be identified.

Possibly, companies DubiChem and / or Adfert could be operators of a nitric acid plant in the UAE:

- DubiChem identify themselves on their website as "Nitric acid manufacturer, exporter, producer and supplier… in UAE" (DubiChem 2022)

- Adfert is an UAE producer of fertilizers. However, the description of production facilities do not explicitly mention any (intermediate) production of nitric acid. (Adfert 2017)

According to international trade statistics, the UAE did export relatively small volumes of nitric acid, approximately 0.07 % of total Asian nitric acid exports (OEC 2020)

There are no indications that ***adipic acid*** or ***caprolactam*** would be produced in the UAE.

2.13.3 Policies affecting N_2O emission levels

In 1999, the UAE have passed a law[41] which forms the basis for the Environment Agency or Ministry to set conditions for operating licenses for a variety of activities, including chemical industry. However, it is unclear whether greenhouse gases are considered to be environmental pollutants under that law. Respective executive orders spelling out conditions e.g. related to NOx or N_2O emissions from nitric acid production or fertilizer production could not be identified in our research.

2.13.4 N_2O abatement in place

No information could be collected.

2.13.5 N_2O emissions

The UAE did not report on any N_2O emissions from industrial processes in their GHG emission inventories contained in their 1st, 2nd, 3rd and 4th National Communications to the UNFCCC (United Arab Emirates 2007; 2010; 2013; 2018).

However, as potential plausible range of N_2O emissions from UAE nitric acid production is estimated as follows:

UAE nitric acid production capacities are estimated in the range of 150 – 500 t/a, resulting in annual production amounts of 0.04 – 0.15 million tonnes nitric acid per year. Assuming emission factors ranging between 0.5 kg N_2O/t (well maintained N_2O abatement) and 10 kg N_2O/t no abatement, annual N_2O emission from UAE nitric acid production could plausibly range between 0.02 and 1.5 kt N_2O/a or 0.01 – 0.4 Mt CO_2e/a [GWP AR5].

2.13.6 N_2O mitigation potentials

Due to the limited information available, a quantification of the N_2O mitigation potential is not possible.

[41] Federal Law No. 24 of 1999 for the protection and development of the environment

2.14 United Kingdom

2.14.1 United Kingdom summary

The United Kingdom used to be a Member State of the European Union until its withdrawal which took effect in 2020.

In the UK, approximately 1.1 million tonnes of nitric were produced in 2020. Key N_2O mitigation policies include coverage under the EU emissions trading scheme (until 2020) and the new UK emissions trading scheme (since 2021). Secondary catalytic N_2O abatement technologies are in place. Average specific N_2O emissions are estimated at about 0.1 kg/tonne of nitric acid. Given the low emissions level, no additional N_2O mitigation potentials are estimated for the UK.

Table 38: Country Profile United Kingdom

	Nitric Acid	Adipic Acid	Caprolactam
Number of facilities	4 production lines at two sites	-	-
Relevant climate policies	Inclusion in EU ETS until 2020; since 2021: UK-ETS	-	-
N_2O Abatement Technologies in Place	Full coverage with secondary catalytic abatement measures	-	-
Annual Production (2020)	~1.1 Mt [100% HNO_3]	-	-
Annual N_2O emissions (2020)	0.2 kt N_2O / 0.04 Mt CO_2e	-	-
N_2O emissions uncertainty estimate	low	-	-
Specific N_2O emissions (2020)	0.1 kg N_2O/t		
N_2O mitigation potential	none	-	-

Note: N_2O amounts converted into CO_2 equivalents using the GWP of 265 as set out in the 5th IPCC Assessment Report (AR5)
Source: (United Kingdom 2022b; 2022d)

2.14.2 Presence of N_2O-emitting chemical industries

In the United Kingdom, production of nitric acid takes place in 4 production facilities at two sites while production of adipic acid and of caprolactam is absent (United Kingdom 2022d).

UK production levels of nitric acid have been rather constant in the past ten years at approximately 1.1 million tonnes per year (see Table 39).

2.14.3 Policies affecting N_2O emission levels

As a Member of the EU, the UK until 2020 took part in the EU emissions trading scheme (EU-ETS) which covers N_2O emissions from nitric acid production. For more details related to the EU-ETS, see section 2.4.2. Since the UK's withdrawal from the EU coming into effect on 1st January 2021, the UK operates its own emission trading scheme (United Kingdom 2022a) (UK ETS[42])

2.14.4 N_2O abatement in place

The UK reports in its GHG inventory, that since 2011 all of the UK nitric acid production facilities are fitted with EnviNOx SCR abatement which includes heating of the tail gases from the production vessels, followed by NOx and N_2O destruction in a catalyst bed using ammonia gas and hydrocarbon inputs to mitigate the NO_X and N_2O. The UK installations apply the technology in process variant 2 design, which achieves N_2O mitigation performance of around 99.5%.

2.14.5 N_2O emissions

UK N_2O emissions from nitric acid production for 2000-2020 are given in Table 39. Emission intensities were drastically reduced in particular between 2005 and 2011. Since then 2010, specific emissions are rather at very low levels of approximately 0.1 kg N_2O/tonne nitric acid.

Table 39: N_2O emissions from nitric acid production in the United Kingdom

	nitric acid production million tonnes (100% nitric acid)	**N_2O emissions nitric acid production,**	
		kt N_2O	**kg N_2O / t nitric acid**
	reported by the United Kingdom to UNFCCC		
2000	2.03	14.1	6.9
2005	1.71	6.5	3.8
2010	1.21	4.2	3.5
2015	1.13	0.1	0.1
2016	1.17	0.1	0.1
2017	1.22	0.1	0.1
2018	1.08	0.1	0.1
2019	1.19	0.1	0.1
2020	1.14	0.2	0.1

Source: (United Kingdom 2022b)

UK reports the uncertainty of N_2O emission estimates, based on continuous monitoring systems, at 5-10% (United Kingdom 2022d).

2.14.6 N_2O mitigation potentials

UK average specific N_2O emissions from nitric acid production are among the lowest reported from countries covered by the EU-ETS (see Annex I). No additional N_2O mitigation potential can be quantified.

[42] https://www.gov.uk/government/publications/participating-in-the-uk-ets/participating-in-the-uk-ets.

2.15 United States of America

2.15.1 USA summary

Production of nitric acid, adipic acid and caprolactam takes place in the USA. No mitigation policies targeted at N_2O emissions from Chemical industry were identified for the USA beyond NO_x performance standards.

Approximately 8 million tonnes of ***nitric acid*** were produced in 2020. Approximately half of the 32 US nitric acid plants is equipped with N_2O abatement. Average specific N_2O emissions were at 3.9 kg/ tonne of nitric acid. Additional N_2O mitigation potentials are estimated at ~90 %.

Approximately 0.7 million tonnes of ***adipic acid*** were produced in 2020. The two plants are equipped with N_2O abatement. However, low reduction rates are reported. Average specific N_2O emissions were at about 40 kg/ tonne of adipic acid. Additional N_2O mitigation potentials are estimated at ~90 %.

Approximately 0.45 million tonnes of ***caprolactam*** were produced in 2020. No N_2O abatement has been reported. A ~95% N_2O mitigation potential is estimated, compared to the IPCC default of 9 kg N_2O/tonne caprolactam, used for the US GHG inventory.

Table 40: Country Profile USA

	Nitric Acid	Adipic Acid	Caprolactam
Number of facilities	32 facilities, 52 lines	2	2
Relevant climate policies	Performance standards requiring the reduction of NO_x emissions for new or modified plants No federal GHG reduction target but several states have reduction targets which include N_2O. N_2O from nitric acid production is included in the California Cap-and-trade system		
N_2O Abatement Technologies in Place	Abatement technologies at 15 of 32 facilities	Yes, partly of poor quality	n.a.
Annual Production (2020)	8.0 Mt	~0.7 Mt	0.45 Mt
Annual N_2O emissions (2020)	31.2 kt N_2O	27.9 kt N_2O	4.1 kt N_2O
N_2O emissions uncertainty estimate	±5 %	±5 %	~±30 %
Specific N_2O emissions (2020)	3.9 kg N_2O/t	~40 kg N_2O/t	9 kg N_2O/t (IPCC default estimate)
N_2O mitigation potential	Gap to emission intensity benchmark of ambitious mitigation policy: ~ 90% / ~26 – 29 kt N_2O/a ~7-8 Mt CO_2e/a 'Low-hanging fruit' potential in unabated plants: ~71% /~22 kt N_2O/a ~5.9 Mt CO_2e/a	~ 90% / ~25 t N_2O/a ~6.75 Mt CO_2e/a	~ 93% / ~3.8 t N_2O/a ~1.0 Mt CO_2e/a

Note: N_2O amounts converted into CO_2 equivalents using the GWP of 265 as set out in the 5th IPCC Assessment Report (AR5)
Source: Number of facilities and information on abatement technologies from EPA (2022b), Annual production and N_2O emissions from United States of America (2022a), EPA (2022a), own calculation of Öko-Institut

2.15.2 Presence of N_2O-emitting chemical industries

In the USA, there is production of nitric acid, adipic acid and caprolactam.

Nitric Acid

In 2020, there were 32 facilities in the US producing nitric acid, with an annual production of 7970 kt. Less than half of those plants (15 out of 32) have N_2O abatement technologies installed (EPA 2022b).

Adipic Acid

There were 2 facilities producing adipic acid in the US in 2020, Ascend Performance Materials in Florida and INV Nylon Chemicals Americas in Texas, both of which have abatement technologies in place. Both plants are also producing nitric acid (EPA 2022b). However, according to Phil McKenna (2022), the abatement facility at the plant in Florida only abated 70 % of its N_2O emissions and while the company announced to improve their N_2O destruction, it remained unclear whether those efforts were met at the time of writing of this report.

Caprolactam

As of 2020, two companies in the United States produce caprolactam at two facilities: AdvanSix in Virginia and BASF in Texas (EPA 2022a). There were three facilities in operation until 2018 and one additional one operating 2000-2001 and 2007-2005.

2.15.3 Policies affecting N_2O emission levels

In 2014, U.S. EPA revised the New Source Performance Standards (NSPS) emissions standards for nitric acid facilities. The standards limit emissions of NO_x from new, modified, and reconstructed nitric acid plants, which will need to meet a NO_x emission limit of 0.5 lb NO_x per ton of nitric acid produced, as a 30-day average emission rate. This emission limit always applies, including periods of start-up, shutdown and malfunction[43].

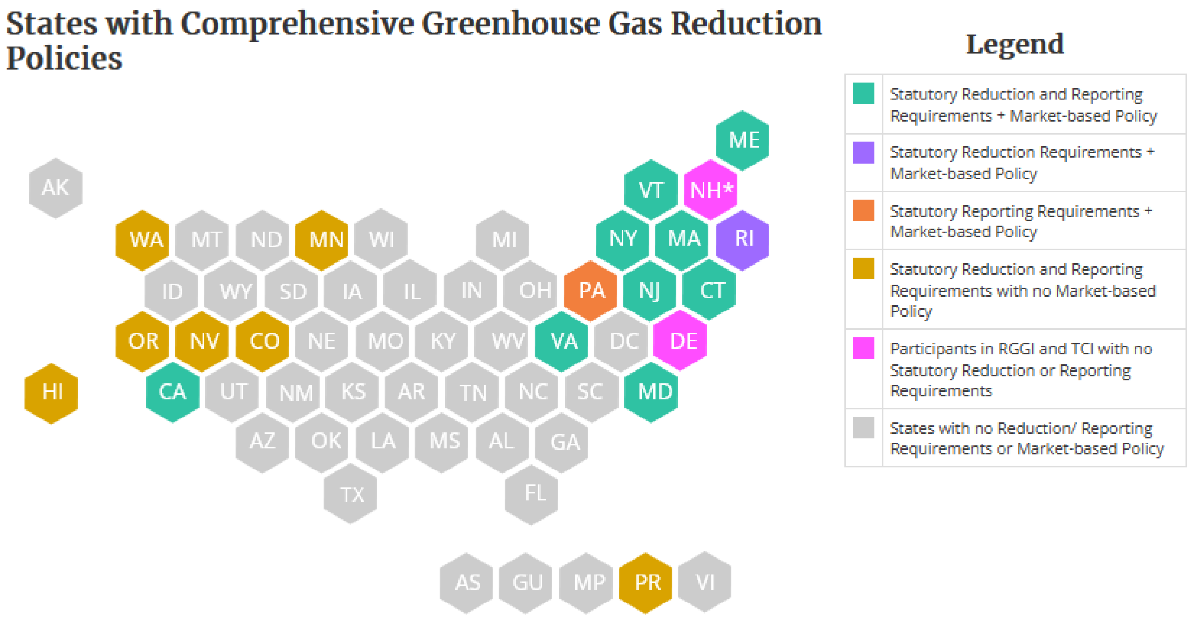
Currently, there is no federal reduction target for GHG emissions in effect.

The state of California has a cap-and-trade program, and nitric acid facilities are covered entities under that system[44]. Adipic acid and caprolactam producing facilities are not covered but there is no production of either taking place in California. Other cap-and-trade programs in the US are only targeting emissions from power generation.

Further states have GHG targets or are considering GHG targets: 16 states and Puerto Rico have introduced legislation on GHG emission reductions. These targets mostly include emissions from N_2O. Others have no binding targets but require GHG reduction trough executive action[45].

[43] https://www.epa.gov/stationary-sources-air-pollution/nitric-acid-plants-new-source-performance-standards-nsps#rule-summary
[44] https://ww2.arb.ca.gov/our-work/programs/cap-and-trade-program
[45] https://www.ncsl.org/research/energy/greenhouse-gas-emissions-reduction-targets-and-market-based-policies.aspx

Figure 2: Overview on GHG reduction legislation in the USA



Source: National Conference of State legislatures, https://www.ncsl.org/research/energy/greenhouse-gas-emissions-reduction-targets-and-market-based-policies.aspx

2.15.4 N_2O abatement in place

Nitric Acid

According to the data available in the US EPA's FLIGHT database (EPA 2022b), 15 out of 32 facilities producing nitric acid are equipped with N_2O abatement technologies. The majority of those are indicated to be NSCR (10). Furthermore, the list contains one SCR installation, 3 non-specified secondary N_2O abatement catalysts and 2 tertiary catalysts (one of which is installed in combination with a secondary abatement catalyst).

Adipic Acid

Both of the adipic acid production facilities have abatement technologies in place (EPA 2022b). According to EPA (2022a), Pollution control measures in the late 1990s lead to the installation of abatement technologies, after which the emissions from adipic acid production decreased by 45 %. However, according to Phil McKenna (2022), one of the plants which is the world's largest adipic acid plant did abate N_2O emissions by only 70 % while other operators achieve 95 % or more emission abatement.

Caprolactam

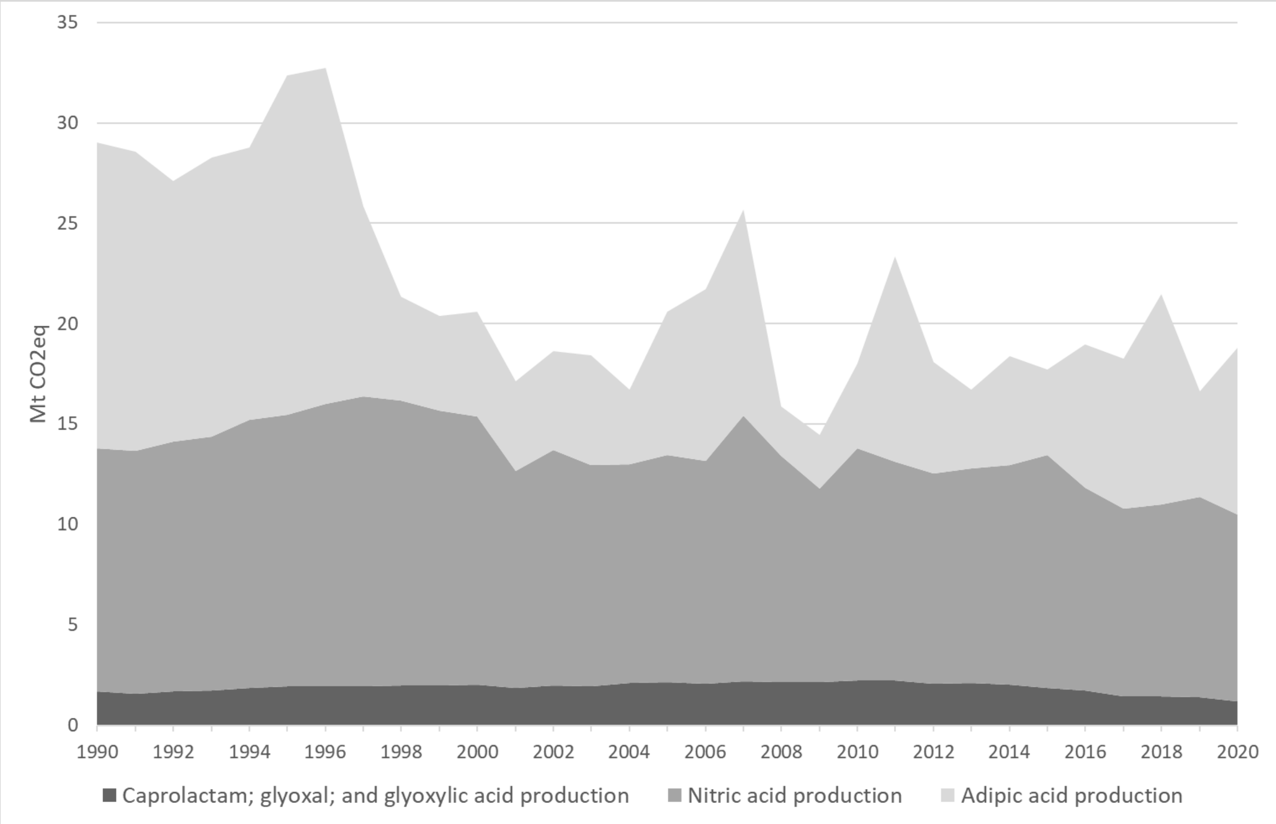
No detailed information on abatement technologies available. The operator of the caprolactam plant in Virginia indicates the installation of a system reducing NO_x emissions from the site by

~80 %/year[46]. In the US GHG inventory N_2O emissions from caprolactam are calculated using the IPCC default emission factor of 9 kg N_2O/t caprolactam, assuming no N_2O abatement.

2.15.5 N_2O emissions

Figure 3 shows emissions from nitric acid, adipic acid and caprolactam production for the years 1990 to 2020 (in CO_2e).

Figure 3: U.S. GHG emissions from Nitric acid, adipic acid and caprolactam production



Source: EPA (2022a)

46 https://www.advansix.com/hopewell/about-us/

Nitric acid production

N_2O emissions from nitric acid production in the USA have decreased from about 44 kt N_2O/a in 2000 to about 31-33 kt N_2O/a in 2017-2020 (see Table 41). Since the production of nitric acid remained fairly constant at ~7-8 million tonnes of nitric acid, this indicates the installation of abatement technologies within this time period.

Table 41: N_2O emissions from USA nitric acid production

	Nitric acid production	N_2O emissions of nitric acid production	
	million tonnes (100% nitric acid)	kt N_2O	kg N_2O / t nitric acid
	reported by USA to UNFCCC		
2000	7.90	44.7	5.7
2005	6.71	38.0	5.7
2010	7.45	38.7	5.2
2015	7.21	38.8	5.4
2016	7.81	34.0	4.4
2017	7.78	31.3	4.0
2018	8.21	32.1	3.9
2019	8.08	33.5	4.1
2020	7.97	31.2	3.9

Source: United States of America (2022a), own calculations Öko-Institut

The uncertainty of N_2O emissions from nitric acid production in the US Inventory is indicated with ±5 % for the period after 2010, while uncertainty on production data is estimated to be at ±2 % (EPA 2022a).

Adipic acid production

N_2O emissions from US adipic acid production (Table 42) occur in the same order of magnitude as N_2O from nitric acid production (Table 41).

Adipic acid production in the USA has decreased by approximately 7 % over the period of 1990-2020, and was at about 0.7 Mt in 2020, according to EPA (2022a). The exact value for adipic acid production between 2010 and 2020 are considered confidential in the US GHG inventory since there currently are only two active facilities. However, production quantities for many years considered confidential in the GHG inventory have been published by the American Chemistry Council (cited in EPA (2022a)). N_2O emissions from adipic acid production were estimated to be about 28 kt N_2O in 2020. Over the period 1990 through 2020, facilities have reduced emissions by about 45 % due to pollution control measures enforced starting in the late 1990s. Operation of the N_2O abatement installation at one adipic acid facility was not continuous, leading to significant fluctuations in emissions over the period from 2016-2020 (EPA 2022a).

Table 42: N_2O emissions from USA adipic acid production

	adipic acid production		N_2O emissions of adipic acid production	
	million tonnes (100% adipic acid)		kt N_2O	kg N_2O / t adipic acid
	reported by USA to UNFCCC	American Chemistry Council	reported by USA to UNFCCC	Calculated here from emissions and production data
1990	0.76	0.76	51.0	67.6
1995	0.80	-	56.6	70.8
2000	0.89	-	17.6	19.8
2005	0.87	0.87	24.0	27.7
2010	C	-	14.2	C
2015	C	-	14.3	C
2016	C	0,86	23.9	27.8
2017	C	0.83	25.0	30.2
2018	C	0.83	35.2	42.7
2019	C	0.81	17.6	21.8
2020	C	~0.7	27.9	~40

Note: C: confidential
Source: United States of America (2022a), EPA (2022a); own calculations Öko-Institut

The uncertainty of N_2O emissions from nitric acid production in the US Inventory is indicated with ±5 % for 2020 (EPA 2022a).

Caprolactam production

Trends in N_2O emissions from US caprolactam production are mostly influenced by the operation of less facilities over the years (see section 2.15.5). Production has been declining since 2013 (EPA 2022a).

Table 43: N_2O emissions from USA caprolactam production

	caprolactam production	N_2O emissions of caprolactam production	
	million tonnes (100% caprolactam)	Kt N_2O	kg N_2O / t caprolactam
	reported by USA to UNFCCC		
2000	0.76	6.8	9.0
2005	0.80	7.2	9.0
2010	0.84	7.5	9.0
2015	0.70	6.3	9.0
2016	0.64	5.8	9.0
2017	0.55	4.9	9.0
2018	0.53	4.8	9.0
2019	0.52	4.6	9.0
2020	0.45	4.1	9.0

Source: United States of America (2022a), own calculations Öko-Institut

EPA (2022a) indicates the uncertainty for N_2O emissions from caprolactam production in 2020 to be at ~±31-32 %.

2.15.6 N_2O mitigation potentials

Nitric acid

US specific emissions of ~ 4 kg N_2O/t nitric acid are very high compared to European levels.

Benchmarks derived from the EU-ETS countries would be 0.43 kg/t as EU-ETS average, 0.26 kg/t as average of the top half of EU-ETS or 0.6 kg/t for the bottom half of EU-ETS participants (see Annex I).

These EU-ETS benchmarks are at ~7-15% of present US emission intensities. Respective mitigation potentials for N_2O from the US's nitric acid production add up to ~26 – 29 kt N_2O/a or ~ 7-8 Mt CO_2e/a (GWP AR5).

From data retrieved from EPA (2022b), 17 out of 32 facilities producing nitric acid in 2020 did not have N_2O abatement technologies installed. Retrofitting some or all of those plants with abatement systems could thus substantially reduce US N_2O emissions from nitric acid production.

In a bottom-up perspective focussing on nitric acid plants without any present N_2O abatement we consider a ~95 % reduction of unabated N_2O emissions at all sites presently without abatement and thus estimate a low-cost mitigation potential at approximately 22 kt N_2O/a or 5.9 Mt CO_2e / a (i.e. approximately 71 % of the U.S.'s 2020 N_2O emissions from nitric acid production).

Adipic Acid

One of the adipic acid plants in the US only abated 70% of its emissions in 2020 (Phil McKenna 2022). Since state-of-the-art abatement technologies for adipic acid plants should achieve higher abatement rates, the mitigation potential for N_2O emissions from adipic acid production in the US is substantial.

Compared to the benchmark for N_2O from adipic acid production developed from EU data in Annex II, the potential for additional N_2O mitigation in US plants is ~90%, or ~25 kt N_2O/a (6.75 Mt CO_2e/a [GWP AR5]).

Caprolactam

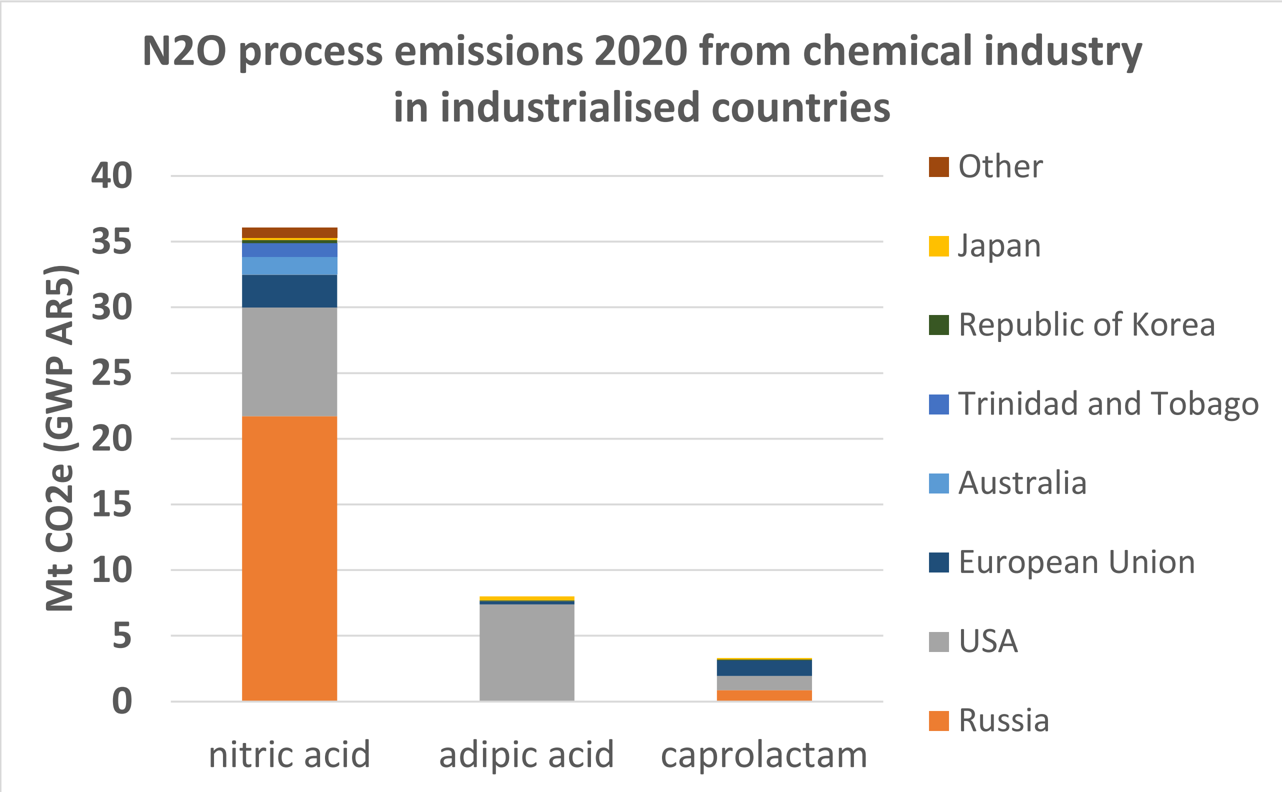
In US caprolactam production no N_2O mitigation appears to be in application so far (beyond NO_x abatement). The benchmark for emission intensities achievable by ambitious waste gas treatment is at 0.6 kg N_2O / t caprolactam (see Annex III), i.e. 7% of the IPCC default of 9 kg/t used for the USA. Application of N_2O abatement thus might lead to a 93% reduction, equal to approx. 3.8 kt N_2O/a (1.0 Mt CO_2e [GWP AR5]).

3 Cross-country overview and conclusions

3.1 N_2O emission from chemical industry overview

2020 process emissions of N_2O from chemical industry in industrialised countries world-wide are estimated at 47.4 Mt CO_2e (GWP AR5), thereof 76 % (36.1 Mt CO_2e) from nitric acid production, 17 % (8.0 Mt CO_2e) from adipic acid production and 7 % (3.3 Mt CO_2e) from caprolactam production (Figure 4).

Figure 4: N_2O process emissions 2020 from chemical industry in industrialised countries



Note: 'Other' countries: Canada, Chile, Israel, Norway, Saudi Arabia, Singapore, United Arab Emirates, United Kingdom
Source: own representation of study results

The countries and regions contributing most to N_2O emissions are Russia, the USA, the EU, Australia and Trinidad and Tobago for nitric acid production, the USA for adipic acid production, and the EU, the USA and Russia for caprolactam production.

Climate policies affecting N_2O emissions from chemical industry for the key contributors are missing in particular for Russia, the USA, Trinidad and Tobago, and, albeit only for caprolactam production, in the EU. An overview on relevant climate policies identified for the studied countries and regions is given in Table 44:

Table 44: Cross-country overview: climate policies affecting N_2O emissions from nitric acid, adipic acid and caprolactam production

	Present production processes	Climate policies affecting N_2O process emissions from chemical industry
Australia	Nitric acid	Emissions Reductions Fund (ERF): voluntary carbon credit scheme; ERF safeguard mechanism: obligation for large emitters to keep GHG emissions below individual baseline, use of carbon credits for compliance is possible
Canada	Nitric acid	Canadian Environmental Protection Act Greenhouse Gas Pollution Pricing Act
Chile	Nitric acid	No active policies targeting N_2O from the chemical industry. Carbon tax targets NO_x on stationary sources
European Union	Nitric acid Adipic acid Caprolactam	Inclusion in EU ETS (nitric acid & adipic acid); none for caprolactam production
Israel	Nitric acid	Limits on N_2O exhaust concentrations as part of environmental permits
Japan	Nitric acid Adipic acid Caprolactam	No active policies targeting N_2O emissions from chemical industry. Under the “J-credits” baseline & credit scheme, no approved methodology is available for N_2O abatement in chemical industry.
Republic of Korea	Nitric acid Adipic acid Caprolactam	N_2O emissions from chemical industry are covered under the Korea Emissions Trading Scheme since the 3rd K-ETS phase starting 2021. In K-ETS phases 1 & 2 (2015-2017 / 2018-2020), exemptions for facilities approved under the CDM applied.
Norway	Nitric acid	Inclusion in EU-ETS
Russia	Nitric acid Caprolactam	No specific policies targeting N_2O from chemical industry. Framework legislation provides foundation for addressing N_2O emissions. However, lack of ambition of 2030 GHG target implies little probability for additional instruments to be applied.
Saudi-Arabia	Nitric acid	None identified
Singapore	Nitric acid	Since 2019: Singapore carbon tax of 5 S$/ t CO_2e (~ 0.7 EUR / S$) scheduled to rise to 25 S$/ t CO_2e by 2024, 45 S$/ t CO_2e by 2026, and 50-80 S$/ t CO_2e by 2030. No policies targeting industry N_2O emission before 2019.
Trinidad and Tobago	Nitric acid	None identified
United Arab Emirates	Nitric acid	None identified
United Kingdom	Nitric acid	Inclusion in EU ETS until 2020; since 2021: UK-ETS
United States of America	Nitric acid Adipic acid Caprolactam	Performance standards requiring the reduction of NO_x emissions for new or modified plants No federal GHG reduction target but several states have reduction targets which include N_2O. N_2O from nitric acid production is included in the California Cap-and-trade system

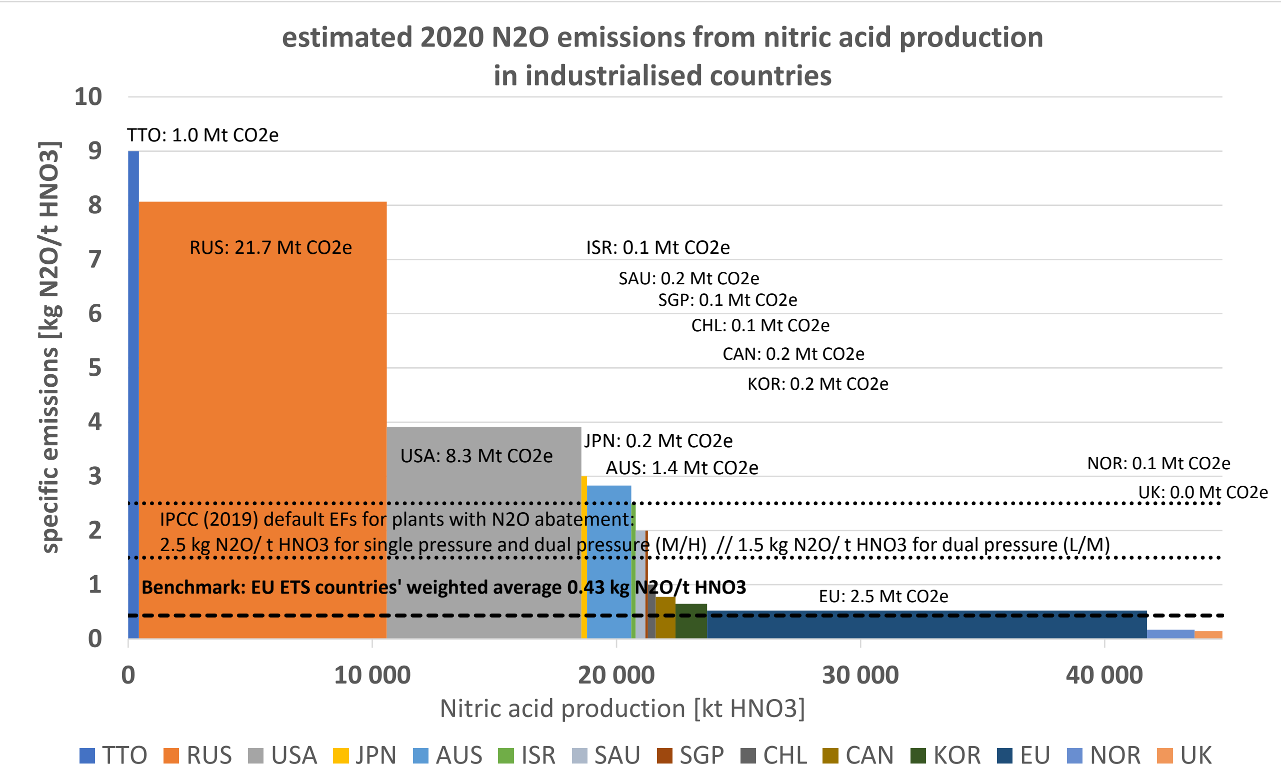
3.2 Nitric acid production overview

For nitric acid production, Figure 5 depicts estimated 2020 N_2O emissions per country as the area of the respective rectangles. Nitric acid production amounts per country are represented by the width of the rectangles while the height represents the emission intensity (specific emissions) of nitric acid production. Estimated emission intensities range from very high 8-9 kg N_2O/ t HNO_3 (Trinidad and Tobago, Russia) to low 0.5 kg/t and less for Western European countries and Korea.

Emission intensities identified for countries can be compared to a set of different benchmarks given as horizontal lines:

- The weighted average of countries participating in the EU-ETS in 2020 (27 EU Member States, Norway, and the United Kingdom) of 0.43 kg N_2O/ t HNO_3 can be considered a benchmark for emission intensities achievable by the means of ambitious climate policies like the EU-ETS. However, the technical effort needed to achieve very low emission intensities is influenced by plant pressure characteristics, and such low emission intensities may be more costly to achieve in countries where predominantly high-pressure plants are operated.
- Thus, 1.5 or 2.5 kg N_2O / t HNO_3 are given by the IPCC as default emission factors assumed realistic for abated nitric acid plants, depending on pressure characteristics of the respective plants.

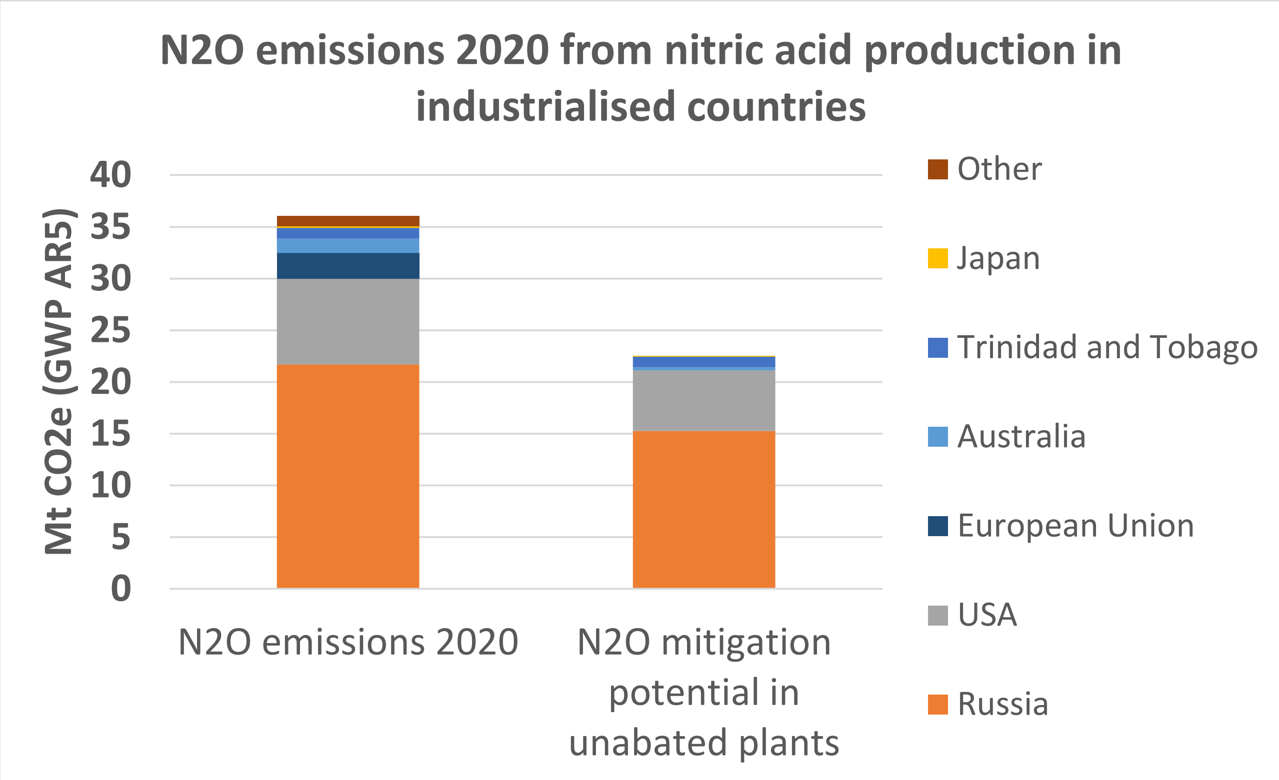
Figure 5: Estimated 2020 N_2O emissions from nitric acid production in industrialised countries



Notes: N_2O amounts converted into CO_2 equivalents using the GWP of 265 as set out in the 5th IPCC Assessment Report (AR5)
TTO: Trinidad and Tobago; RUS: Russian Federation; JPN: Japan; AUS: Australia; ISR: Israel; SAU: Saudi-Arabia; SGP: Singapore; CHL: Chile; CAN: Canada; KOR: Republic of Korea; EU: European Union (27 member states after Brexit); NOR: Norway; UK: United Kingdom; United Arab Emirates not displayed due to high uncertainty
EF: Emission factor
Sources: IPCC (2019), own representation of study results

While Figure 5 visualises benchmark-based N_2O mitigation potentials the realisation of which could possibly involve additional measures to be taken in plants already equipped with N_2O abatement equipment, Figure 6 summarises the results of the identification of rather easily realisable 'low-hanging fruit' mitigation potentials in production plants not yet equipped with any secondary or tertiary N_2O abatement:

Figure 6: 2020 N_2O emissions from nitric acid production in industrialised countries and mitigation potentials in unabated plants



Note: 'Other' countries: Chile, Israel, Republic of Korea, Norway, Saudi Arabia, Singapore, United Arab Emirates, United Kingdom
Source: own representation of study results

Such low-hanging fruit N_2O mitigation potentials in nitric acid production of industrialised countries sum up to 63 % of total N_2O emissions from nitric acid production estimated for 2020 (22.5 Mt CO_2e mitigation potential out of 36.1 Mt CO_2e 2020 emissions). These mitigation potentials are primarily located in Russia, the USA and Trinidad & Tobago. Additional single plants without abatement were identified for Australia and Japan. For Australia, however, a retrofit project was reported to be underway, for Canada an abatement upgrade was reported as completed in 2022, reducing Canadian emissions by 25 % or 0.04 Mt CO_2e/a.

A full cross-country overview of key information collected for N_2O from nitric acid production is given in Table 45:

Table 45: Cross-country overview nitric acid production

	Number of facilities	N_2O Abatement Technologies in Place	Annual Production (2020)	Annual N_2O emissions (2020)	Specific N_2O emissions (2020)	'low-hanging fruit' N_2O mitigation potential in unabated plants
Australia	12 lines / 6 locations	Secondary / tertiary catalysts installed in ~ 80 % of HNO_3 production capacity	1.8 Mt [100% HNO_3]	1.4 Mt CO_2e Uncertainty ± 15 %	2.9 kg N_2O/t	~20 %
Canada	8 lines / 5 locations	All plants are equipped with abatement technologies, mostly tertiary catalysts	0.8 Mt [100% HNO_3]	0.6 Mt CO_2e Uncertainty ~1 %	0.8 kg N_2O/t	No unabated plants. However, emission reduction of ~25 % achieved by upgrade of abatement system
Chile	3 lines/ 1 location	Secondary catalysts partly installed, partly unclear	~0.3 Mt [100% HNO_3]	0.1 Mt CO_2e Uncertainty: ~3 %	1.0 kg N_2O/t	Unclear. One Plant has no abatement installed but has unclear operational status
European Union	~60 facilities in 19 Member States	Widespread application of secondary and/or tertiary abatement measures	~18 Mt [100% HNO_3]	2.5 Mt CO_2e Uncertainty ~ 9 %	~0.5 kg N_2O/t	Not estimated
Israel	4 lines / 2 locations	N_2O abatement was installed under the CDM before 2010. Present ambition of use of mitigation equipment is unclear.	~ 0.2 Mt [100% HNO_3]	~ 0.12 Mt CO_2e Uncertainty: - 50 % / + 300 %	~2.5 kg N_2O/t	Not estimated
Japan	10	Catalytic decomposition units at least partly in use (estimated at 75 % of capacity)	0.23 Mt [100% HNO_3]	0.2 Mt CO_2e Uncertainty: 73 %	3.0 kg N_2O/t	~50%
Republic of Korea	6	All plants are equipped with abatement technologies	1.3 Mt [100% HNO_3]	0.2 Mt CO_2e Uncertainty estimate not available	~ 0.6 kg N_2O/ t	none

	Number of facilities	N_2O Abatement Technologies in Place	Annual Production (2020)	Annual N_2O emissions (2020)	Specific N_2O emissions (2020)	'low-hanging fruit' N_2O mitigation potential in unabated plants
Norway	2	complete application of secondary catalytic abatement measures	~2 Mt [100% HNO_3]	0.1 Mt CO_2e Uncertainty: low (~1-7 %)	0.2 kg N_2O/t	none
Russia	64 production lines / 14 operators	catalytic NO_x abatement in place, no targeted N_2O abatement	10.2 Mt [100% HNO_3]	GHG inventory: 5.4 Mt CO_2e Own estimate: 21.7 Mt CO_2e Uncertainty: very high	GHG inventory: 2 kg N_2O/t Own estimate: 8.1 kg N_2O/t	~70 %
Saudi-Arabia	1	Yes. No information on type of system	Plant capacity ~0.4 Mt HNO_3 /a	~0.05 – 0.25 Mt CO_2e Uncertainty very high	Not available 2019 IPCC refinement defaults: 1.5-2.5 kg N_2O/t1	Not estimated
Singapore	1	Uncertain: 2012 CDM application for tertiary catalytic N_2O destruction was cancelled.	Plant capacity ~ 0.1 Mt HNO_3/a	Uncertain If unabated, up to ~0.27 Mt CO_2e	Not available	Not estimated
Trinidad and Tobago	1	None	Plant capacity: ~0.5 Mt HNO_3 /a	~1 Mt CO_2e Uncertainty: high	Possibly ~ 9 kg N_2O/t for an unabated plant	~98%
United Arab Emirates	Unclear, possibly 1 or 2	No information available	Not available possibly in the range 0.04 – 0.15 Mt	Not available Possibly in the range ~0.01 - 0.4 Mt CO_2e	Not available	Not estimated
United Kingdom	4 production lines at two sites	Full coverage with secondary catalytic abatement measures	~1.1 Mt [100% HNO_3]	0.04 Mt CO_2e Uncertainty: low	0.1 kg N_2O/t	none
United States of America	32 facilities, 52 lines	Abatement technologies at 15 of 32 facilities	8.0 Mt	8.3 Mt CO_2e Uncertainty: ±5 %	3.9 kg N_2O/t	~71%

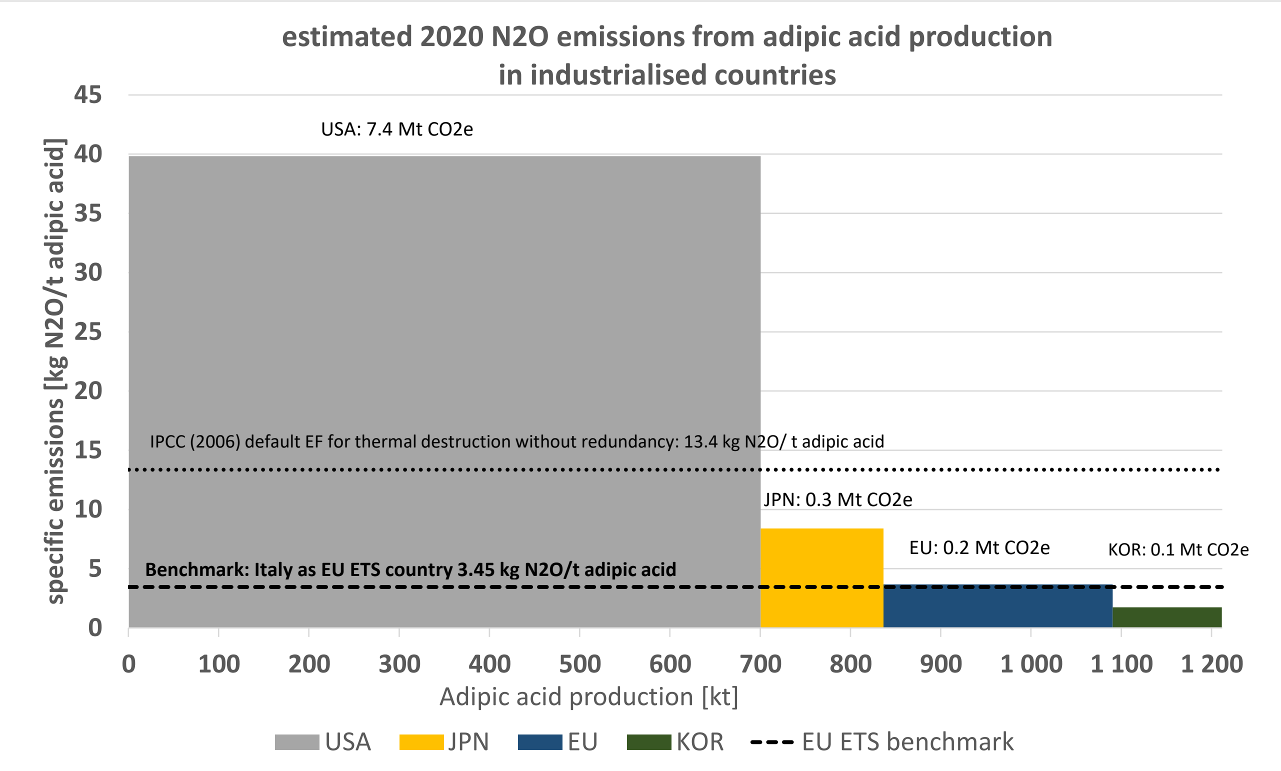
Note: N_2O amounts converted into CO_2 equivalents using the GWP of 265 as set out in the 5th IPCC Assessment Report (AR5)

3.3 Adipic acid production overview

For adipic acid production, Figure 7 depicts estimated 2020 N_2O emissions per country in comparable representation used for nitric acid in Figure 5. Estimated emission intensities range from a very high 40 kg N_2O/ t (USA) to as low as 2-4 kg/t and less for the EU and Korea.

Adipic acid production is taking place in only six of the industrialised countries studied, i.e., the USA, Japan, Korea and the EU Member States France, Germany and Italy. While ambitious mitigation is taking place in Japan, Korea and the EU, the mitigation efforts in the USA are insufficient, as available mitigation equipment appears to be operated poorly.

Figure 7: Estimated 2020 N_2O emissions from adipic acid production in industrialised countries



Notes: N_2O amounts converted into CO_2 equivalents using the GWP of 265 as set out in the 5th IPCC Assessment Report (AR5)
JPN: Japan; EU: European Union (27 member states after Brexit); KOR: Republic of Korea
EF: Emission factor
Sources: IPCC (2006), own calculations of Öko-Institut, own representation of study results

A full cross-country overview of key information collected for N_2O from adipic acid production is given in Table 46:

Table 46: Cross-country overview adipic acid production

	Number of facilities	N_2O Abatement Technologies in Place	Annual Production (2020)	Annual N_2O emissions (2020)	Specific N_2O emissions (2020)	'low-hanging fruit' N_2O mitigation potential in unabated plants
Canada	None active (plant closed 2009)	-	-	-	-	-
European Union	5	Widespread application of secondary and/or tertiary abatement measures	~0.25 Mt	0.25 Mt CO_2e Uncertainty: ~9 %	Not available for EU27 ~ 4 kg N_2O /t (Italy)	none
Japan	1	N_2O decomposition unit installed 1999	not available (~0.17 Mt/a production capacity)	0.3 Mt CO_2e Uncertainty: 9 %	Not available	none
Republic of Korea	1	Yes	0.12-0.14 Mt (in 2012)	~0.1 Mt CO_2e Uncertainty estimate not available	~ 1.7 kg N_2O/ t	none
Singapore	None active (1 plant closed 2012)	Plant was equipped with N_2O abatement	-	-	-	-
United States of America	2	Yes, but partly of poor quality	~0.7 Mt	7.4 Mt CO_2e Uncertainty: ±5 %	~40 kg N_2O/t	Not estimated

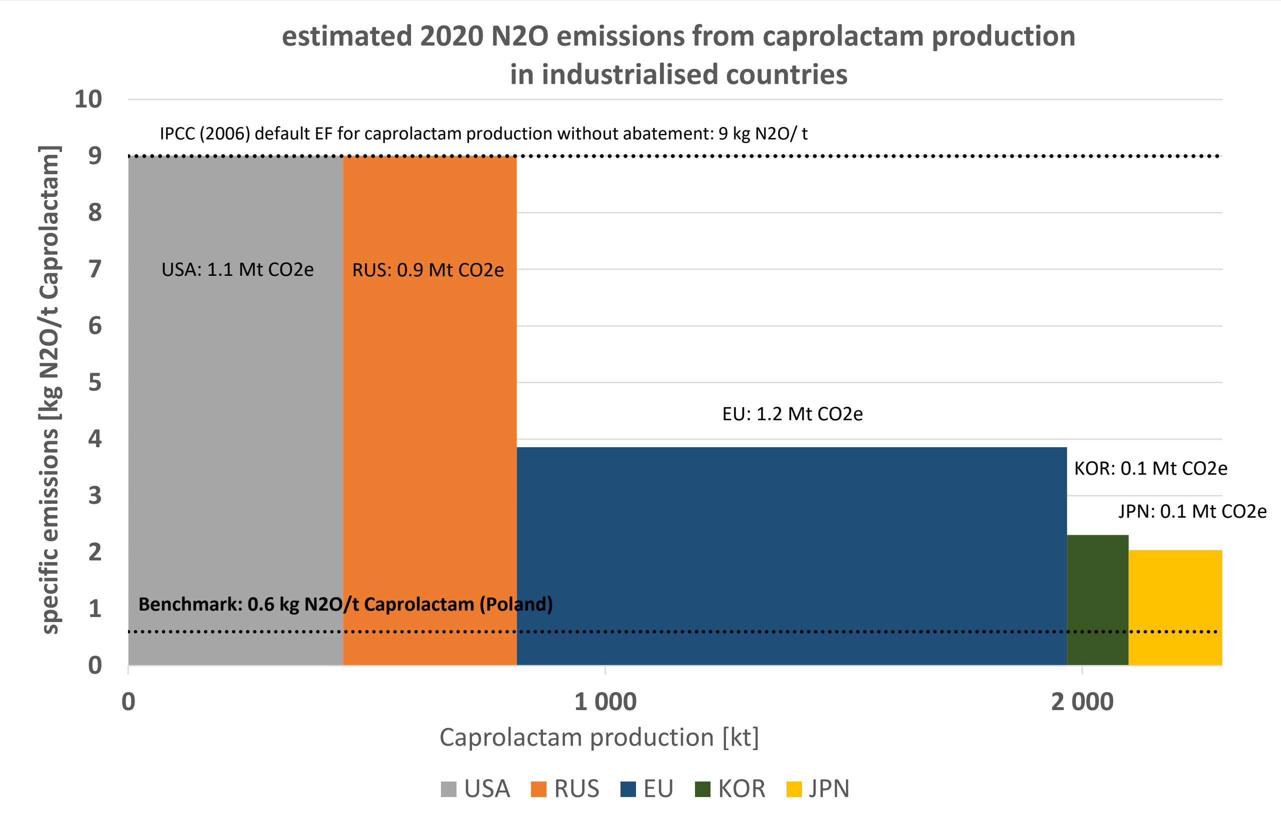
Note: N_2O amounts converted into CO_2 equivalents using the GWP of 265 as set out in the 5th IPCC Assessment Report (AR5)

3.4 Caprolactam production overview

For caprolactam production, Figure 8 depicts estimated 2020 N_2O emissions per country in a comparable representation used for nitric acid in Figure 5 and for adipic acid in Figure 7. Estimated emission intensities range from a very high 9 kg N_2O/ t (IPCC (2006) default emission factor applied for the USA and Russia) to as low as 2 kg/t for Japan and Korea. Even lower emission rates were reported for some EU Member States such as Poland (0.6 kg N_2O/t) and Germany (nearly complete elimination).

Caprolactam production is taking place in ten of the industrialised countries studied, i.e. the USA, Russia, Japan, Korea and the six EU Member States Belgium, Czechia, Germany, Netherlands, Poland and Spain. While ambitious mitigation is taking place in Japan, Korea and some EU countries, the mitigation efforts are insufficient in the USA, Russia and other EU countries (unlike nitric acid and adipic acid production, N_2O emissions from caprolactam production are not covered by the EU-ETS).

Figure 8: Estimated 2020 N_2O emissions from caprolactam production in industrialised countries



Notes: N_2O amounts converted into CO_2 equivalents using the GWP of 265 as set out in the 5th IPCC Assessment Report (AR5)
RUS: Russian Federation; EU: European Union (27 member states after Brexit); KOR: Republic of Korea, JPN: Japan
EF: Emission factor
Sources: IPCC (2006), own representation of study results

A full cross-country overview of key information collected for N_2O from caprolactam production is given in Table 47:

Table 47: Cross-country overview caprolactam production

	Number of facilities	N_2O Abatement Technologies in Place	Annual Production (2020)	Annual N_2O emissions (2020)	Specific N_2O emissions (2020)	'low-hanging fruit' N_2O mitigation potential from unabated plants
European Union	~10	Partial application of primary or tertiary abatement measures	~1 Mt	1.2 Mt CO_2e Uncertainty: ~9 %	Not available for EU27 ~ 4 kg N_2O/t (Belgium/Poland)	Not estimated
Japan	3 (one of those announced to be closed in October 2022)	abatement units at least partly in use (estimated at 80 % of capacity)	0.2 Mt	0.1 Mt CO_2e Uncertainty: 99 %	2.0 kg N_2O/t	Not estimated
Republic of Korea	1	Yes	0.13 Mt (in 2010), production capacity in 2020: 0.27 Mt	~0.1 Mt CO_2e Uncertainty estimate not available	˜ 2.3 kg N_2O/ t	None
Russia	3 operators	no N_2O abatement		0.9 Mt CO_2e Uncertainty: ±40 %	9 kg N_2O/t (IPCC default estimate)	Not estimated
United States of America	2	No information available	0.45 Mt	1.1 Mt CO_2e Uncertainty: ±30 %	9 kg N_2O/t (IPCC default estimate)	Not estimated

Note: N_2O amounts converted into CO_2 equivalents using the GWP of 265 as set out in the 5th IPCC Assessment Report (AR5)

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Annexes

Annex I. Benchmark for N_2O Emissions from nitric acid production

2020 emissions and production data from countries participating in the EU-ETS were used to derive a benchmark for the quantification of N_2O mitigation potentials in this study. Considered countries (Table 48) include Norway and the United Kingdom which are/were participating in the EU-ETS. The United Kingdom has left the EU-ETS after Brexit, the UK ETS is operational since 2021.

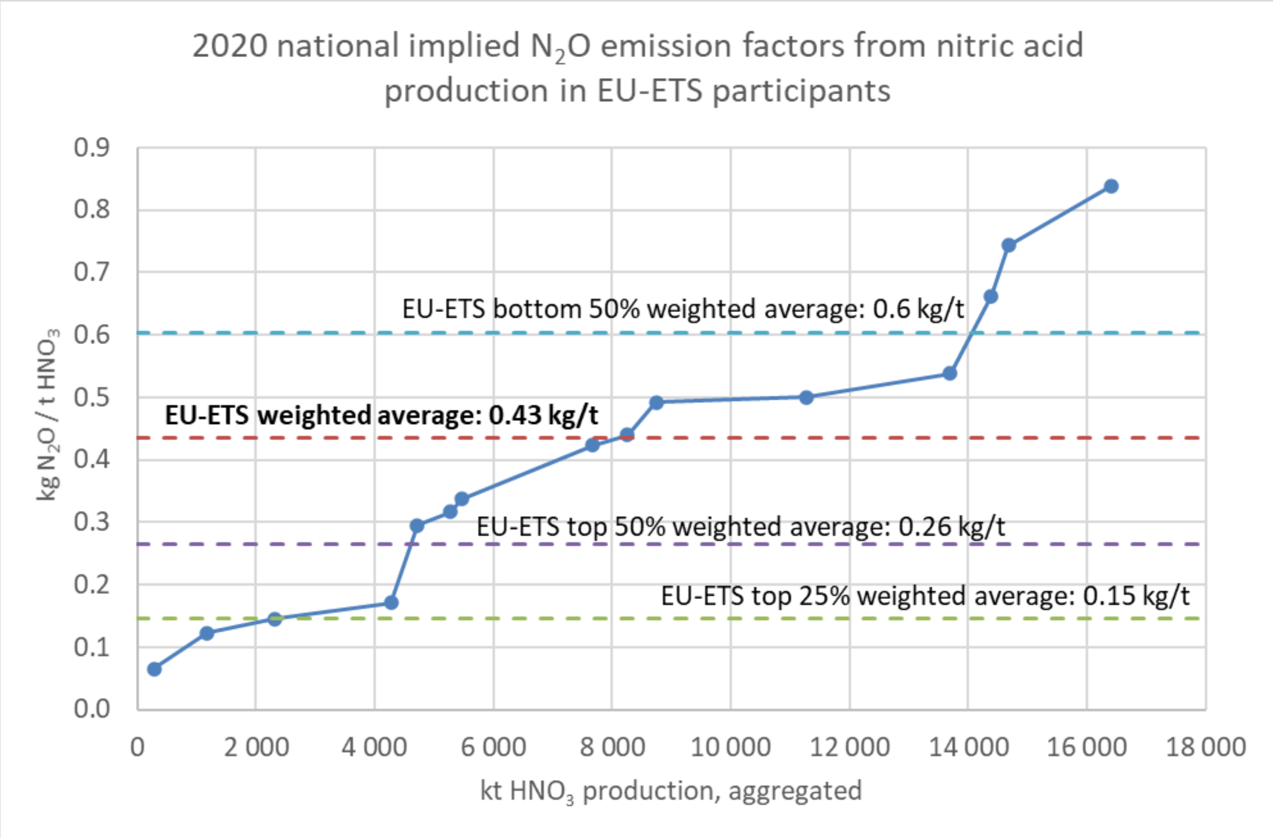
Table 48: 2020 production of nitric acid and related N_2O emissions in European countries participating in the EU-ETS

Considered ETS participants	2020 Nitric acid production *kt Nitric acid (100% HNO_3)*	2020 N_2O Emissions *kt N_2O*	2020 implied emission factor *kg N_2O /t HNO_3*
Sweden	280	0.02	0.07
Hungary	900	0.11	0.12
United Kingdom	1141	0.17	0.15
Norway	1951	0.33	0.17
Italy	447	0.13	0.30
Austria	557	0.18	0.32
Greece	189	0.06	0.34
Belgium	2209	0.93	0.42
Slovakia	580	0.25	0.44
Czechia	492	0.24	0.49
Germany	2535	1.27	0.50
Poland	2413	1.30	0.54
Spain	692	0.46	0.66
Croatia	294	0.22	0.74
France	1731	1.45	0.84
Total considered EU-ETS	**16412**	**7.1**	**0.43**
Not considered ETS participants with nitric acid production			
Finland (reported emissions data include integrated fertiliser production)	659	0.76	1.15
Bulgaria	confidential	0.27	confidential
Netherlands	confidential	0.67	confidential
Portugal	confidential	0.11	confidential
Romania	confidential	0.31	confidential

Source: (Sweden 2022a; Hungary 2022a; Norway 2022a; Italy 2022a; Austria 2022a; Greece 2022a; Belgium 2022a; Slovakia 2022; Czechia 2022a; Germany 2022a; Poland 2022a; Spain 2022a; Croatia 2022a; France 2022a; United Kingdom 2022c); own calculations

Finnish data were not used for the analysis as Finland reports in CRF category 2.B.2 N_2O-Emissions from fertiliser production jointly with N_2O emissions from nitric acid production (Finland 2022b). Data from Bulgaria, the Netherlands, Portugal and Romania could not be used as nitric acid production levels were not publicly reported for confidentiality reasons. EU Member States not included in Table 48 do not host nitric acid production. Figure 9 presents the distribution of respective national implied emission factors and weighted averages:

Figure 9: 2020 N_2O implied emission factors for nitric acid production in EU-ETS countries



Sources: (Sweden 2022a; Hungary 2022a; Norway 2022a; Italy 2022a; Austria 2022a; Greece 2022a; Belgium 2022a; Slovakia 2022; Czechia 2022a; Germany 2022a; Poland 2022a; Spain 2022a; Croatia 2022a; France 2022a; United Kingdom 2022c); own calculations

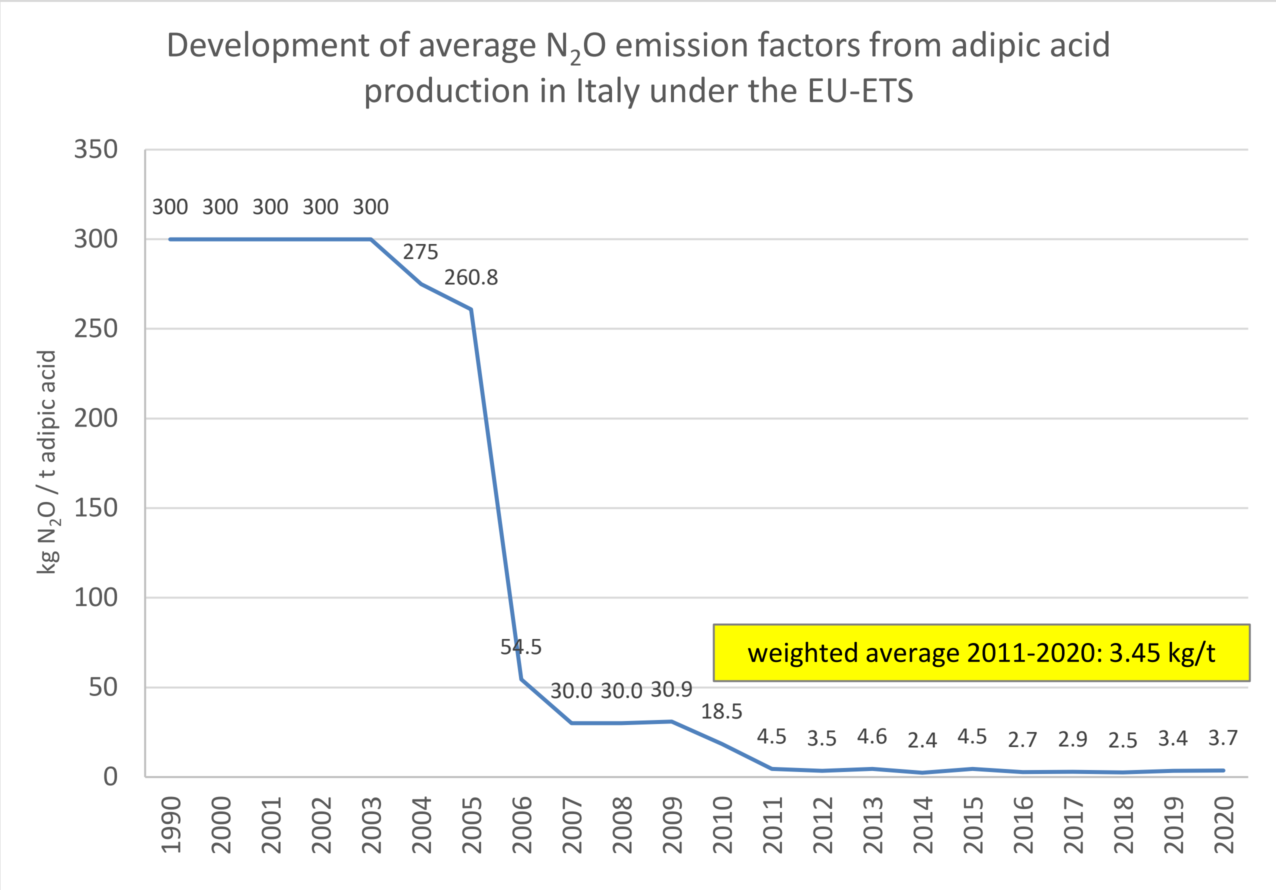
Benchmarks derived from this analysis range around the 2020 EU ETS weighted average of 0.43 kg N_2O/t HNO_3, between 0.15 kg N_2O/t HNO3 (25 % best performing HNO_3 production in EU ETS countries) and 0.6 kg N_2O/t HNO_3 (bottom 50 %). We acknowledge that the technical feasibility of specific N_2O emission and related costs do depend on plant specifics, in particular single pressure / dual pressure and low/medium /high pressure characteristics of individual plants. However specific emissions in the range well below 1 kg N_2O/t HNO_3 can be considered achievable if incentives to plant operators are accordingly set with ambitious climate policies targeting N_2O emissions.

Annex II. Benchmark for N_2O Emissions from adipic acid production

Italy is the only country which so far reported under the UNFCCC a non-confidential time series of adipic acid production and related N_2O emissions, thus allowing to calculate a time series of implied emission factors (Table 49).

Figure 10 displays the development of the average Italian emission factor for N_2O from adipic acid production (Table 49), reflecting the introduction of abatement measures under the influence of the EU-ETS: As reported by Italy with its inventory submission to the UNFCCC (Italy 2022b) pilot operation of catalytic decomposition facilities started 2005, full scale deployment was reached 2007 which led to an emission factor of approximately 30 kg N_2O / t adipic acid, compared to the IPCC default EF of 300 kg/t (assuming no N_2O abatement) used for the first years of the time series. After 2011 further technical improvements were introduced leading to less frequent downtimes of the abatement equipment. Since 2011, the emission factor has been rather stable at levels between 2.5 and 4.5 kg/t.

Figure 10: N_2O implied emission factors for adipic acid production in Italy



Source: (Italy 2022a), own calculations

The weighted 2011-2020 average of 3.45 kg N_2O / t adipic acid can thus be considered a benchmark for emission levels reflecting the application of ambitious policy instruments for N_2O abatement.

Table 49: Italian production of adipic acid and related N_2O emissions

	adipic acid production *kt*	**N_2O Emissions** *kt N_2O*	**implied emission factor** *kg N_2O /t adipic acid₃*
1990	49.2	14.8	300
2000	71.4	21.4	300
2001	75.3	22.6	300
2002	74.0	22.2	300
2003	69.0	20.7	300
2004	77.9	21.4	275
2005	75.1	19.6	260.8
2006	84.0	4.6	54.5
2007	84.1	2.5	30.0
2008	76.0	2.3	30.0
2009	78.2	2.4	30.9
2010	85.4	1.6	18.5
2011	82.6	0.4	4.5
2012	78.8	0.3	3.5
2013	80.3	0.4	4.6
2014	84.2	0.2	2.4
2015	81.8	0.4	4.5
2016	83.3	0.2	2.7
2017	86.8	0.2	2.9
2018	86.4	0.2	2.5
2019	76.3	0.3	3.4
2020	72.9	0.3	3.7

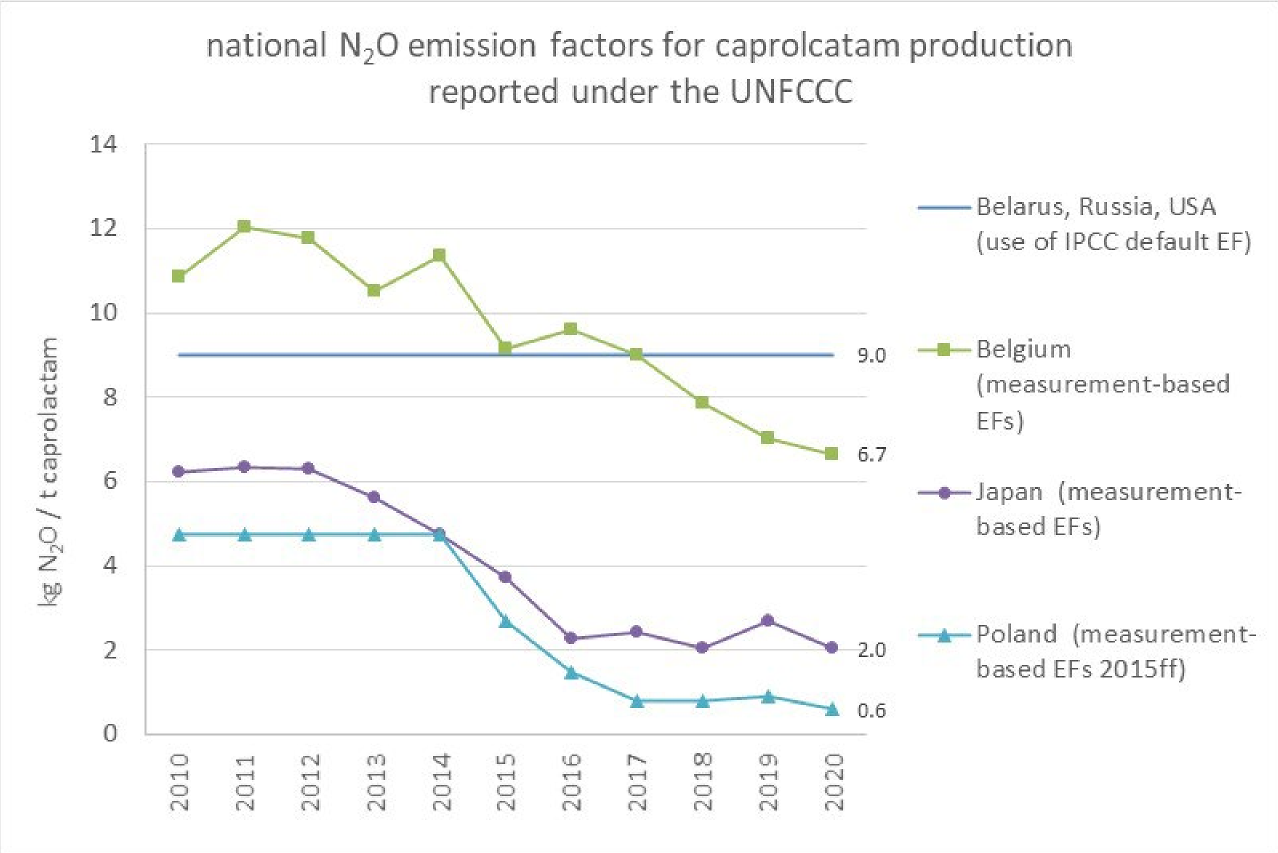
Source: (Italy 2022a)

Annex III. Benchmark for N_2O Emissions from caprolactam production

Under the UNFCCC, six countries have been reporting a non-confidential time series of caprolactam production and related N_2O emissions, thus allowing to calculate a time series of implied emission factors: Belarus, Belgium, Japan, Poland, Russia and the USA.

While Belarus, Russia and the USA use the IPCC default emission factor (assuming no N_2O abatement) of 9 kg N_2O / t caprolactam for their emission calculations (Belarus 2022; Russian Federation 2022b; United States of America 2022b), the emissions reported by Belgium, Japan and Poland are based on measurements (Belarus 2022; Japan 2022b; Poland 2022b). The respective time series from 2010 to 2020 are displayed in Figure 11:

Figure 11: N_2O implied emission factors for caprolactam production



Source: (Bulgaria 2022a; Belgium 2022a; Japan 2022a; Poland 2022a; Russian Federation 2022a; United States of America 2022a), own presentation

Belgium explains the declining trend in the emission factor by primary measures taken after 2010 in the single Belgian caprolactam production facility, leading to an IEF of 6.7 kg/t in 2020, compared to 12.1 kg/t in 2011 (Belgium 2022b). Both Japan and Poland report measurement-based emission factors significantly below the IPCC default emission factor of 9 kg N_2O / t caprolactam: Japan's average emission factor has declined from 6.3 kg/t in 2011 to 2.0 kg/t in 2020. However, no explanation e.g. with respect to N_2O abatement measures possibly taken are given in the inventory report (Japan 2022b).

Poland's average emission factor declined from 2.7 kg/t (2015) to 0.6 kg/t (2020) based on measurements (Poland 2022b) the emission factor of 4.7 kg/t used until 2014 had been based on a technical study dated 2001. However, the Polish inventory report (Poland 2022b)does not give any information with respect to N_2O abatement measures possibly taken which would possibly explain the trend observed 2014-2020.

It should be noted, however, that specific emissions close to zero are technically possibly as reported by Germany for a plant equipped with a thermal waste-gas treatment system to destroy nitrous oxide in redundant design: Detailed information available to the German single national entity in charge of the GHG inventory indicates that the pertinent post-combustion system can be assumed to completely eliminate the nitrous oxide quantities involved (Germany 2022b). However, a quantified N_2O emission factor for caprolactam production is not reported in the German GHG inventory.

The performance of a redundant thermal waste-gas treatment system can be estimated as follows in accordance with calculations performed by Germany, subject to approval by independent technical inventory review (Germany 2022b): 98.5 % reduction rate for the primary waste-gas treatment system, 97 % utilisation rate for the primary system, 97 % reduction rate for the redundant waste-gas treatment system, resulting in an overall reduction rate of 98.455 %. Applied to the 9 kg/t IPCC default EF assuming no abatement, such a reduction rate would be equivalent to an emission factor of 0.14 kg N_2O / t caprolactam.

Thus, we consider an emission factor of about 0.6 kg/t, as reported by Poland, as a conservative benchmark for N_2O emission levels from caprolactam production achievable by ambitious policy instruments.