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CARBON CAPTURE

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1 NE/CERC DISPERSION AND DEPOSITION MODELLING

Norsk Energi, has made dispersion modelling of emissions as a part of a revised permit application to the WtE plant at KEA. As a part of the dialogue with Norwegian Environmental Agency (NEA) regarding the application for a permit to the carbon capture plant it is partly emerged demands for new dispersion calculations. Norsk Energi in cooperation with Cambridge Environmental Research Consultants (CERC) which has developed an amine chemistry model ADMS, has been engaged to prepare a new dispersion and deposition modelling of the emission. The work has had two intensions:

1. Compare the ADMS model with the model used by NILU
2. Make new dispersion and deposition modelling partly based on the experiences from the pilot plant.

1. Norsk Energi have performed dispersion modelling and deposition modelling of nitrosamines and nitramines from emissions at the CC plant. Cambridge Environmental Research Consultants has provided specialized modelling support (ADMS 5 with amine chemistry module). Calculations based on the same preconditions as the 2018 calculations from NILU have been performed to compare the different models as far as possible. In this case the amine concentration at the emission point was set to 0,4 ppmV.

The new model gives another topological emission picture showing a maximum amine concentration level occurring substantially closer to the plant. The reasons for these differences have not yet been concluded but will be investigated further. To ensure the required quality of the results the differences between the NILU and the Norsk Energi calculations must be better understood.

2. New modelling has been based on the measured amine emission from the pilot plant and comprises cases without and with reheat of the flue gas. The amine concentration in the emission point is set to 0,2 ppmV. In the case with reheat the temperature is 65 C and without reheat 44 C.

NO_x emissions must also be calculated since these are crucial for meeting the air quality criteria. The calculations show minor differences with and without reheat of the flue gas and none of the cases contribute to exceedance of the NO_x air quality criteria.

The modelling of maximum annual concentration contribution of nitros- and nitramines show values below the air quality guideline both with and without reheat, but the emission picture varies quite a lot from the NILU model. Modelling of deposition in water does also deviate from the NILU-modelling. A preliminary report dated 30.10.2019 was presented in the FEED phase (NOC3 -KEA-S-RA-008).

A revised and final report was published 13.01.2020. The content and the results are mainly the same with some minor text adjustments. All the input values have been double checked and NE/CERC have argued for their choice of input values. The final report is attached.

The report has in chapter 7 some suggestions for further work. To follow up one of these, NIVA has been engaged to carry out more detailed catchment calculations to obtain more accurate calculations of the deposition in water. The results are expected in the end of May 2020.

2 ATTACHMENTS

Norsk Energi report dated 13.01.2020. "Dispersion and deposition modelling NO₂, nitrosamines and nitramines".

Dispersion and deposition modelling NO₂, nitrosamines and nitramines

Klemetsrud Carbon capture plant

Status: **Final version**

Date: 13.01.2020

Created by: **Catheryn Price, CERC and Dag Borgnes, Norsk Energi**

Client: **COWI**

Report

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Abstract:

Norsk Energi and Cambridge Environmental Research Consultants (CERC) have performed dispersion and deposition modelling and a rough calculation of drinking water concentration for emissions from the planned Klemetsrud Carbon Capture plant. The modelling was done for planned combustion capacity of 410 000 tonnes of waste per year.

NO₂ dispersion modelling was carried out with the US EPA model AERMOD. Nitrosamines and nitramines dispersion and deposition modelling was carried out with the CERC model ADMS 5 with amine chemistry module. Three cases were modelled: NILU comparison case, Reheat case and No Reheat case.

The results from nitrosamines and nitramines modelling and calculations were compared to the Norwegian Institute of Public Health (NIPH) guidelines which is based on N-nitroso dimethylamine (NDMA) risk estimates. NDMA is one of the most potent and best investigated nitrosamines. NIPH consider this to be a conservative approach for total air concentration. If an amine with greater toxicity constitutes a significant proportion of the total emissions of these substances, NIPH recommends that a new risk assessment be made.

There is a lack of knowledge about nitramines, but the substances in this group are generally believed to be less carcinogenic than the nitrosamines according to NIPH. NIPH recommends that the NDMA risk estimate should be used for the total concentration of both nitrosamines and nitramines in air and water.

Based on the NIPH recommendations, we use 0,3 ng/m³ (sum nitrosamines+nitramines) as air quality guideline value, and 4 ng/l as drinking water guideline value (sum nitrosamines+nitramines).

NILU comparison case - Nitrosamines and nitramines

NILU performed dispersion and deposition modelling of nitrosamines and nitramines for Klemetsrud Carbon Capture in 2018. NILU's dispersion modelling showed that the guideline value for drinking water was the determining limitation for the amine emissions. Calculated limit value for amine concentrations in the emitted flue gas is 1,1 ppmv. Because of the uncertainty, NILU has calculated a lowest and highest emission concentration using a factor of 3.

Efficient, environmentally friendly and safe utilization of energy

We have performed modelling using NILUs lowest emission concentration value (*0.4 ppmvol amine, 0.58 weight-% nitrosamine*) and the same stack outlet parameters, (one 80 m high stack, same stack outlet temperature and velocity). Our modelling gave nitrosamine+nitramine air concentration contributions of 0.25, 0.27 and 0.21 ng/m³ for meteorology data from 2015, 2016 and 2017. This is below the air quality guideline value of 0.3 ng/m³. Max concentration occurs about 800 meters north/northeast of the plant for all cases with our model. In NILUs report max concentration is at approximately 7 km distance from the plant.

Our estimated annual average water concentration in the lake with highest concentration (Nord-Elvåga) for the worst-case year (2016) is 12.9 ng/l. This is more than 3 times the guideline value of 4 ng/l. The water concentration calculations include degradation of nitrosamine deposited in water as in the NILU Klemetsrud report (steady state concentration of 4.1%). The calculation of drinking water concentration gives a very rough estimate. A better estimate could be made by also doing catchment modelling for the specific lakes.

Some of the known differences between our and NILUs modelling and calculations are related to the dispersion models and OH concentrations. We used an advanced, gaussian model modified with amine chemistry. NILU used WRF-EMEP with 1x1 km resolution and a gaussian model (CONCX) for the area close to the source to look at variation within the nearest grid route.

We used twice as high OH concentration as NILU. Our sensitivity calculations show that the air concentrations of nitrosamine+nitramine at the modelled lakes were almost twice as high with the OH we used as with the OH NILU used. This will also affect the drinking water concentrations, and further calculations of this may be performed.

Reheat case and No Reheat case - NO₂, nitrosamines and nitramines

The Reheat and No Reheat cases have been carried out with 65 and 44°C stack outlet temperature. The flue gas is assumed to be led to the two existing 80 m high stacks.

NO₂

Typical NO_x emission resulted in maximum hourly contribution of 14 and 16 µg NO₂/m³ for the Reheat and No Reheat cases. The dispersion NO₂ modelling thus shows that reheat will not give a significant decrease in the hourly contribution of NO₂. The maximum hourly contribution from the Klemetsrud plant will to a very limited extent coincide with high contributions from road traffic at E6, as these will normally occur under different meteorological conditions.

Nitrosamines and nitramines

The Reheat and No Reheat cases were performed with emission concentration values of *0.2 ppmvol amine and 0.58 weight-% nitrosamine*.

Modelled nitrosamine+nitramine concentration contributions in the **Reheat** and **No Reheat** cases were 0.20 and 0.23 ng/m³ for meteorology data from 2016. This is below the air quality guideline value of 0.3 ng/m³. The share from directly emitted nitrosamines are 50-70% of total nitrosamines for both cases.

Our estimated annual average water concentration in the lake with highest concentration (Nord-Elvåga) for the worst-case year (2016) is 3.4 ng/l in the **Reheat case**. This is below the guideline value of 4 ng/l. The **No Reheat case** has annual concentration 6.6 ng/l, which is above the guideline value. The water concentration calculations include degradation of nitrosamine deposited in water as in the NILU Klemetsrud report (steady state concentration of 4.1%).

The calculation of drinking water concentration gives a very rough estimate. A better estimate could be made by also doing catchment modelling for the specific lakes.

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1 Introduction

The Klemetsrud WtE plant converts municipal and industrial residual waste to heat and power. Norsk Energi has performed dispersion modelling of NO₂ and dispersion and deposition modelling of nitrosamines and nitramines from emission at the planned Klemetsrud WtE CO₂ capture plant. Concentration in water bodies has been calculated.

CERC has provided specialized modelling support (ADMS 5 with amine chemistry module), work on text for the report and reviewing.

Three cases have been modelled: NILU comparison case, Reheat case and No Reheat case.

In the NILU comparison case the flue gas was assumed to be emitted from one 80-meter-high stack with outlet temperature 70°C.

The Reheat and No Reheat cases have been carried out with 65 and 44°C stack outlet temperature respectively. Both alternatives were modelled with planned waste incineration capacity of 410 000 tonnes per year and 95 % CO₂ capture. The flue gas is assumed to be led to the two existing stacks for incineration line 1,2 and 3.

1.1 Klemetsrud WtE plant

The Klemetsrud WtE plant consists of three separate waste incineration lines with total capacity 375 000 tonnes waste per year.

Line 1 and 2

Nitrogen oxide emissions are reduced in the boilers using selective non-catalytic reduction (SNCR) with aqueous urea injection. The flue gas is treated with calcium hydroxide (Ca(OH)₂) slurry and activated carbon (HOK). Further downstream are bag filters.

Line 3

The first part of the flue gas treatment consists of an electrostatic precipitator for particle removal, followed by a 4-stage wet scrubber. Finally, it is treated in the selective catalytic reduction (SCR) reactor with aqueous ammonia injection.

During summer 2017, a heat pump was installed in the scrubber circuit. This is removing approx. 10 tons/h water and cooling down the flue gas to approx. 43 °C at the scrubber outlet. The heat pump is planned to be in operation during wintertime to supply heat to the district heat net but will also be considered kept in operation during summer as a pre-treatment for the CC-plant with use of auxiliary cooling.

1.2 Klemetsrud Carbon capture plant

The Norwegian Government announced in 2013 that it would support the development of a cost-effective technology for capture and storage of CO₂ as part of the Sundvolden policy declaration. The Government's Carbon Capture and Storage (CCS) strategy was presented by the Ministry of Petroleum and Energy in its Proposition 1 S (2014-2015) to the Norwegian Parliament (Stortinget). The strategy has since then been funded and supported in the National Budget.

Fortum Oslo Varme (FOV) Klemetsrud Waste to Energy (WtE) plant was in 2015 selected as one of the potential CO₂ capture sites. The target for the plant future operation is to capture as much of the CO₂ as possible, while minimizing the impact on the existing plant operation (production of electricity and district heating).

FOV has been completing the pre-project of a full-scale plant for capture of CO₂ from the flue gas of its Klemetsrud WtE plant. The scope for FOV includes all the works for integration of the carbon capture plant (CC Plant) to the existing plant. The scope also includes Interim storage at Klemetsrud, transport to the Oslo harbour with truck loading/unloading stations and Interim storage at Port of Oslo. The CO₂ capture plant will be based on regenerable amine technology.

1.3 Previous dispersion and deposition modelling at the Klemetsrud plant

1.3.1 Norsk Energi 2016 and 2019

Norsk Energi performed dispersion modelling of NO₂ and calculations of SO₂ and PM contribution in 2016 and 2019 as part of permit applications for increasing waste incineration capacity. Model runs in 2019 included limit value emission concentration and typical emission concentration and 375 and 410 000 tonnes waste per year. Hourly meteorology data from 2010 meteorology and 2015 and a constant O₃-value of 80 µg/m³ were used in the model.

1.3.2 NILU 2018

NILU performed dispersion and deposition modelling of nitrosamines and nitramines for Fortum Varme KEA AS in 2018. Three different amine compositions (among them the DC103 Amine, called scenario 2) have been the subject for calculations of nitros- and nitramines based on a method developed for the Mongstad test facility for amine-based CCS (TCM). NILU used a gaussian model with stability classes (CONCX) and WRF-EMEP for the modelling. The finest resolution in the nesting in WRF-EMEP model was 1x1 km. The gaussian model was used to look at variation within the nearest grid route.

The dispersion modelling shows that in order to comply with the air quality guideline value of 0.3 ng/m³, the maximum emission rate of amines is a total of 1.68 g/s, assuming a stack height of 80 m. (Emissions equal to 1 g / s give a maximum concentration of 0.18 ng/m³. Then emissions of 1.68 g/s will give a maximum concentration of 0.3 ng/m³.)

The calculations further show that the limit value for fresh water is the determining limitation for the amine-emissions. Calculated limit value for amine concentrations in the emitted flue gas is 1,1 ppmV (at STP) for DC103. Because of the uncertainty NILU has calculated a lowest and highest emission concentration using a factor of 3 times the emission concentration (in mg/Nm³). We have performed the comparison with the lowest NILU value (0,4 ppmvol).

Degradation of nitrosamine after deposition in water is according to the NILU Klemetsrud report calculated by the methodology described in NILU OR 52/2011 (steady state concentration of 4.1% of applied concentration). Deposited nitramine is not reduced from degradation in water phase in the calculations.

2 Amine chemistry: Hydroxyl radical-initiated reactions

2.1 Dimethylamine, monomethylamine, monoethanolamine and their products

A small amount of the amines used in the carbon capture process are lost and may react to nitrosamines and nitramine in the stack or in the atmosphere. The tables below show dimethylamine, monomethylamine, monoethanolamine and reaction products.

Table 1 Dimethylamine and its products

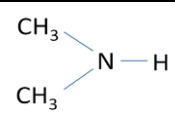
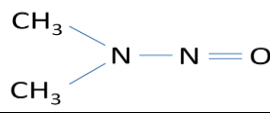
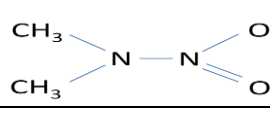
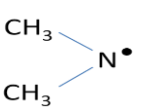
Short name	Full name	Type of compound	Chemical formula	Structure
DMA	Dimethylamine	Amine (secondary)	(CH ₃) ₂ NH	
NDMA	N-nitroso dimethylamine	Nitrosamine	(CH ₃) ₂ NNO	
DMN	N-nitro dimethylamine / dimethylnitramine	Nitramine	(CH ₃) ₂ NNO ₂	
rDMA	Dimethylamino radical	Free radical (reaction intermediate)	(CH ₃) ₂ N•	

Table 2 Monomethylamine and its products

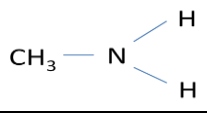
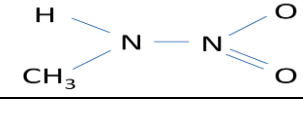
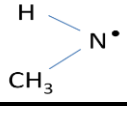
Short name	Full name	Type of compound	Chemical formula	Structure
MMA	(mono) Methylamine	Amine (primary)	CH ₃ NH ₂	
MAN	N-nitro methylamine	Nitramine	CH ₃ NHNO ₂	
rMMA	Methylamino radical	Free radical (reaction intermediate)	CH ₃ N•	

Table 3 Monoethanolamine and its products

Short name	Full name	Type of compound	Chemical formula	Structure
MEA	Monoethanolamine	Amine (primary, with an alcohol group)	HOCH ₂ CH ₂ NH ₂	$\text{HO}-\text{CH}_2-\text{CH}_2-\text{N} \begin{array}{l} \text{H} \\ \text{H} \end{array}$
MEN	N-nitro monoethanolamine	Nitramine	HOCH ₂ CH ₂ HNNO ₂	$\text{HO}-\text{CH}_2-\text{CH}_2-\text{NH}-\text{N} \begin{array}{l} \text{O} \\ \text{O} \end{array}$
rMEA	Monoethanolamino radical	Free radical (reaction intermediate)	HOCH ₂ CH ₂ N [•] H	$\text{HO}-\text{CH}_2-\text{CH}_2-\text{N}^{\bullet}$

2.2 Formation of nitrosamine and nitramine

Hydroxyl radicals in the atmosphere act to abstract (remove) a hydrogen atom from the amine. The site of initial attack determines the type of species formed, through two separate branches of reactions. For amines in general, the [•]OH can attack a hydrogen atom on the N atom (N—H) or one of the hydrogen atoms in the methyl groups (C—H). Only abstraction of an N—H hydrogen atom results in the formation of nitrosamines and nitramines. The ratio between the rate of attack on the C—H hydrogen and an N—H hydrogen is known as a *branching ratio*.

The product of the attack of the N-H by [•]OH results in the formation of an amino radical species. For dimethylamine, for example, the radical species is (CH₃)₂N[•]

Once the H atom has been removed from the nitrogen atom of the amine, the next step is the reaction of the resulting species, (CH₃)₂N[•], with nitric oxide (NO) or nitrogen dioxide (NO₂) present in the atmosphere, to form the nitrosamine or nitramine, respectively. The amount of nitrosamine and nitramine formed depends on the amount of NO_x (that is, the total amount of NO₂ plus NO) present, and also on the ratio of NO to NO₂.

The figures below show formation routes for nitrosamine and nitramine. The reaction numbering system is based on that of the DMA reaction scheme¹.

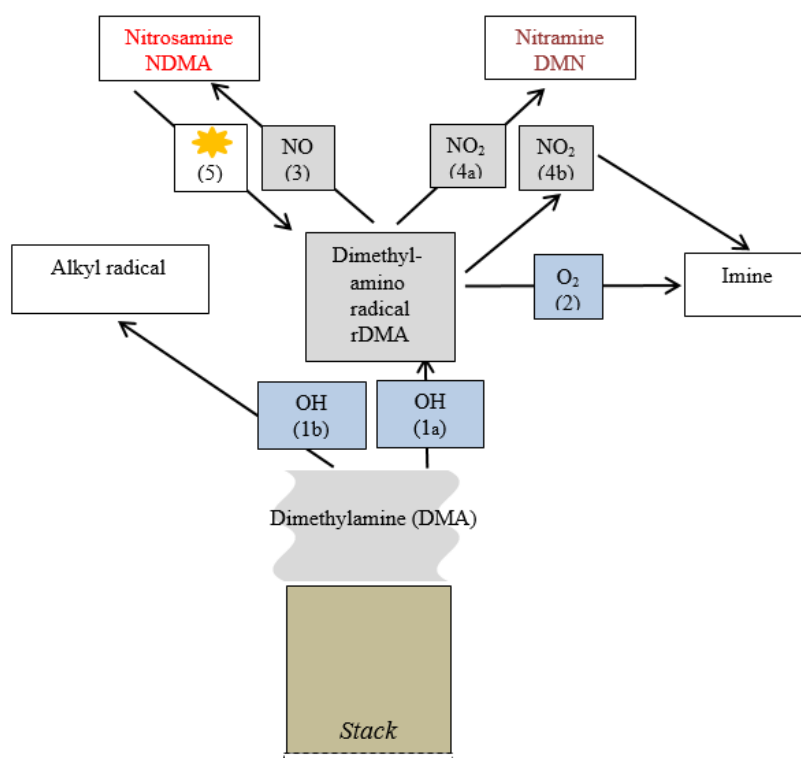
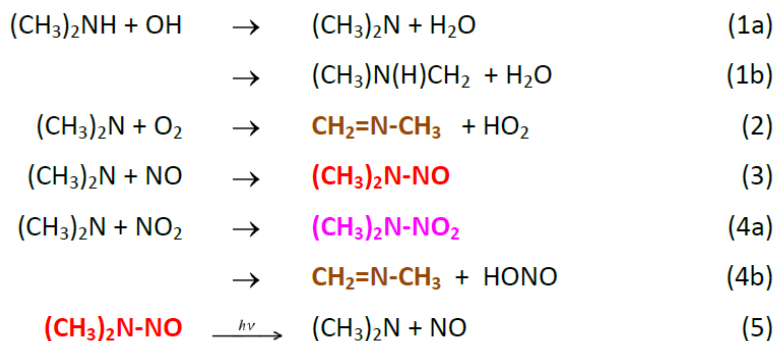


Figure 1 Dimethylamine (DMA). Formation routes for nitrosamine and nitramine

¹ NILU OR 2 2011: Atmospheric degradation of amines (ADA). CLIMIT project no. 201604

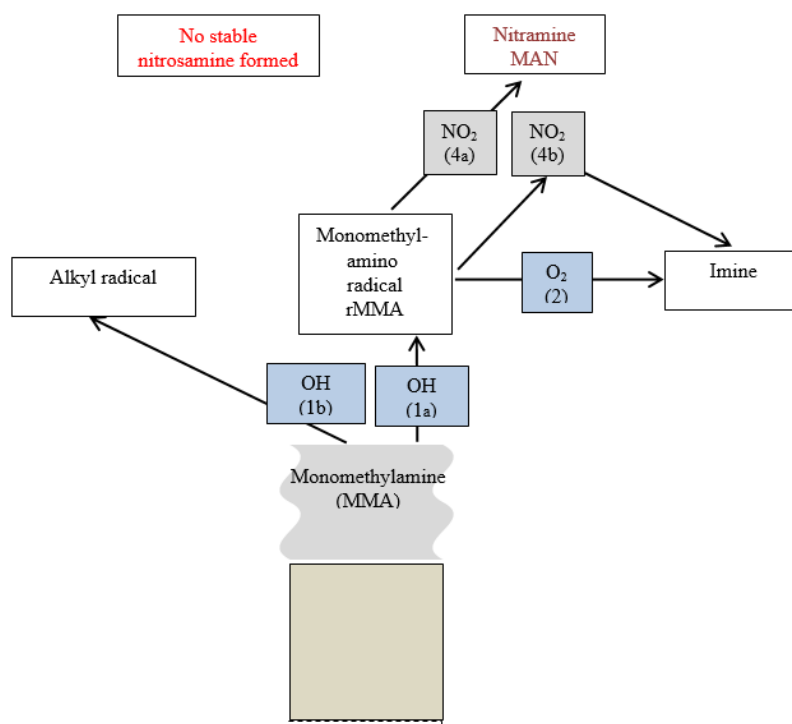


Figure 2 Monomethylamine (MMA). Formation routes for nitrosamine and nitramine

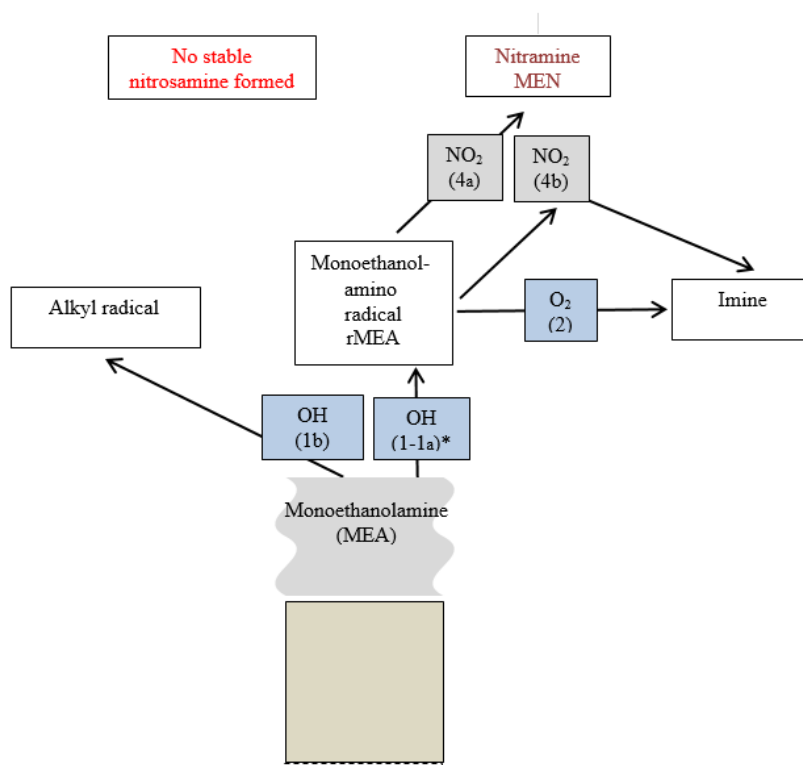


Figure 3 Monoethanolamine (MEA). Formation routes for nitrosamine and nitramine

* There is more than one alternative reaction depending on which of the two carbon atoms is attacked

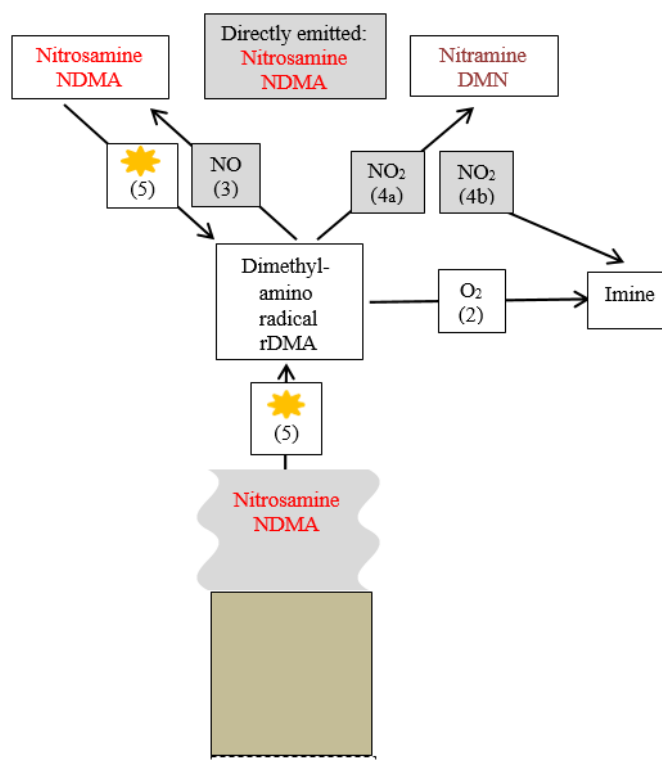


Figure 4 Directly emitted nitrosamine (NDMA). Formation routes for nitrosamine and nitramine

2.2.1 Reaction rates and constant that determines hourly-varying OH concentration

Values for the rate constants k_1 , k_{1a}/k_1 (branching ratio), k_2 , k_3 , k_4 , k_{4a} , j_5/j_{NO_2} (photochemical rate constant ratio) are needed for the amine chemistry modelling.

In ADMS the hydroxyl radical concentration $[OH]$ is modelled by the equation

$$[OH] = c[O_3]j_{NO_2}$$

The constant c that determines hourly-varying OH concentration has been calculated based on annual average of OH- and ozone concentrations and j_{NO_2} . The average value for the OH is estimated to 1×10^6 molecules/cm³ based on information in Tel-Tek report no. 2211030-CC08 v2 (2012), table 5.1² (latest information CERC received as part of the Gassnova/Statoil projects). Average value for O₃ was based on measured concentrations. Average j_{NO_2} was derived from the meteorological data (incoming solar radiation).

The table below shows rate constants, O₂ concentration and constant c that determines hourly-varying OH concentration.

² https://www.gassnova.no/no/Documents/AtmosphericChemistryComparisonClandBrChemistry_Tel-Tek.pdf

Table 4 Rate constants, O₂ concentration and constant c that determines hourly-varying OH concentration. Klemetsrud solvent

Parameter	Parameter		Unit	Data for ADMS	Unit
Amine/OH reaction rate constant	k1	2.50E-10*	cm ³ molecule ⁻¹ s ⁻¹	6.25	ppb ⁻¹ s ⁻¹
Amino radical/O ₂ reaction rate constant	k2	5.40E-20**	cm ³ molecule ⁻¹ s ⁻¹	1.35E-09	ppb ⁻¹ s ⁻¹
Rate constant for formation of nitrosamine	k3	2.13E-13**	cm ³ molecule ⁻¹ s ⁻¹	5.33E-03	ppb ⁻¹ s ⁻¹
Rate constant for formation of nitramine	k4a	3.18E-13**	cm ³ molecule ⁻¹ s ⁻¹	7.95E-03	ppb ⁻¹ s ⁻¹
Amino radical/NO ₂ reaction rate constant	k4	3.82E-13**	cm ³ molecule ⁻¹ s ⁻¹	9.54E-03	ppb ⁻¹ s ⁻¹
Branching ratio for amine/OH reaction	k1a/k1			0.37*	
Ratio of j (nitrosamine) to j(NO ₂)	j5/jNO ₂			0.34*	
Constant for OH concentration calculations	c			2015: 4.59E-04 2016: 4.90E-04 2017: 5.01E-04	s
Atmospheric oxygen concentration				209406000	ppb

*From Claus J. Nielsen: «Klemetsrud-Solvent for modellers», attachment to email from Claus J. Nielsen 6 September 2019

**Calculated by C. Price, CERC based on info in «Klemetsrud-Solvent for modellers»

3 Air quality limit values, air quality criteria (NO₂) and guideline value (nitrosamine and nitramine)

3.1 Air quality limit values and air quality criteria (NO₂ and PM) for the protection of human health

The authorities have specified limit values and air quality criteria for concentrations of particulate matter and NO₂ in outdoor air. The limit values are given in Chapter 7 of the Pollution Control Regulations.

The Environment Agency and the Norwegian Institute of Public Health have established air quality criteria for various air pollution components based on existing knowledge about what health effects they cause ("Effects of Air Pollution on Health" (2013/9. Updated in 2015. Replaced by online publication 2018).

Table 5 Air quality limit values and air quality criteria (NO₂ and PM)

			1 hour	24 hours	1 year
Air quality limit values (health)	NO ₂	µg/m ³	200*		40
	PM ₁₀	µg/m ³		50**	25
	PM _{2,5}	µg/m ³			15***
Air quality criteria (health)	NO ₂	µg/m ³	100		
	PM ₁₀	µg/m ³		30	20
	PM _{2,5}	µg/m ³		15	8

* The limit value must not be exceeded more than 18 times per year

** The limit value must not be exceeded more than 30 times per year

*** From 1 January 2016

3.2 Guideline value for the protection of human health (nitrosamine and nitramine)

The Norwegian Institute of Public Health (NIPH) gave a risk assessment and guideline value for the protection of human health for nitrosamines and nitramines in 2011³. NIPH states that «We have not worked on risk assessment of nitrosamines/nitramines after this, and what is on the website is therefore our latest updates.»⁴ On the website we find the following summary (Norwegian summary translated to English)⁵:

«In a mandate from the Climate and Pollution Directorate (Klif), the Norwegian Institute of Public Health (NIPH) has been commissioned to assess the risk of potential health damage in connection with emissions of amines, nitrosamines and nitramines from CO₂ capture plants. As part of this, Klif requested a thorough review of the risk estimate for nitrosodimethylamine (NDMA) in air and water, prepared by foreign institutions. In addition, Klif wanted NIPH to assess whether there is a basis for developing air quality criteria for NDMA. NIPH has now completed its assessment of risks related to exposure to nitrosamines and nitramines.

Several international institutions have set tolerable risk levels for carcinogens in case of lifelong exposure of the general population. These levels are in the range of 10⁻⁶ and 10⁻⁵. This means that for life-long exposure, one can expect an increase in cancer incidence, which is between one and ten extra cases per million inhabitants.

³ <https://www.fhi.no/globalassets/dokumenterfiler/rapporter/2011/health-effects-of-amines-and-derivatives-associated-with-co2-capture.pdf>

⁴ E-mail from Marit Låg, NIPH, dated 30 August 2019

⁵ <https://www.fhi.no/en/publ/2011/co2-capture-health-effects-of-amine/>

Nitrosamines and nitramines are groups of substances, which are formed by the breakdown of amines. Although there is relatively little data available on the health effects of many of these substances, it is known that substances in both groups can be highly carcinogenic.

Among the nitrosamines, NDMA is one of the most potent and best investigated substances. NDMA is therefore used as a basis for calculating the concentrations of nitrosamines and nitramines that can lead to an increase in the risk of cancer in the population. Concentrations of NDMA in drinking water presenting negligible or minimal risk have been prepared by several institutions (WHO, Health Canada, US EPA and California EPA), primarily on the basis of a comprehensive study by Peto and co-workers (1991a; 1991b).

This study is very solid and well suited to calculate the risk of tumor development in the liver. Overall, the risk estimates from the various authorities varied within a factor of 10. Based on available information, NIPH has assessed that the Health Canada risk estimate is a well-founded and conservative proposition. A lifelong use of drinking water with 40 ng/l or 4 ng/l NDMA will lead to an increased risk of cancer of 10^{-5} and 10^{-6} respectively.

Risk estimates for exposure through air are set only by the US EPA. These are also based on the drinking water study by Peto and co-workers. Therefore, the NIPH has calculated the risk estimates drawn up by the other drinking water authorities to apply to air concentrations. The conversion was carried out in accordance with recommendations from REACH (EU chemicals regulations). In addition, NIPH has used an inhalation study by Klein and co-workers (1991) to calculate cancer risk in exposure to NDMA via air.

This study suggests that NDMA may be more potent when ingested via inhalation than through drinking water. Compared to the drinking water study, the inhalation study used few doses, with fewer animals in each exposed group. In addition, the reporting of the study is somewhat incomplete. Therefore, there are some uncertainties associated with the results of the inhalation study for Klein and co-workers.

Based on the data from the drinking water study, a lifelong exposure to an air concentration of 0.3 ng/m³ will cause a cancer risk of 10^{-6} . That is, in a population of 1 million that is exposed throughout life, one additional case of cancer may result from this exposure. The study of Klein and co-workers presents a somewhat higher risk than this. Overall, NIPH considers that the concentration of NDMA in air should not exceed 0.3 ng/m³.

NIPH has also assessed the carcinogenic potential of other nitrosamines that may be relevant for CO₂ purification. NDMA was found to be one of the most potent, and we therefore consider it conservative if the value of this substance is used to calculate the risk from the total amount of nitrosamines in the air, which together should therefore not exceed 0.3 ng/m³. However, there is one nitrosamine that is probably more potent than NDMA, N-nitrosodiethylamine (NDEA). If NDEA constitutes a significant proportion of the total emissions of these substances, NIPH recommends that a new risk assessment be made.

When it comes to nitramines, there is a great lack of knowledge, but the substances in this group are generally believed to be less carcinogenic than the nitrosamines. However, studies show that the most known nitramine (N-nitrodimethylamine) is a highly carcinogen, though not as potent as NDMA. The NIPH therefore recommends that the NDMA risk estimate be used for the nitramines as well. This must be regarded as a conservative risk estimate that will provide good protection for the population. If nitramines are detected in significant quantities in discharges, there will be a need for more knowledge in order for NIPH to carry out a complete risk assessment.

Therefore, when discharging from CO₂ capture facilities, NIPH recommends that the NDMA risk estimate should be used for the total concentration of both nitrosamines and nitramines in air and water.»

Based on the NIPH recommendations, we use 0,3 ng/m³ (sum nitrosamines+nitramines) as air quality guideline value, and 4 ng/l as drinking water guideline value (sum nitrosamines+nitramines).

4 Dispersion and deposition modelling - calculation of concentration in water bodies

4.1 Overview

The list below shows studies covered in this report. All studies apply to waste incineration capacity of 410 000 tonnes per year and 95 % CO₂ capture.

NO₂:

Dispersion modelling of NO₂ *with and without reheat* (AERMOD model, meteorology 2015). Typical NO_x emission values are used (not the limit values as these are much higher than real emission). Both cases were modelled with emission through the existing **two** stacks.

Nitrosamines and nitramines:

NILU case

Dispersion and deposition modelling of nitrosamines and nitramines with the same stack outlet parameters as NILU used (using ADMS model, meteorology 2015, 2016 or 2017). Calculation of concentration in water bodies based on deposition results.

Reheat and No Reheat cases

Dispersion and deposition modelling of nitrosamines and nitramines with and without reheat. Meteorological data from 2015, 2016 or 2017 based on which year that gave the highest results in the NILU case.

Sensitivity runs

Sensitivity of different OH concentrations.

4.2 Method

4.2.1 NO₂ dispersion modelling

NO₂ dispersion modelling has been carried out with the US EPA model AERMOD. AERMOD is an advanced Gaussian plume model. Building and terrain impacts, and impact of different surface roughnesses can be taken into account.

Meteorological hourly data (wind speed, direction, ambient temperature and observed cloud cover) from a meteorological station is used in the model. Meteorological data sets based on prognostic meteorological data (WRF) can also be used. AERMOD is used in the US and several other countries as authority approved model.

Atmospheric chemistry is generally not included. However, the model has included simplified NO_x chemistry (Plume Volume Molar Ratio Method (PVMRM), Ambient Ratio Method (ARM) and Ozone Limiting Method (OLM)). Grid size is 50 meters.

4.2.2 Nitrosamines and nitramines dispersion and deposition modelling

Nitrosamines and nitramines dispersion and deposition modelling has been carried out with the CERC model ADMS 5. ADMS 5 is an advanced Gaussian plume model. Impacts of buildings, terrain, variations in surface roughness and dry and wet deposition can be modelled.

ADMS 5 has an in-built meteorological pre-processor that allows processing of both hourly sequential and statistical data. ADMS is used for a large proportion of the regulatory modelling in the UK, as well as by the main regulators themselves. It is also used extensively for regulatory modelling in many countries.

The model includes atmospheric chemistry; reaction of NO with O₃, photolysis of NO₂ and amine chemistry. The rate expressions for amine chemistry used in the model are as follows:

1. Loss of the AMINE

$$\frac{d[AMINE]}{dt} = -k_1[AMINE][OH]$$

2. Production of the amino RADICAL

$$\begin{aligned} \frac{d[RADICAL]}{dt} = & k_{1a}[AMINE][OH] + j_5[NITROSAMINE] - k_2[RADICAL][O_2] \\ & - k_3[RADICAL][NO] - k_4[RADICAL][NO_2] \end{aligned}$$

3. Production of NITRAMINE

$$\frac{d[NITRAMINE]}{dt} = k_{4a}[NO_2][RADICAL]$$

4. Production of NITROSAMINE

$$\frac{d[NITROSAMINE]}{dt} = k_3[RADICAL][NO] - j_5[NITROSAMINE]$$

The methodology is further described in users guides for ADMS 5 and amine chemistry⁶.

Grid resolution is 100 m and grid extent 10x10 km. To cover the lakes of interest we have used specified point receptors.

⁶ ADMS 5 User guide, Cambridge Environment Research Consultants, 2016

ADMS 5 Amine Chemistry Supplement, Cambridge Environment Research Consultants, 2016

4.2.3 Calculation of concentration in water bodies

ADMS amine chemistry scheme was used to predict concentrations in air and deposition of nitrosamines and nitramines at a selection of locations representing freshwater (drinking water) bodies around Klemetsrud.

The deposition fluxes of the nitrosamines and nitramines were calculated by modelling wet and dry deposition of an inert tracer and using this to post-process the air concentrations.

Deposition parameters are extremely important for modelling dry and wet deposition, but specific parameters are not available for nitrosamines and nitramines. For the dry deposition run, the pollutant was run as «reactive gas» option in ADMS. For the wet deposition run, ADMS default values were applied. The precipitation rates were derived from the meteorological data.

A rough approximation of the resulting concentration of nitrosamines and nitramines in each water body was made by postprocessing the deposition results. This calculation assumes that the nitrosamines and nitramines in the aqueous phase are well-mixed to a depth of 1 m below the surface of the water.

4.3 Modelling and calculation inputs and assumptions

4.3.1 Building data, stack parameters and emissions

The figure below shows Klemetsrud plant with carbon capture; stacks and building heights used in the model.



Figure 5 Klemetsrud WtE plant with carbon capture; stacks and building heights used in the model. Building for «new Line» is not included in the model

The flue gas is emitted through two stacks. The two stacks are modelled with the same emission velocity, outlet temperature and concentrations. The distance between them is approx. 10 meters. This means that separation is more than three diameters, and they should be modelled as two separate sources. Amine chemistry can be used with multiple sources. However, the dilution and entrainment option - which is recommended using when modelling amine chemistry - can only be used with a single point source. Therefore, we ran each stack separately in two runs, and combined the results afterwards.

The figure below shows flue gas flow diagrams and volumes, temperatures and CO₂-capture for the cases without and with reheater.

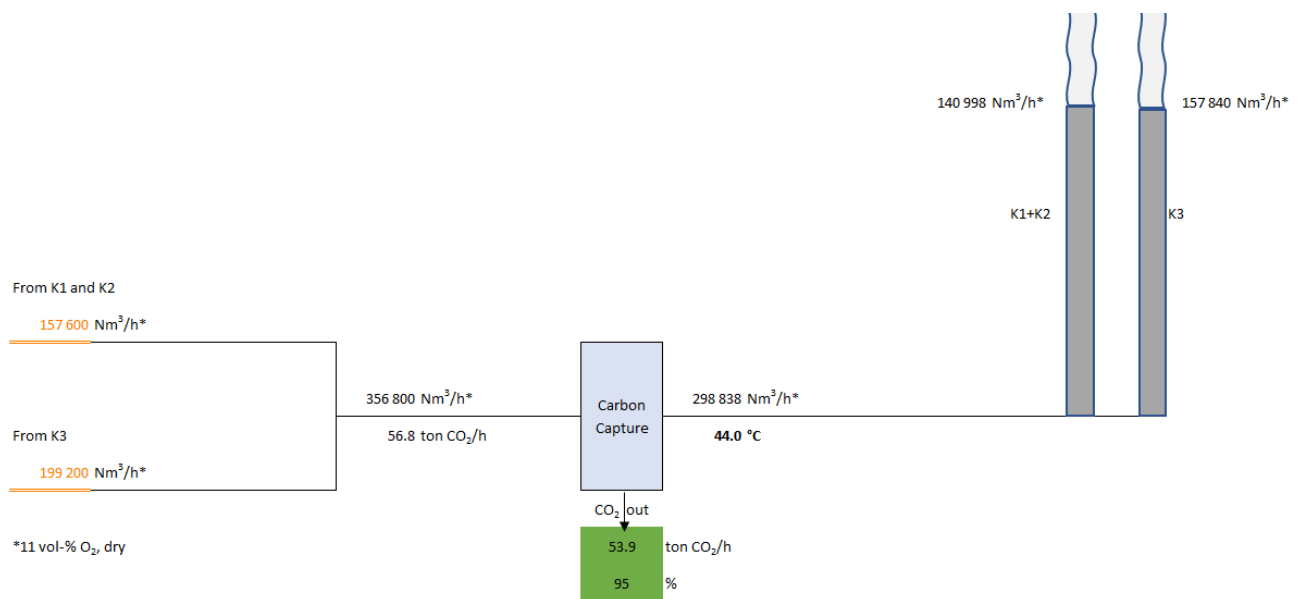


Figure 6 Flue gas flow diagrams and volumes, temperatures and CO₂-capture. Without reheater

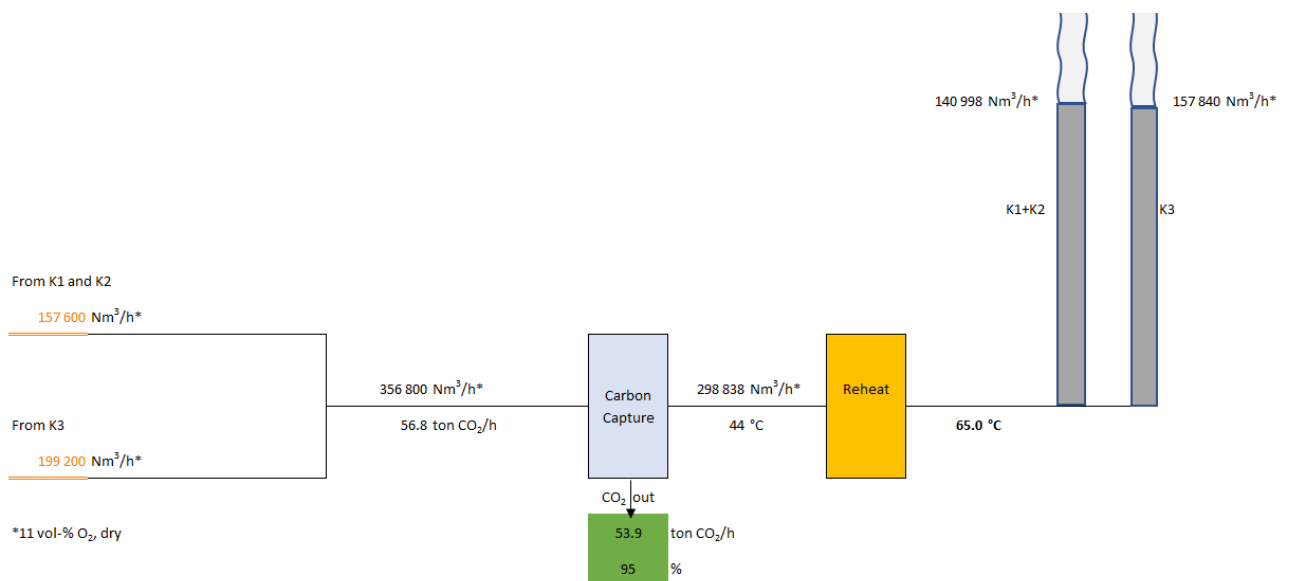


Figure 7 Flue gas flow diagrams and volumes, temperatures and CO₂-capture. With reheater

The table below shows detailed input data for the dispersion modelling. The data has been obtained from our client.

Table 6 Data used in the dispersion modelling. Amine type DC103.

	Unit	95 % CO ₂ capture, Reheat			95 % CO ₂ capture, No reheat			NILU case
		Stack 1+2	Stack 1 K1 + K2	Stack 2 K3	Stack 1+2	Stack 1 K1 + K2	Stack 2 K3	Stack 1+2
Waste incinerated	tonnes/year	410000			410000			
Volume flow rate	Nm ³ /h, dry, 11 % O ₂	298 838	140 998	157 840	298 838	140 998	157 840	
Oxygen concentration	vol-%, dry		7.3	7.3		7.3	7.3	
Flue gas temperature*	°C	65	65	65	44	44	44	70
Volume flow rate	m ³ /h, dry	272 381	128 515	143 866	255 465	120 534	134 932	
Humidity in flue gas	vol-%	8.3	8.3	8.3	8.3	8.3	8.3	
Volume flow rate	m ³ /h, wet	297 134	140 194	156 940	278 681	131 487	147 194	310000
Volume flow rate	m ³ /s, wet	83	39	44	77	37	41	86
Stack outlet diameter	m		2 x 1.35	2.02		2 x 1.35	2.02	2.7
Stack outlet area	m ²	6.1	2.9	3.2	6.1	2.9	3.2	
Emission velocity	m/s	13.6	13.6	13.6	12.8	12.8	12.8	15
Stack height	m		80	80		80	80	80
NO _x emission (as NO ₂)	Nm ³ /h, dry, 11 % O ₂	56	56	56	56	56	56	
NO _x emission (as NO ₂)	g/s	5.6	2.7	3.0	5.6	2.7	3.0	
NO ₂ share	vol-%	0	0		0	0		
Amine emission Sum of all amine species	ppmv, wet	max 0.2**	max 0.2**	max 0.2**	max 0.2**	max 0.2**	max 0.2**	0.4***
Share of amines/nitrosamines (stack)	weight-%	99.42 weight-% DC103, 0.58 weight-% nitrosamine	99.42 weight-% DC103, 0.58 weight-% nitrosamine	99.42 weight-% DC103, 0.58 weight-% nitrosamine	99.42 weight-% DC103, 0.58 weight-% nitrosamine	99.42 weight-% DC103, 0.58 weight-% nitrosamine	99.42 weight-% DC103, 0.58 weight-% nitrosamine	99.42 weight-% DC103, 0.58 weight-% nitrosamine ****
Nitramine emission (stack)	ppmv, wet	0*****	0*****	0*****	0*****	0*****	0*****	0

*Reheat winter temperature is 65 C. In summer the temperature is 80 C

**Currently (with the pilot plant) no unknown amine species of significance (above 5 ppbv) have been detected. The sum of all amines is based on proprietary information

***Concentration that will not give exceedance of drinking water limit value; lowest (calculated by an uncertainty factor of 3 (NILU report 11/2018))

****from NILU report 11/2018

*****0/Negligible. Confirmed with Shell 8 October according to email from Johan Fagerlund, CCS Advisor, Partners Fortum

Modelling of amines with ADMS requires information about molecular weight. We have arranged the modelling in such a way that only CERC needs the info about molecular weight: Norsk Energi send the almost complete model file to CERC. Then CERC add the conversion rate for ppbmV to µg/m³ for the amines, run the model at CERC, and send the model results to Norsk Energi.

4.3.2 NO_x modelling assumptions

The NO_x emissions from the plant will mainly exist as NO. Under the influence of sunlight and ozone, some NO will be oxidized to NO₂. The proportion oxidized depends on several factors, including wind speed, distance from the source, solar radiation and the availability of ozone (O₃).

The dispersion modelling has been performed in AERMOD with typical values NO_x emission values and assuming that some NO is oxidized to NO₂ by O₃ (AERMODs Plume Volume Molar Ratio Method, fixed O₃ value 80 µg/m³).

4.3.3 Terrain and surface roughness

Digital terrain data was used in the NO₂ (AERMOD) modelling. The meteorology data was corrected for surface roughness in the area around Klemetsrud.

Nitrosamine and nitramine (ADMS) modelling have been performed with no (flat) terrain. Surface roughness of 0.5 m, representative of parkland/open suburbia, was chosen for the modelling both for meteorology data site and source site.

4.3.4 NO₂ concentrations in Oslo

Maximum hourly NO₂ concentrations in Oslo are periodically significantly higher than the recommended air quality criteria in some areas. The maximum concentrations occur especially when it is high pressure, cold and cloudless (inversion). Road traffic is the main cause of pollution problems.

The number of exceedances of the limit value for hourly average and the annual average for NO₂ for measurement stations in Oslo for the period 2005-2018 is shown in the figure below. The nearest measuring station to the Klemetsrud plant is the measuring station at E6 at Manglerud.

Figur 3. Antall overskridelser av forurensningsforskriftens grenseverdi for timemiddel av NO₂ (nitrogendioksid) i perioden 2005 til 2018. Den røde horisontale streken angir forurensningsforskriftens grenseverdi som har vært gjeldende siden 2010.

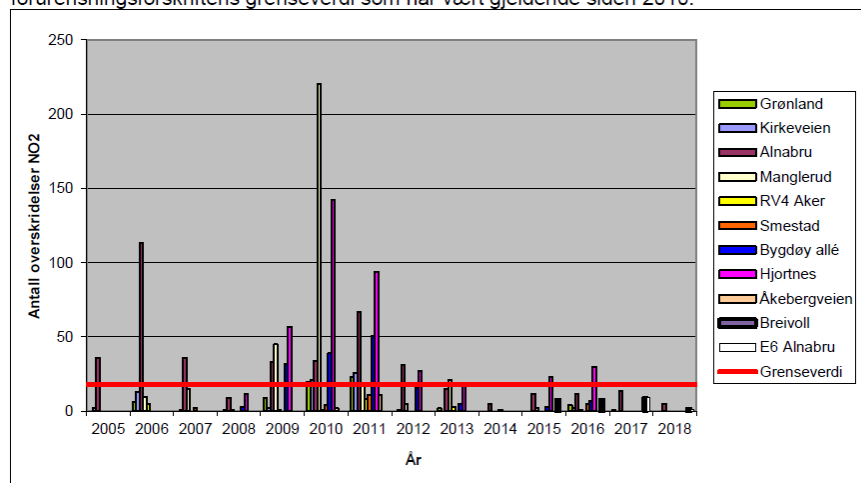


Figure 8 Number of exceedances of the limit value for the hourly average of NO₂. Measuring stations in Oslo 2005-2018.⁷

⁷ http://www.luftkvalitet.info/Libraries/Rapporter/Luftkvaliteten_i_Oslo_i_2018_-_En_oppsummering.sflb.ashx

Figur 4. Årsmiddelskonsentrasjoner (i mikrogram per kubikkmeter) av NO₂ i perioden 2005 til 2018. Den røde horisontale streken angir forurensningsforskriftens grenseverdi som har vært gjeldende siden 2010.

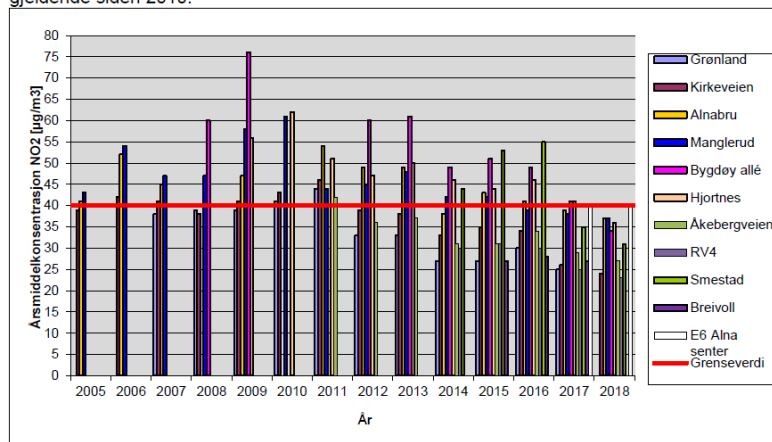


Figure 9 Annual average of NO₂. Measuring stations in Oslo. 2005-2018.⁸

The figure above shows that in the last 5 years period (2014-2018), the air quality limit value for NO₂ was exceeded in 2015 (Alnabru) and 2016 (Hjørtnes). Annual average value at Manglerud was somewhat higher than the limit value/air quality criteria (40 µg/m³) in 2014, but lower than 40 in 2015-2018.

4.3.5 Background concentrations used in chemistry modelling with ADMS

Background values for O₃, NO and NO₂ for 2015, 2016 and 2017 were input as hourly sequential background data files. The data were obtained from the measurement station at Haukenes, approx. 100 km southwest of Oslo. Haukenes was chosen because both NO, NO₂ and O₃ data were available, and because most of the chemical reaction will occur near stack outlet 80 m above ground (and therefore far from road sources). The total oxidant (NO₂+O₃ in units of ppb) at Haukenes was checked against the total oxidant at Grønland. The values were similar, and we can be confident that the total oxidant is robust.

4.3.6 Meteorology and dispersion

Stability conditions and wind speed are important for how the emissions are dispersed. Weak winds and unstable atmosphere normally give normally high concentration from high stacks, but low concentrations from near ground sources. Such conditions will typically occur in sunny weather in the summer.

If the atmosphere is neutral, the maximum concentrations from a high stack will occur further from the source. High winds may give high concentrations close to the stack too, due to building and stack downwash.

Weak to moderate winds and stable atmosphere (inversion) occur in winter and at night in summer. Such conditions give normally maximum concentrations nearby for ground sources, while contribution from a high stack is often far from the source. Even on days with very stable situations (high pressure winter time), however, good mixing of the bottom layer in the morning / day often occurs because of solar heating.

⁸ http://www.luftkvalitet.info/Libraries/Rapporter/Luftkvaliteten_i_Oslo_i_2018_-_En_oppsummering.sflb.ashx

In a previous assignment, we have obtained a statement from a meteorologist⁹ about inversion heights in Oslo based on model runs with MM5 and UM model:

- For sustained cold periods mid-winter with heavy inversion, the height can be 400-500 m. The inversion then builds up over several days and is part of a larger inversion over Eastern Norway.
- The model calculations also show that inversion heights of 100-200 m also occur during cold winter weather.
- Central to Oslo (away from the hills), the inversion height will tend to be lower when submerged in high pressure areas.
- Inversions of spring / autumn, which are broken down during the day, will be shallower, perhaps typically 50-200 m

There are no relevant measured meteorology data at the site. Trinity (supplier of AERMOD and meteorology data) proposes to use meteorology data from Blindern, and data for 2015 have been used in the NO₂ dispersion modelling.

The area around Klemetsrud consists of wooded and residential areas. The meteorology data is corrected for surface roughness in the area around Klemetsrud.

The meteorological data used for all the modelling studies with ADMS are from Blindern met station for the years 2015, 2016 and 2017. The data include precipitation data (from Blindern), with the solar radiation from the Årnes site (as the cloud cover data from Blindern is only 3-hourly).

The figure below shows wind roses.

⁹ Spredningsberegninger Klemetsrudanlegget, Norsk Energi, rapport nr 25493-RV-0001-E02b

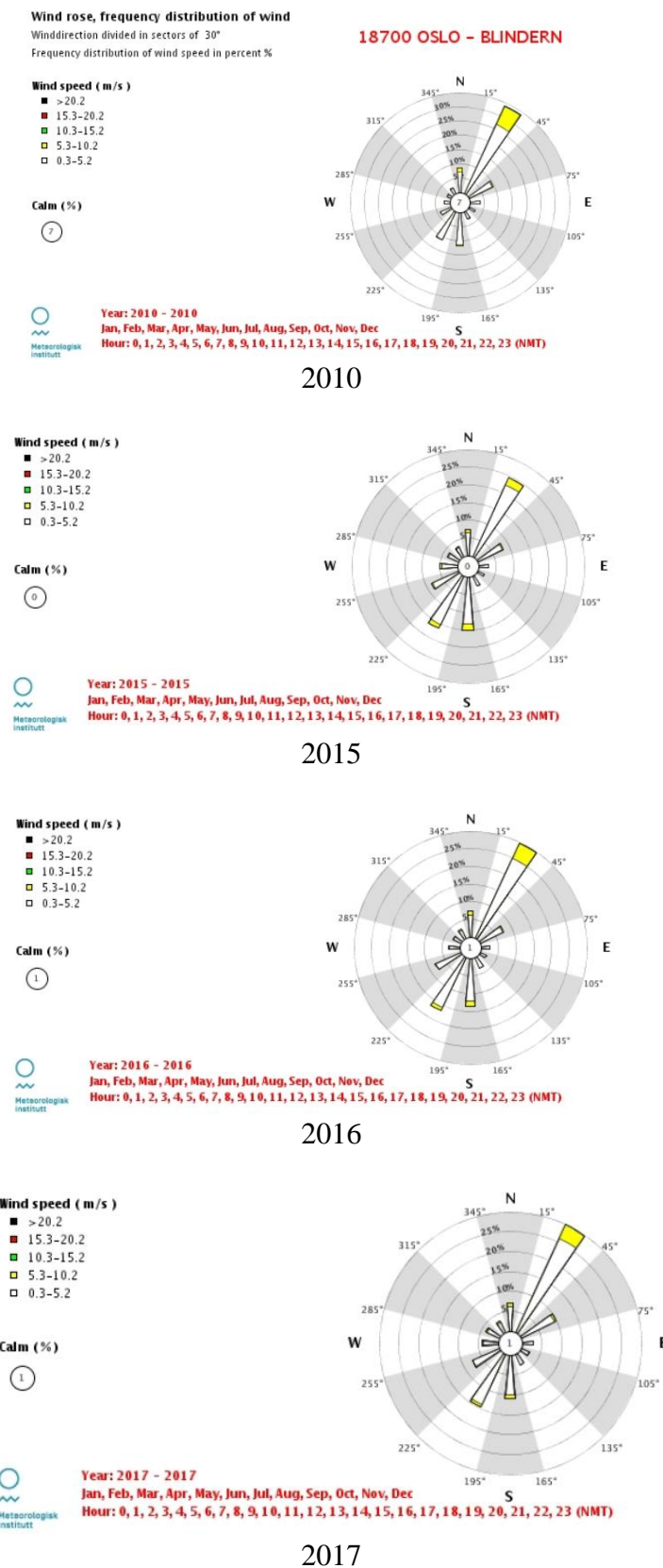


Figure 10 Wind roses for Blindern, 2010, 2015, 2016 and 2017

4.3.7 Lakes and drinking waters

Oslo has two water treatment facilities; one at Skullerud and one at Oset at Maridalsvannet. Oset supplies the residents of Oslo with 90% of the total water consumption. Skullerud supplies Oslo East with the remaining 10%. In «Datarapport Drikkevannskvalitet 2018»¹⁰ analysis from the following lakes are included:

- Alnsjøen
- Elvåga (Nord-Elvåga and Sør-Elvåga)
- Helgeren (approx. 10 km North-northwest of Maridalsvannet, not included in the modelling)
- Langlia (approx. 15 km northwest of Maridalsvannet, not included in the modelling)
- Lutvann
- Maridalsvannet
- Store Sandungen (approx. 15 km northwest of Maridalsvannet, not included in the modelling)

Alnsjøen and Langlia are emergency facilities. Lutvann and Store Sandungen are intake reservoirs.

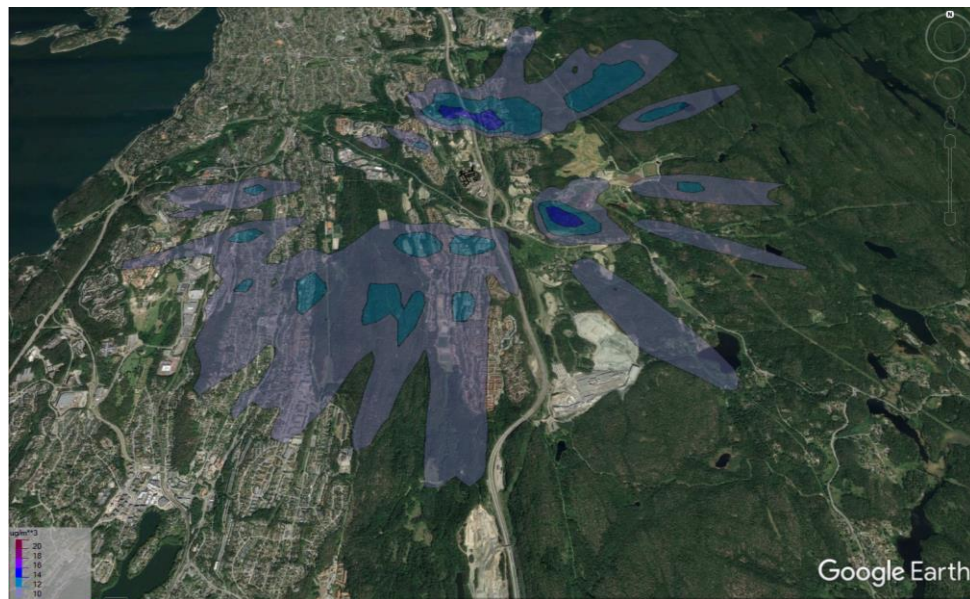
¹⁰ Oslo kommune, Vann- og avløpsetaten; Datarapport Drikkevannskvalitet 2018»¹⁰

<https://www.oslo.kommune.no/getfile.php/13311279-1548684601/Innhold/Vann%20og%20avl%C3%B8p/Drikkevannskvalitet/Datarapport%202018.pdf>

5 Results and discussion

5.1 NO₂

The figure below shows maximum hourly concentration contribution of NO₂. The dispersion modelling has been performed in AERMOD with typical NO_x emission values and assuming that some NO is oxidized to NO₂ by O₃ (AERMODs Plume Volume Molar Ratio Method, fixed O₃ value 80 µg/m³). Meteorology data are from 2015 and flue gas temperature 44 and 65 °C.



Without reheater. Flue gas temperature 44 °C



With reheater. Flue gas temperature 65 °C

Figure 11 Maximum hourly concentration contribution of NO₂ (µg/m³). Meteorology data 2015.

The figure above shows that maximum hourly concentration contributions without and with reheater are less than 16 and 14 µg NO₂/m³ respectively.

5.2 Nitrosamines and nitramines concentration

The table below shows maximum annual average concentration contribution of nitrosamines and nitramines.

Table 7 Maximum annual average concentration contribution

Case	Stack	Amines emitted (ppmv)	Share of amines/nitrosamines (stack) (weight-%)	Total nitrosamines+nitramines (ng/m ³)
NILU case	One 80 m stack, 70 °C	0.4	99.42/0.58	Met.data 2015: 0.25 2016:0.27 2017:0.21
Reheat case	Existing two 80 m stacks, 65°C	0.2	99.42/0.58	Met.data 2016*: 0.20
No reheat case^o	Existing two 80 m stacks, 44°C	0.2	99.42/0.58	Met.data 2016*: 0.23

*The meteorological year 2016 was chosen because it gave the highest concentration contribution in the NILU case.

Modelled nitrosamine+nitramine concentrations in the **NILU case** are 0.25, 0.27 and 0.21 ng/m³ for meteorology data from 2015, 2016 and 2017. Modelled nitrosamine+nitramine concentrations in the **Reheat** and **No Reheat** cases are 0.20 and 0.23 ng/m³ for meteorology data from 2016 (see the table above).

Maximum annual average concentration contribution is below the air quality guideline value of 0.3 ng/m³ for all cases. The share from directly emitted nitrosamines are 50-70% of total nitrosamines for all cases.

The figures below show contour plots of the total nitrosamine+nitramine concentration contribution for the **NILU case** (2015, 2016 and 2017) and for the **Reheat** and **No Reheat** cases (2016).

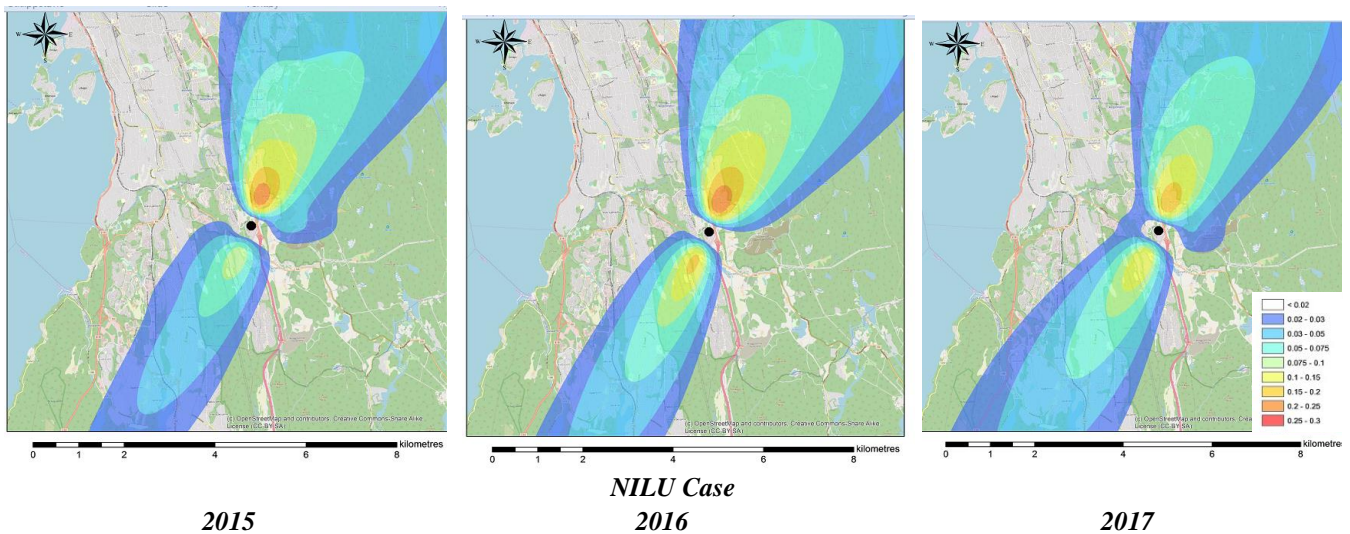


Figure 12 Contour plots of the total nitrosamine+nitramine concentration contribution, ng/m³ (sum of emitted and formed nitrosamines and nitramines). NILU case

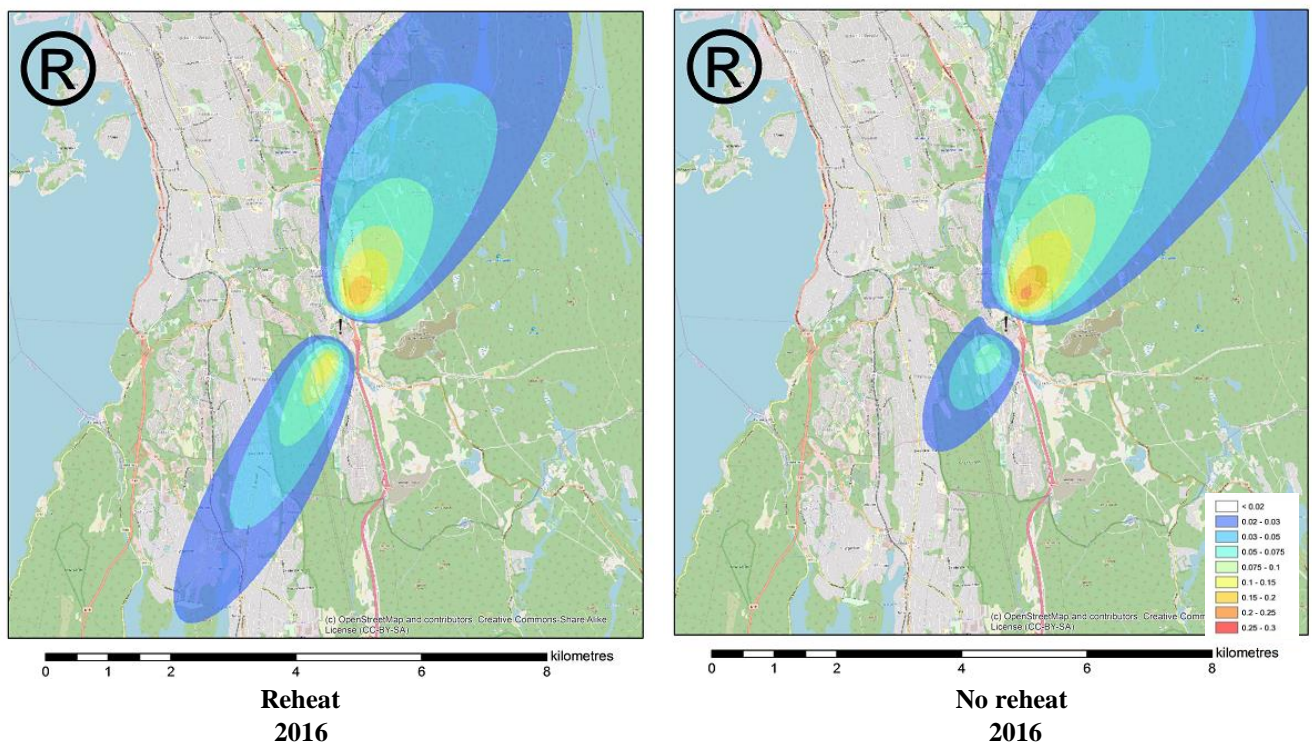


Figure 13 Contour plots of the total nitrosamine+nitramine concentration contribution, ng/m³ (sum of emitted and formed nitrosamines and nitramines). Reheat and No Reheat cases

As seen from the figures above, max concentration occurs about 800 meters north/northeast of the plant for all cases.

5.3 Air concentration, deposition and concentration in water bodies

The figures below show sum of air concentrations (nitrosamine+nitramine) for in the NILU case (2015 and 2016) and 2016 (Reheat and No Reheat cases).

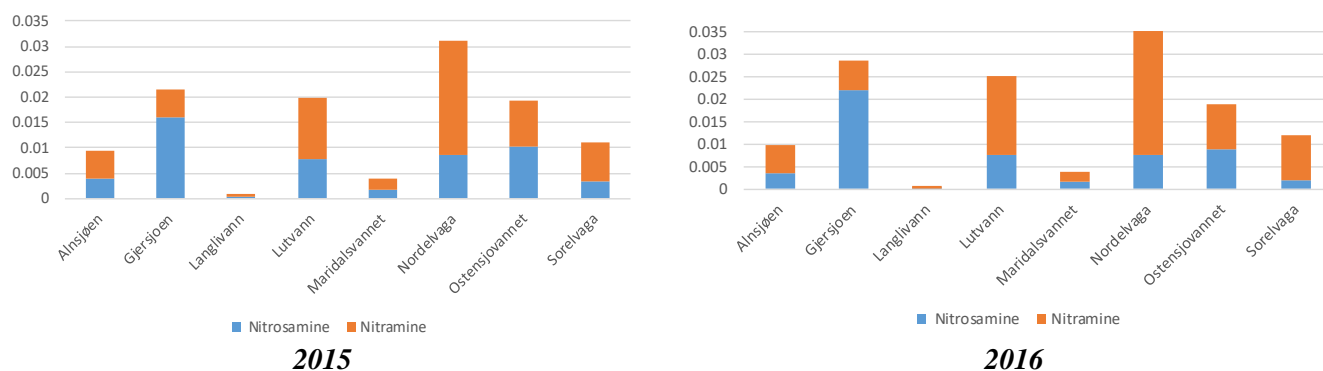


Figure 14 Sum of air concentrations (nitrosamine+nitramine) in 2015 and 2016 at the modelled lakes (ng/m³). NILU case

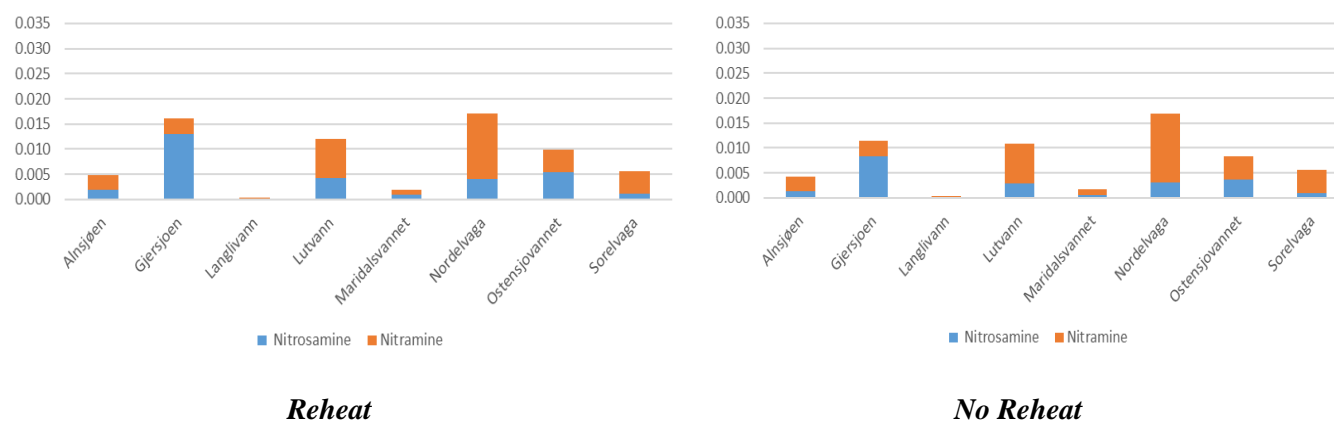


Figure 15 Sum of air concentrations (nitrosamine+nitramine) in 2016 at the modelled lakes (ng/m³). Reheat and No Reheat cases

The figure above shows that air concentration is highest at Nord-Elvåga for all cases. Based on this we have done deposition modelling and drinking water calculation for the drinking water source Nord-Elvåga for 2016. Maridalsvannet, Oslo's main drinking water source is also included in the modelling and calculations.

The table below show concentrations in air, deposition rates and resulting approximate concentrations in water.

Table 8 Concentrations in air, deposition rates and resulting approximate concentrations in water. 2016

Case	Water body	Sum of nitrosamines and nitramines			
		Wet deposition rate	Dry deposition rate	Total (dry plus wet) deposition rate	Annual average concentrations in water (ng/l)
		(ng/m ² /s)	(ng/m ² /s)	(ng/m ² /s)	
NILU case	Maridalsvannet	1.40E-05	2.91E-05	4.32E-05	1.4
	Nord-Elvåga	3.47E-05	3.73E-04	4.08E-04	12.9
Reheat case	Maridalsvannet	9.51E-06	6.14E-06	1.56E-05	0.5
	Nord-Elvåga	9.13E-05	1.56E-05	1.07E-04	3.4
No Reheat case	Maridalsvannet	1.27E-05	6.13E-06	1.88E-05	0.6
	Nord-Elvåga	1.70E-04	3.94E-05	2.09E-04	6.6

From the table above we find that annual average concentration of nitrosamines+nitramines in the lake with highest concentration (Nord-Elvåga) for the worst-case year (2016) is estimated to 12,9 ng/l in the **NILU case**. This is more than 3 times the guideline value of 4 ng/l.

Annual average concentration in the lake with highest concentration (Nord-Elvåga) for the worst-case year (2016) is 3,4 ng/l in the **Reheat case**. This is below the guideline value of 4 ng/l. The **No Reheat case** has annual concentration 6,6 ng/l, which is above the guideline value.

Norsk Energi/CERC method assumes that the nitrosamines and nitramines in the aqueous phase are well-mixed to a depth of 1 m below the surface of the water. In NILUs method, the yearly precipitation at each lake are used (760-1040 mm). This makes the water concentration calculation methods quite similar.

Degradation of nitrosamine deposited in water is according to the NILU Klemetsrud report calculated by the methodology described in NILU OR 52/2011 (steady state concentration of 4.1% of applied concentration)¹¹. Deposited nitramine is not reduced from degradation in water phase in the calculations. We have used this 4,1 % steady state concentration in our calculations as well.

The calculation of drinking water concentration gives a very rough estimate. A better estimate could be made by establishing a run off model, where the catchment of a lake is modelled based on the knowledge of that lake and the transport of water to and from it.

¹¹ NILU OR 52/11: «For nitrosamines, definitely photolysis (life-time 3 weeks) and possibly biodegradation (half-life 40 days to 400 days) (Brakstad et al., 2011) will reduce the concentrations. The effect of photolysis will result in a reduction of the rainwater concentration of nitrosamines to 5.9 % of its initial value as a contribution to the yearly average fresh water concentrations. Biodegradation might reduce the nitrosamine concentration further, down towards 4 % of the rainwater concentration. As the biodegradation varies with different species of nitrosamines, and as its effect is minor, it is not considered in these calculations. »

5.4 Sensitivity runs

The figure below shows air concentrations at the modelled lakes with the OH we used (1×10^6 molecules/cm³, OH used) and the OH NILU used (5×10^5 molecules/cm³, NILU OH).

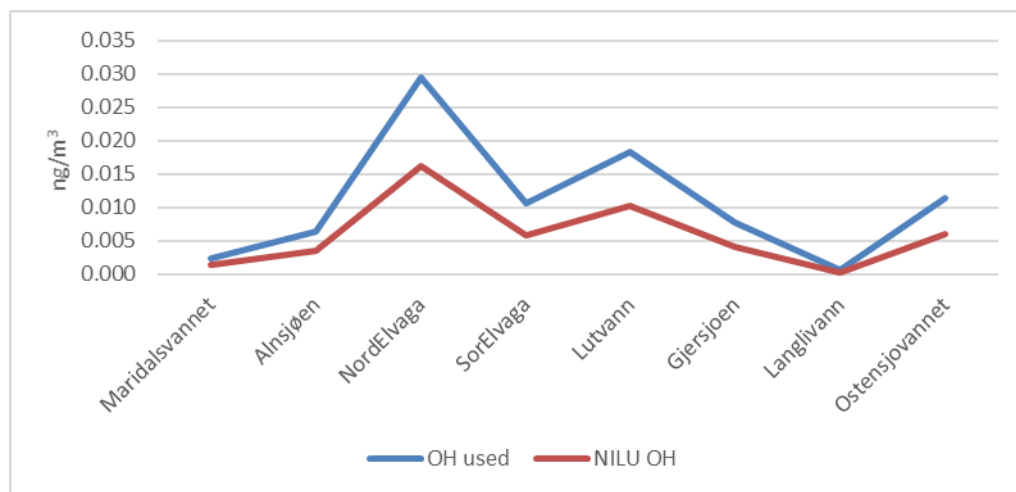


Figure 16 Concentrations of nitrosamine+nitramine at the modelled lakes (ng/m³) with the OH we used (1×10^6 molecules/cm³, original) and the OH NILU used (5×10^5 molecules/cm³, NILU OH). Meteorology data 2016.

The figure above shows that the air concentrations of nitrosamine+nitramine at the modelled lakes were almost twice as high with the OH we used (1×10^6 molecules/cm³) as with the OH NILU used (5×10^5 molecules/cm³).

This will also affect the drinking water concentrations, and further calculations of this may be performed.

6 Uncertainty

Concentration

The uncertainty using dispersion models is related to the following conditions:

- Quality of input data: Emission data, meteorology data, receptor data and terrain data
- Scope: Highest short-term average value, short-term average value at a specific location or annual average value at a specific location.
- Mathematical formulas in the model: How well the formulas in the model describe reality
- Inherent uncertainty: uncertainty due to the fact that the dispersion varies under the same meteorological conditions

The US EPA Guideline on Air Quality Models (2005) lists the following about uncertainty in the dispersion models including AERMOD (this will also apply to ADMS):

- the models are better suited for estimating average concentrations for longer periods than for estimating short-term concentrations at specific locations;
- the models are reasonably reliable in estimating the magnitude of the highest concentrations that occur once, somewhere within a range (errors of the highest estimated concentrations of ± 10 to 40 percent are found to be typical);
- calculated concentrations at a particular hour are poorly correlated with actual observed concentrations and have high uncertainty;
- uncertainty of five to ten degrees in the measured wind direction transporting the plume can result in concentration errors of 20 to 70 percent for a specific time and place, depending on stability and the location of the station. Such uncertainties do not mean that estimated concentration does not occur, but that time and place for it are uncertain;
- The US EPA has estimated that even for a perfect model, inherent uncertainty alone can result in typical deviations from true concentration of up to $\pm 50\%$

Deposition

The deposition calculations are based on the concentration calculations. Additional calculation factors mean larger uncertainties than for concentration calculations.

The algorithms used for deposition calculations in the ADMS and AERMOD models are very similar. In the science documents about deposition parameterization used in AERMOD, the following is stated about uncertainty¹²: "However, work on the deposition velocities for most of the gaseous HAPs (hazardous air pollutants) is limited. Because field experiments have not been conducted to evaluate the deposition of the gaseous HAPs quantitatively, development of a description of the deposition velocities must rely considerably on findings from laboratory studies and theoretical considerations, and the accuracy of the resulting equations cannot be fully determined. "

Model validation for AERMOD: <https://www.epa.gov/scram/air-quality-dispersion-modeling-preferred-and-recommended-models#aermod>

Model validation for ADMS: <http://www.cerc.co.uk/environmental-software/model-validation.html>

¹² "Deposition Parameterization for the Industrial Source Complex (ISC3) Model". ISC3 is the US EPA model used before AERMOD

7 Suggestions for further work

Further work could include the following:

- further calculations of air concentration, deposition and drinking water concentration using lower OH value
- further calculations using other stack parameters and amine emission
- evaluation and comparisons of dispersion models and methods for calculations
- catchment modelling for specific lakes