**Ministry of Environment and Gender Equality**
Environmental Protection Agency

# NACAT
# $N_2O$ Abatement by Catalytic Treatment
# MUDP-project

MUDP

November 2025

Publisher: The Danish Environmental Protection Agency

Editors:
Anna Katrine Vangsgaard, Envidan
Nina Almind-Jørgensen, VandCenter Syd
Nerea Uri Carreño, VandCenter Syd
Janus Emil Münster-Swendsen, Topsoe
Abhilasha Dixit Mishra, Hillerød Forsyning
Klaus Bäckström Nielsen, Tårnby Forsyning
Xavier Flores Alsina, DTU
Krist V. Gernaey, DTU
Jeanette Agertved Madsen, Envidan

ISBN:
978-87-7564-057-7

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MUDP-sekretariatet i Miljøstyrelsen
Lerchesgade 35, 5000 Odense| Tlf. +45 72 54 40 00

Mail: ecoinnovation@mst.dk
MUDP's hjemmeside

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# Foreword

The development project "**N**$_2$O **A**batement by **CA**talytic **T**reatment (NACAT)" has contributed to increased knowledge about the potentials and challenges of catalytic reduction of the greenhouse gases nitrous oxide and methane in off-gas streams from covered process tanks at wastewater treatment plants. The project has been supported by the Environmental Technology Development and Demonstration Program (MUDP) under the Danish Ministry of Environment since 2021.

VandCenter Syd has been the project owner, and the other partners were Topsoe, Hillerød Forsyning, Tårnby Forsyning, the Technical University of Denmark (DTU), and Envidan.
The project had its kick-off in January 2022, but due to COVID-19 and the war in Ukraine, the project was extended, with this final report being delivered in June 2025. The pilot test unit used in the project ended up being rented, which limited the flexibility in choosing the test periods and influenced the results obtained.

The report is written for readers with a solid understanding of wastewater treatment, environmental effects of greenhouse gas emissions, and modelling.
A large part of the development work has taken place at the participating utilities' wastewater treatment plants. A special thanks therefore goes to the great efforts made by the utility staff in carrying out the many experiments.

# Summary

The purpose of the $N_2O$ Abatement by Catalytic Treatment (NACAT) project is to demonstrate the potential for catalytic treatment of $N_2O$ from wastewater treatment plants (WWTP) to reduce greenhouse gas (GHG) emissions. The Danish government has set a national target of becoming $CO_2$-neutral by 2050 with an intermediate goal in 2030 to achieve 70% reduction compared to 1990 emission levels. As a consequence of this, it is expected that a regulation of $N_2O$ emissions from WWTP is going to be implemented in Denmark within the next couple of years. This will incentivise utilities to reduce emissions, in some cases through catalytic abatement, as this technology in this project is demonstrated with a positive business case.

In the project a pilot plant containing an adsorption guard, blower, and reactor with the catalyst was tested at three Danish WWTPs - on two mainstream off-gas streams and two sidestream deammonification off-gas streams. To measure the conversion of $N_2O$, a gas analyser was installed together with the pilot plant to measure inlet and outlet concentrations.
The pilot plant testing was carried out for the three test sites over a period of five months from medio September 2023 to start February 2024. The pilot test unit ended up being rented, which limited the flexibility of time at each test site, which in turn influenced the amount of data collected for economic and environmental assessment.

At the first test site a lot of practical challenges were met, a lot of troubleshooting were done, and derived learnings were made. Therefore, the first part of the testing campaign at Hillerød Centralrenseanlæg Syd (HCR Syd) was used to tackle challenges with sulphur deactivation of the catalyst, challenges with heat tracing and condensation in the sulphur guard, multiplexer sampling time, electrical installation issues, and methane in the off-gas, which all added to reduce efficiency of the $N_2O$ conversion. After the preliminary challenges data collection from the catalytic tests could be conducted.

At HCR Syd first treatment of the off-gas from the mainstream process tanks was tested. However, the off-gas from the mainstream process tanks had low concentrations of $N_2O$, with an average concentration of 0.5 ppm, resulting in difficulty measuring the concentrations in both the inlet and outlet and establishing a conversion efficiency. Because of the low concentrations, it was decided to change to treat the off-gas from the combined ventilation consisting of off-gas from a sidestream deammonification process (Demon) and other building ventilations. This stream had an average $N_2O$ concentration around 50 ppm, and a conversion result of first 30% was observed followed by a decrease to 20%. Tests on the existing biological odour removing filters showed no conversion of $N_2O$ in these.

Second test site was at Ejby Mølle WWTP treating the off-gas from a sidestream deammonification tank treating reject water from the final sludge dewatering. Because of the relatively low conversion at HCR Syd and some practical challenges, preliminary tests of the sulphur guard and the catalyst was carried out, concluding that the sulphur guard was saturated and therefore the catalyst was deactivated due to sulphur. A new sulphur guard and catalyst were therefore installed to achieve usable conversion data. Conversion results in periods with stable $N_2O$ concentrations reached 80% and conversion of methane ($CH_4$) was also observed with an efficiency of 55%.

Third and last test site was Tårnby WWTP treating off-gas from the mainstream process tanks. In the test campaign low concentrations of $N_2O$ was often measured in the inlet to the catalyst making the evaluation of the conversion challenging. In a short period with a daily $N_2O$ peak in the range of 4-22 ppm a conversion around 80% was observed. Tests conducted on the existing activated carbon odour removing filters showed no conversion of $N_2O$ in these at both high and low inlet $N_2O$ concentrations.

Based on the results from the three test sites, five scenarios were investigated regarding their economic feasibility; Mainstream process tank off-gas treatment at HCR Syd, Mainstream process tank off-gas treatment at Tårnby, Sidestream deammonification process off-gas treatment at HCR Syd, Sidestream deammonification process off-gas treatment at Ejby Mølle with high $N_2O$ concentrations, and Sidestream deammonification process off-gas treatment at Ejby Mølle with low $N_2O$ concentrations. For the economic assessment a cost of 750 DKK/ton $CO_{2,eq}$ was used for to assess the savings potential. Two of the five scenarios resulted in a positive business case – the two being Mainstream process tank off-gas treatment at Tårnby and Sidestream deammonification process off-gas treatment at Ejby Mølle with high $N_2O$ concentrations. The calculated $CO_2$ shadow price ranged from 400 to 4500 DKK/ton $CO_2$ for the five scenarios.
This assessment gives a clear picture that installation of a catalytic GHG reduction process is highly dependent on the initial $N_2O$ emissions and could be an appropriate treatment technology for high emission sites. The main cost driver is the CAPEX followed by cost for change of sulphur guard and heating of the gas making up the main contributors to the OPEX. The economic assessment results underline that the feasibility of implementing the technology will have to be made at a case-by-case level focussing on identifying high emission sites to be targeted.

Modelling efforts within the project resulted in a digital twin approach combining mechanistic and hybrid models that lead to accurate prediction of $N_2O$ emissions under real operational conditions at Ejby Mølle's sidestream deammonification process. To achieve this, data pretreatment (e.g., filtering, interpolation, pH correction) is paramount. In the sidestream deammonification process nitrifier denitrification (ND) pathway was the dominant $N_2O$ source under low oxygen and high nitrite conditions, while the nitrifier nitrification (NN) pathway remained negligible. Based on the model result, a generic assessment was conducted in the Benchmark Simulation Model 2 (BSM2) framework, resulting in proposal of optimal control strategies to minimize GHG emissions.

To achieve the needed GHG reduction in the future, an integrated approach where reduction and removal technologies complement each other, as one or the other is not expected to be able to tackle all emission sites. The NACAT project has increased the knowledge level in both of these areas, and it is believed that implementation of $N_2O$ destruction will play in role once regulation and carbon taxation come into force.

# Sammenfatning

Formålet med projektet **N**$_2$O **A**batement by **Ca**talytic **T**reatment **(NACAT)** er at demonstrere potentialet for katalytisk behandling af lattergas ($N_2O$) i afkastluft fra renseanlæg med henblik på at reducere udledningen af drivhusgasser. Den danske regering har sat et nationalt mål om $CO_2$-neutralitet i 2050 og som et delmål en reduktion på 70 % i 2030 sammenlignet med 1990-niveauet. Afledt heraf forventes det, at der inden for få år vil blive indført regulering af $N_2O$-udledninger fra renseanlæg i Danmark. Dette vil skabe incitamenter for forsyningsselskaber til at reducere udledninger – blandt andet gennem katalytisk behandling, som via dette projekt viser potentiale for at være en økonomisk fordelagtig løsning.

I projektet blev et pilotanlæg med adsorptionsfilter, blæser og reaktor med katalysator testet på tre danske renseanlæg - på to afkast fra de biologiske hovedstrømstanke og på to afkast fra anammoxbaserede rejektvandsbehandlinger. For at måle fjernelsen af $N_2O$ blev der installeret en gasanalysator, som målte koncentrationerne før og efter katalysatoren. Testene blev gennemført over fem måneder fra midten af september 2023 til begyndelsen af februar 2024. Grundet pilotanlægget var lejet, var længden af testperioderne på de enkelte anlæg begrænsede, hvilket påvirkede mængden af data til de tekniske, økonomiske og miljømæssige evalueringer.

Først blev der testet på Hillerød Centralrenseanlæg Syd (HCR Syd), hvor mange praktiske udfordringer ventede, herunder svovlforgiftning af katalysatoren, problemer med varmeisolering og kondens i adsorptionsfilteret, udfordringer med elektriske installationer og endelig metan i afkastluften. Disse forhold reducerede effektiviteten af $N_2O$-konverteringen i pilotanlægget. Efter indledende fejlfinding kunne dataindsamlingen begynde.

På HCR Syd blev der først testet på afkastluften fra de biologiske hovedstrømstanke, men $N_2O$-koncentrationerne var lave (gennemsnitligt 0,5 ppm), hvilket gjorde det vanskeligt at måle fjernelsesgraden. Derfor blev testen ændret til at pilotanlægget behandlede en kombineret ventilationsstrøm fra afkastluft fra rejektvandsbehandlingen og øvrig bygningsventilation, hvor $N_2O$-koncentrationen var omkring 50 ppm. Her blev der først målt en fjernelsesgrad på 30 %, som senere faldt til 20 %. Test på det eksisterende biologiske filter til lugtfjernelse viste at ingen $N_2O$-fjernelse opnås i dette filter.

Andet renseanlæg var på Ejby Mølle Renseanlæg, hvor afkastluft fra anammoxbaseret rejektvandbehandling blev testet. Pga. den lave fjernelsesgrad observeret på HCR Syd blev der foretaget nogle indledende analyser af adsorptionsfilteret til svovl og katalysatoren, hvilket viste at adsorptionsenheden var mættet og katalysatoren deaktiveret grundet svovl. Adsorptionsmediet og katalysatoren blev derfor udskiftet inden test på Ejby Mølle for at opnå mere retvisende data. Dette resulterede i en observeret fjernelsesgrad på op til 80 % for $N_2O$ og i tillæg en fjernelsesgrad af metan ($CH_4$) på 55 %.

Det tredje renseanlæg var Tårnby Renseanlæg, hvor pilotanlægget behandlede afkastluft fra de biologiske procestanke der behandler hovedstrømmen af spildevandet. Her var $N_2O$-koncentrationerne generelt lave, men i en kort periode, med daglige spidsudledninger på 4–22 ppm, blev der observeret en konvertering på ca. 80 %. Test på det eksisterende aktivt kul filter til lugtfjernelse viste ingen $N_2O$-fjernelse – hverken ved høje eller lave koncentrationer.

På baggrund af resultaterne fra de tre renseanlæg blev der foretaget en økonomisk analyse af fem scenarier: to hovedstrøms scenarier (HCR Syd og Tårnby) og tre sidestrømsscenarier (HCR Syd, Ejby Mølle ”høj udledning” og Ejby Mølle ”lav udledning”). Ved en anvendt $CO_2$-pris på 750 DKK/ton $CO_2$-ækvivalent viste to scenarier en positiv business case. Dette var hovedstrømsscenariet på Tårnby og sidestrømsscenariet i Ejby Mølle med høje $N_2O$-koncentrationer. Den beregnede $CO_2$-skyggepris for de fem scenarier varierede mellem 400 til 4.500 DKK/ton $CO_2$. Analysen viser, at den økonomiske bæredygtighed afhænger af hvor meget $N_2O$ der i udgangspunkt skal behandles og at denne teknologi især kan være relevant for anlæg med høje $N_2O$-udledninger. De største omkostningsdrivere er anlægsinvesteringer (CAPEX) efterfulgt af driftsomkostninger (OPEX) til opvarmning og udskiftning af adsorptionsmedie til svovl. De økonomiske analyser understreger at muligheden i at implementere denne teknologi og hvorvidt den er et økonomisk attraktivt alternativ vil variere fra sted til sted og der bør derfor fokuseres på at identificere anlæg med høje $N_2O$-udledninger.

Projektet udviklede også en digital tvilling-model, som kombinerer mekanistiske og hybridmodeller til præcis forudsigelse af $N_2O$-udledninger under reelle driftsforhold på Ejby Mølles rejektvandsbehandling. For at opnå dette for forbehandling og datavask i form af filtrering og interpolation essentielt for at opnå et fornuftigt resultat. Via modellen blev $N_2O$-produktionsvejen nitrificerende denitrifikation (ND) identificeret som den dominerende kilde til $N_2O$ under lave ilt- og høje nitritforhold. Resultaterne blev overført til og anvendt i Benchmark Simulation Model 2 (BSM2), hvori holistiske vurderinger inkluderende udløbskoncentrationer, drivhusgasudledninger og driftsudgifter blev brugt til at foreslå optimale styringsstrategier.

For at opnå fremtidige reduktioner i drivhusgasudledninger anbefales en integreret tilgang, hvor både reduktions- og fjernelsesteknologier er i spil og supplerer hinanden, da en tilgang alene ikke vil kunne løse udledningsproblematikken på alle anlæg alene. NACAT-projektet har bidraget væsentligt til viden på området og det forventes at $N_2O$-fjenelse i afkastluft vil komme til at spille en rolle, når regulering og $CO_2$-beskatning forventeligt træder i kraft.

# 1. Background

## 1.1 $CO_2$ footprint of wastewater treatment

Global warming and climate change are international issues, and several studies have established the significance of greenhouse gas (GHG) emissions from the wastewater process contributions to these issues. For the removal of contaminants in wastewater the treatment processes utilize biological, physical, and chemical processes. During the treatment and energy generation from produced biogas direct process emissions occur (scope 1 emissions). These primarily consist of carbon dioxide ($CO_2$), methane ($CH_4$), and nitrous oxide ($N_2O$). In addition to these fugitive emissions caused by degradation of organic matters and nitrogen, there is an indirect emission of $CO_2$ of fossil origin due to energy and materials consumption related to operation of wastewater treatment plants (Vijayan, Saravanane and Sundararajan 2017). These emissions comprise scope 2 and 3 according to the GHG Protocol.
The aerobic treatment processes produce primarily $CO_2$, whereas the anaerobic processes, including sludge digestion, produce a mixture of $CH_4$ and $CO_2$ emissions. During biological nitrogen removal through nitrification and denitrification $N_2O$ is produced. These emissions are categorized as direct emissions (on-site GHG emissions). The emissions from the usage of electricity and chemicals during the operation and maintenance of the wastewater treatment plant (WWTP) and disposal of sludge are considered as indirect emissions (Off-site GHG emissions). Other indirect emissions include those caused by the production and transportation of materials off-site (Vijayan, Saravanane and Sundararajan 2017).

The carbon footprint of WWTP is expressed as the total set of GHG emissions caused by the activity or product expressed in terms of carbon dioxide equivalents, and its irrespective from which specific GHG was actually emitted. To convert other gases to $CO_2$ equivalents, global warming potential (GWP) is used. The definition of the GWP of a GHG is the ratio of heat trapped by one unit mass of the gas compared to one unit of $CO_2$ over a specified period (typically 100 years). Implying that gases with a higher GWP absorb more energy, than gases with a lower GWP, and thereby contribute more to warming Earth. The GWP is 27,2 and 273 for $CH_4$ and $N_2O$, respectively (EPA, Understanding Global Warming Potentials 2024). Even small amounts of $N_2O$ emissions therefore have a huge impact on the $CO_2$ footprint and is most often the largest single contributor in the carbon footprint of the operational phase of wastewater treatment plant with biological nitrogen removal.

At a national level, Denmark has set a goal to become $CO_2$-neutral by 2050 and aims to achieve 70% of the reduction target by 2030 compared to 1990 emission level. The Danish branch association DANVA has set an ambitious goal for a climate and energy neutral Danish water sector in 2030. Moreover, a climate and energy neutral water sector is one of the main priority areas defined by MUDP (under the Danish EPA) in their Strategy for 2020-2023. It is expected that regulation of $N_2O$ emissions from WWTP is on its way in Denmark, which will incentivise utilities to monitor, control, and reduce their emissions. Reducing 80% of the $N_2O$ emissions from the four largest WWTPs in Denmark alone, would reduce 23% of the national $N_2O$ emissions from the whole wastewater sector, which would correspond to ~38,000 tons $CO_{2,eq.}$ per year.

Nitrous oxide mitigation efforts at WWTP’s up to date have focused on minimizing the production and emission of nitrous oxide by controlling the biological processes. There are currently no technological solutions on the market specifically aimed to eliminate nitrous oxide emissions from WWTP’s. This development project demonstrate the first attempt at using abatement technologies that focus on the removal of nitrous oxide from exhaust gas streams of covered biological process units. The project purpose is a proof-of-concept of a new generation of catalysts for $N_2O$ abatement developed by Topsoe applied in a new market for WWTP's.

## 1.2 $N_2O$ sources

Emissions of $N_2O$ are increasing and it contributes to the global anthropogenic greenhouse gas emission with about 6 percent (EPA, Overview of Greenhouse Gases 2024). $N_2O$ is naturally present in the atmosphere as a part of the Earth's nitrogen cycle but more and more originates from human activities such as agriculture, fuel combustion, industrial processes, and wastewater management. The $N_2O$ molecules are an average of 121 years in the atmosphere before they are removed either by a sink or destroyed by chemical reactions (EPA, Overview of Greenhouse Gases 2024). Direct emissions of $N_2O$ are of great concern since $N_2O$, as previously mentioned, has a global warming potential 273 times higher than $CO_2$.

Apart from being a significant contributor to the carbon footprint of the operation of WWTPs, $N_2O$ emissions vary substantially between plants and in time within a single treatment plant, ranging from negligible to substantial. This is possibly due to different designs and operational conditions. The mechanisms behind the $N_2O$ emission in wastewater treatment plants are therefore important to understand to effectively mitigate and apply the right solutions at the right time and place.

### 1.2.1 $N_2O$ in mainstream secondary treatment

$N_2O$ is produced and emitted primarily during the biologically nitrogen conversion processes in the process tanks at WWTP's. This can happen via several different pathways, it is currently widely accepted that three biological and one abiotic pathway are mainly responsible for $N_2O$ production. In the biological process of nitrification, where ammonium ($NH_4^+$) is oxidized to nitrite ($NO_2^-$) by ammonia-oxidizing bacteria (AOB), $N_2O$ can be produced as a byproduct i.e. the nitrifier nitrification (NN) pathway, where hydroxylamine is oxidized to $N_2O$ and nitrifier denitrification (ND) pathway where the nitrifiers can reduce $NO_2^-$ to $N_2O$.
During the denitrification process, $NO_2^-$ is reduced to nitrogen gas ($N_2$) through several intermediate steps by denitrifying bacteria under anoxic conditions. $N_2O$ is produced and converted as one of these intermediates in the denitrification. If the process is incomplete or disrupted $N_2O$ can be accumulated and eventually released (Law, et al. 2012).

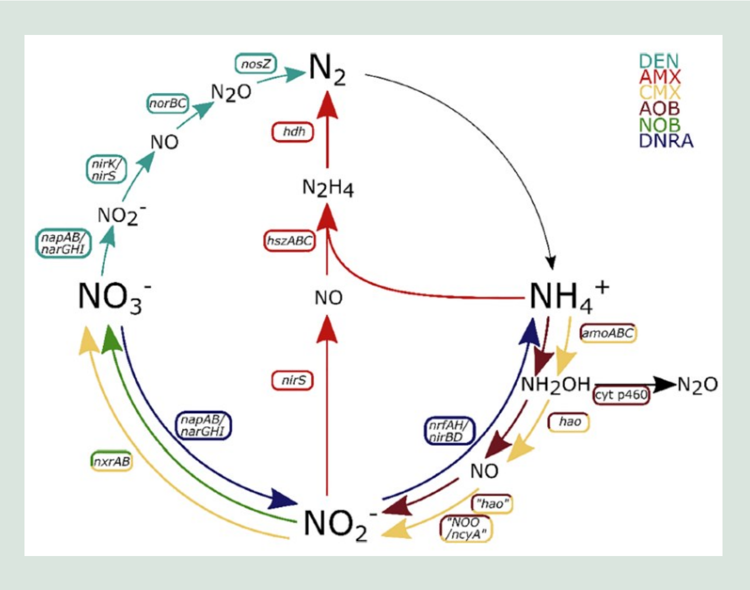


**FIGURE 1.** Overview of the nitrogen cycle. Denitrification from nitrate to dinitrogen gas (turquoise), ammonia oxidation (AOB) (brown), nitrite oxidation (green), anammox (red) (Valk, et al. 2022).

Different factors in the wastewater treatment process can affect the production of $N_2O$. Dissolved oxygen concentration, both low and high, can in certain cases lead to increased $N_2O$ production. Conditions with low oxygen concentrations can favour the ND pathway causing increased $N_2O$ production, while high oxygen concentrations can cause increased $N_2O$ production through the NN pathway. The rate and efficiency of the denitrification process is affected by the availability and type of carbon source, where a limited or complex-to-degrade carbon source can lead to an accumulation of $N_2O$ due to incomplete denitrification.

The temperature will affect the microbial activity and composition. In several Danish and international WWTPs a peak in the $N_2O$ production has been observed in the late spring/early summer months, which coincides with increasing temperature and often decreasing sludge age. A shift in the microbial composition during this time is therefore believed to be causing this increase in $N_2O$ production. A longer sludge retention time can enhance the growth of nitrifying and denitrifying bacteria and potentially lead to more stable nitrogen removal processes and thereby lower $N_2O$ emissions.

The amount of produced $N_2O$ at a WWTP is typically expressed as an emission factor (EF), which is the ratio between how much of the nitrogen load to a plant is converted to $N_2O$. The standard factor from the IPCC is 1.6% (IPCC 2019), whereas the Danish national standard factor is 0.84% (Miljøstyrelsen 2020).

### 1.2.2 N2O in sidestream secondary treatment

The effluent water from the dewatering of anaerobically digested sludge consists of an ammonia rich stream, often with a concentration above 1000 mgN/l. Normally this stream is led back to the mainstream treatment in the process tanks, sometimes leading to peaks in the N load to process tanks and a need for addition of external carbon source. By including a dedicated reject water treatment step (sidestream secondary treatment), e.g. a deammonification process, that treats the reject water before it returns to the process tanks, this can be prevented.

In a deammonification process $NH_4^+$ is removed by a partial nitritation process followed by anaerobic ammonium oxidation (anammox) process (PN/A), in which the remaining ammonia ($NH_4^+$) is converted with nitrite ($NO_2^-$) into nitrogen gas ($N_2$). The process requires an oxygen-free environment, as oxygen inhibits the activity of deammonification bacteria. In addition, there is no requirements for extra organic carbon (Lin, Ma and Yang 2022).

One of the down sides of deammonification through this process, is the considerable amount of produced $N_2O$ during the partial nitritation. As mentioned previously, $N_2O$ is produced through three pathways, nitrifier nitrification, nitrifier denitrification and heterotrophic denitrification (see FIGURE 1). Due to low concentrations of readily degradable COD in the reject water, the heterotrophic denitrification occurs to a limited extension. This means that there is no conversion pathway active in any significant amount, which in turn means that produced $N_2O$ will not get removed once produced. The partial nitritation process often takes place at high specific reaction rates (gN/h/gVSS) due to high substrate concentrations, which leads to a higher fraction of the converted ammonium ending up as $N_2O$ than in the mainstream. Emission factors in sidestream treatments have been reported in wide ranges, but often in amounts up to 10-fold of the values for emission factors observed in mainstream treatment.
Approximately 10-15% of the N load of a treatment plant with anaerobic digestion comes from the dewatering of digested sludge, which means that the size of the emission from the mainstream and sidestream are very comparable in amount of $kgN_2O/d$ emitted.

# 2. Project purpose

The purpose of this project is to address an important and urgent global challenge: Greenhouse gas emissions and the accompanying climate change. In this project the possibility to reduce or even eliminate one of the significant emission sources – $N_2O$ – from WWTP's has been tested.

The project had five main goals:

1. To investigate the performance of $N_2O$ reduction by existing odour reduction technologies by measuring $N_2O$ before and after the biofilter at Hillerød Centralrenseanlæg syd (HCR Syd) and the activated carbon filter at Tårnby WWTP.
2. To investigate the performance of catalytic processes to treat the off-gas from the biological reactors (two mainstream and two sidestream) at three different WWTPs and demonstrate its ability to abate $N_2O$ emissions.
3. To assess the environmental impact of implementing such technologies and develop management strategies, primarily through process optimization and to monitor $N_2O$ emissions from the biological processes at wastewater treatment plants.
4. To build business case scenarios for the catalytic technology with linkage to future national and international regulation.
5. To develop a set of mathematical models (digital twins) and sustainability assessment methods to virtually predict process performance and serve as a decision tool to balance variables such as effluent quality, energy consumption, cost, and $N_2O$ emissions simultaneously.

The aim of these goals is to show other water utilities the necessary effort to reduce harmful emissions of $N_2O$ from treatment plants and thereby help improve their carbon footprint. The project aspired to demonstrate if a significant improvement in terms of urban emissions was possible with a relatively modest investment. There are currently a limited number of technological solutions on the market, specifically aimed to eliminate $N_2O$ emissions from WWTPs. This project will help Denmark to be in a position as a front runner concerning an active effort towards a $CO_2$ neutral wastewater sector.

In addition, the project will provide a significant source of information for the authorities in their continued effort to achieve Denmark's climate goal of a 70% reduction in $CO_2$ emissions compared to 1990 emission levels and to form an improved documentation basis for emission factors and is a logical continuation of some of the latest research efforts in this area, such as those undertaken in the MUDP Lattergaspujle (2019), and the MUDP funded projects ARES (2024) and VARGA (2023).

**Structure of report**

First, an introduction to the tested catalytic technology and pilot-scale setup is given in chapter **Fejl! Henvisningskilde ikke fundet.**. Following on this are three chapters, focusing on each of the tested WWTPs, where an introduction to the plant is given along with an overview of their historic $N_2O$ emissions and results obtained in the abatement tests. In chapter **Fejl! Henvisningskilde ikke fundet.**, business cases built around the historic $N_2O$ emissions and findings from the tests conducted in the project, are presented. Following in chapter **Fejl! Henvisningskilde ikke fundet.** the mathematical models (digital twins) developed in the project to conduct sustainability assessment to virtually predict process performance and serve as a decision support tool can be found. Finally in chapter **Fejl! Henvisningskilde ikke fundet.** and **Fejl! Henvisningskilde ikke fundet.** a sum up of the conclusions and perspectives are presented.

# 3. Demonstration setup

## 3.1 Introduction

Catalytic cleaning of off-gases is well known in other industries, such as $NO_X$ removal, but is not used at WWTP's.

Topsoe has developed an $N_2O$ removal catalyst and the accompanying technology for use in other industries. The knowledge from these developments has been used in developing a new type of catalyst that could be suitable for application in WWTPs. The catalyst is made for direct decomposition of $N_2O$ at low temperatures (400-500 °C). Such a catalyst is currently not offered commercially anywhere in the world.

Most processes in WWTPs occur at atmospheric conditions. However, catalytic abatement requires elevated temperatures. To address this, the gas must be heated and possibly conditioned further for catalytic reactions. By using a heat exchanger, most of the energy used for heating the gas can be recovered by heating up the incoming gas for the reactor. This is known as a feed/effluent heat exchanger.

## 3.2 Technology concept

### 3.2.1 Pilot plant layout

The pilot plant consisted of a container with gas inlet through the roof, the cold adsorption unit, a blower for pushing the gas through the system, a heater to increase temperature, a reactor containing the catalyst, and an outlet chimney on the roof (see FIGURE 2). As the gas stream is heated to high temperatures, the hot parts are well insulated (not shown in the figure).

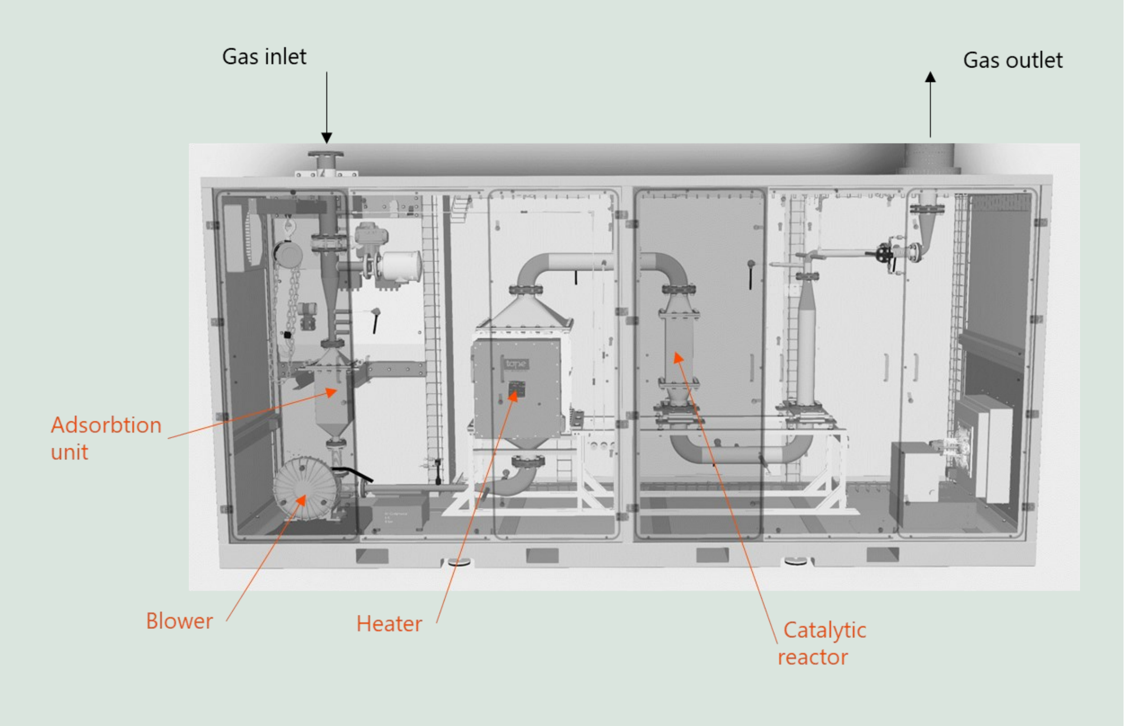
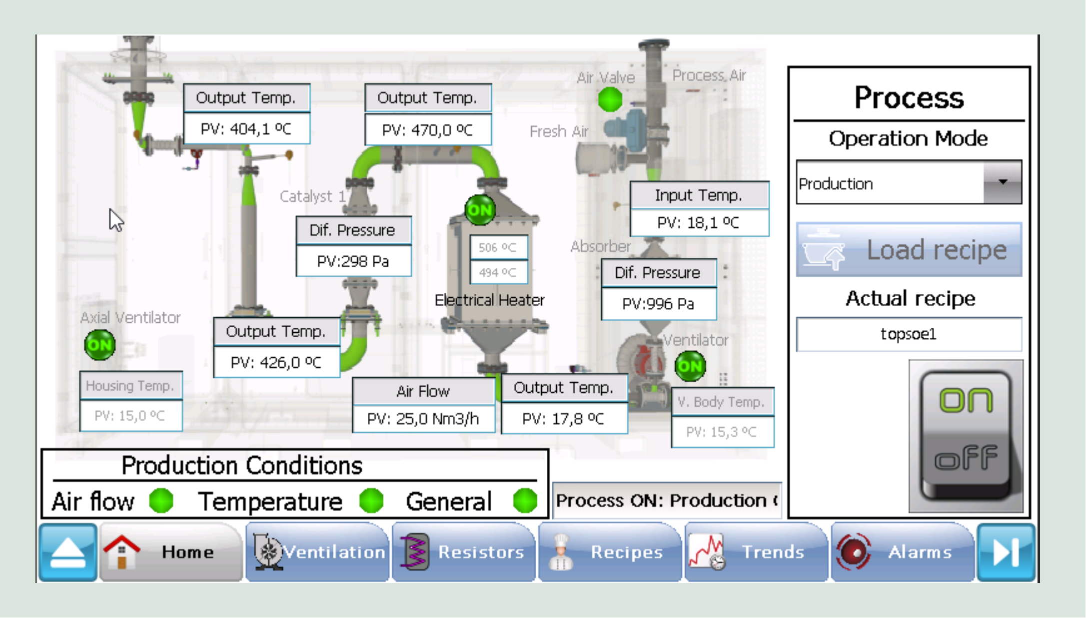


**FIGURE 2.** Illustration of the catalytic pilot plant.

The pilot plant itself contained no measuring equipment, only different sampling ports to extract the gas for analysis. Therefore, a separate container for measurements was used to

house the required instrumentation equipment. This separate container was also used to measure $N_2O$ before and after a biofilter (HCR Syd) and activated carbon filter (Tårnby). The analyser consisted of a Teledyne analyser (model GFC-7002T) and the container had air conditioning to provide suitable and stable conditions for the analyser. The analyser was calibrated every time the pilot was relocated to a new site. This analyser has only one measuring channel, therefore, a multiplexer was added to be able to switch between inlet gas and outlet gas and thereby find the conversion of $N_2O$ across the catalytic reactor.
Both the pilot plant and the analyser could be controlled remotely which made it possible to continuously check the performance of the system that was being tested for $N_2O$ conversion.



Output Temp. PV: 404,1 ºC
Output Temp. PV: 470,0 ºC
Input Temp. PV: 18,1 ºC
Dif. Pressure PV:298 Pa
Dif. Pressure PV:996 Pa
Output Temp. PV: 426,0 ºC
Housing Temp. PV: 15,0 ºC
Air Flow PV: 25,0 Nm3/h
Output Temp. PV: 17,8 ºC
V. Body Temp. PV: 15,3 ºC
506 ºC
494 ºC
Operation Mode: Production
Actual recipe: topsoe1
Process ON: Production (

**FIGURE 3.** Screenshot of the control panel of the pilot plant.

### 3.2.2 Catalytic reactions

The function of a catalyst is to make chemical reactions happen faster and/or control which reactions happens and what the product of these reactions are.
The chemical reaction for direct decomposition of $N_2O$ is simple, as the molecule breaks down to nitrogen and oxygen, the two main components of air.
The reaction is:

$$2\,N_2O \rightarrow 2\,N_2 + O_2$$

A large surface area is required for the reaction to take place, while the pressure drop should be kept at a minimum. For this application, Topsoe believes the best choice is a monolithic catalyst element which has very small channels all the way through, where the catalyst is positioned within these channels. FIGURE 4 illustrates the process and the catalyst function.

The $N_2O$ conversion is the percentage of the $N_2O$ that is removed, and is calculated as:

$$N_2O\ Conversion = \left(1 - \frac{Outlet\ N_2O\ concentration}{Inlet\ N_2O\ concentration}\right)$$

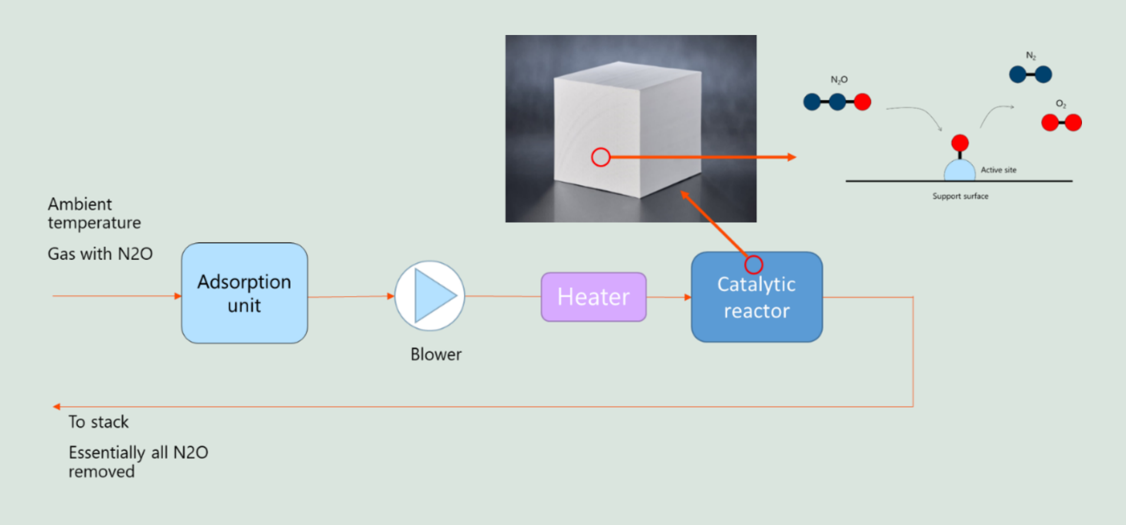


**FIGURE 4.** Block diagram of the process and catalyst function.

When tracking the performance of how the catalyst changes over time, it is optimal that the tests do not to have a high conversion. As a test with enough catalyst to demonstrate a high $N_2O$ conversion, would make it very difficult to see changes in the catalytic performance, while a catalyst with more limited conversion potential would provide more information about sensitivity of the catalyst to operational parameters. The catalyst placed in the pilot plant was designed to have an estimated performance of around 70-90% $N_2O$ at a temperature of 400°C.

General test conditions were:

- 25-50 $Nm^3/h$ off-gas flow
- 400-470°C inlet temperature (due to temperature loss, a higher inlet temperature was needed to keep the average temperature at expected level)

### 3.2.3 Retrofit and modifications

Originally the project entailed revamping an existing catalytic pilot plant owned by Topsoe, but during the project this was deemed unfeasible due to complicated approval processes for new CE marking of the old equipment. Then the construction of a new pilot plant was considered, however it turned out to be above what the project budget allowed. A compromise was found where an existing unit from a third-party collaboration company could be rented for the test period. The unit however, had to be revamped to be able to perform the tests and the feed/effluent heat exchanger could not be added, resulting in higher operating costs to heat the gas. As the gas flow for the test was reduced, this solution was chosen in unison by the entire project team.

During the initial planning, it was believed that there would be limited amounts of sulphur in the off-gas streams where catalytic treatment was to be tested in the project. However, to confirm this, Topsoe went on site at the first test site at HCR Syd, with a handheld $H_2S$ measuring device. The measured $H_2S$ was around 0.1-0.2 ppm on average, with a peak value of around 0.5 ppm.

Despite the low concentrations there was a strong suspicion that the catalyst would be highly sensitive to sulphur, resulting in even a few ppm having a strong negative impact on the catalyst, and deactivate it in a matter of hours or days.

This could potentially become a big issue for the pilot test, but an internal evaluation within Topsoe found a material that was believed to be suitable for cold sulphur adsorption in the given conditions, which could be used to pretreat the off-gas before catalytic treatment. The reconstruction of the pilot plant was already in progress, but fortunately, there was still time to add an adsorption reactor to try and minimize the effects of sulphur on the catalyst. There were however some limitations due to size and available pressure drop.

Adsorption relies on the surface area of the pores of the material. Thus, it is important to prevent water condensation in the material which would fill up the pores, thereby blocking the sulphur adsorption. As the gas from the WWTP processes are saturated with water and the sulphur adsorption unit was before the heating, there was a risk of water condensation. Especially as the testing period was during the Autumn and Winter months, where temperatures outside drop and the gas had to be transported in pipes to the catalytic pilot plant.
After the pilot plant was lifted into place by crane at each site, a pipe connection going from the process to the pilot plant had to be assembled. At Ejby Mølle the pipe could be put down the chimney, but for the other two sites a hole had to be drilled, and a flange fitted on the pipe transporting the off-gas. Due to issues with condensation, the best mitigation option was to heat the gas during this transportation to keep the temperature as high as possible. This was done with electrical tracing of the sample pipes from the off-gas sampling points to the pilot container, by electrically heat-traced underneath the insulation (see FIGURE 5 before insulation).

**FIGURE 5.** Pipe connection from the process tanks off-gas to the pilot plant in HCR Syd before heat tracing and insulation.

## 3.3 Pilot plant time schedule

During the original project planning, the first site for the pilot plant was to be the Ejby Mølle WWTP, located in Odense and the second site was to be the HCR Syd WWTP in Hillerød. Due to the modifications mentioned in the section above, it was decided to start the testing at HCR Syd (mainstream and sidestream), then at Ejby Mølle (sidestream), and finally at Tårnby (mainstream). The main test phases at the three sites are illustrated in FIGURE 6 below.

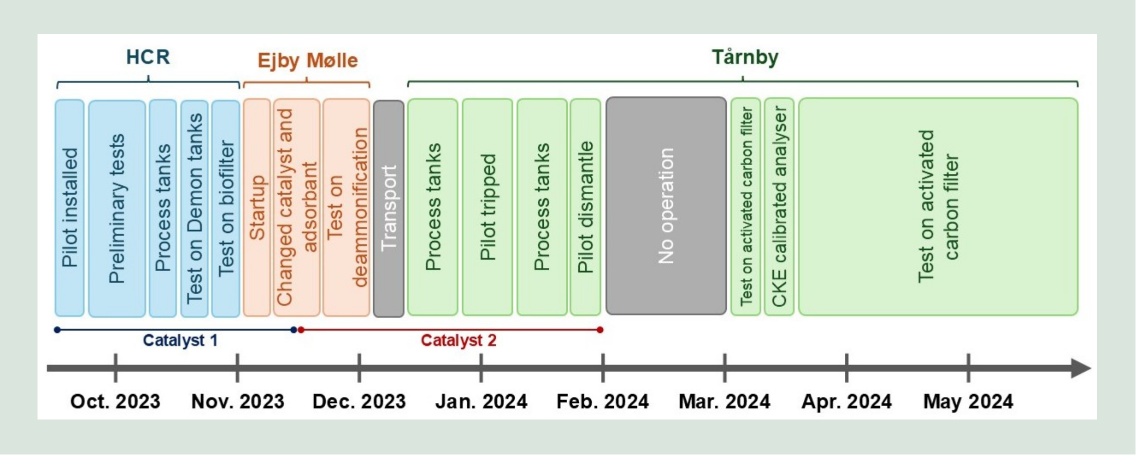


**FIGURE 6.** Timeline of the tests conducted during the project.

# 4. Test on mainstream aeration tanks and sidestream deammonification at HCR Syd

## 4.1 Purpose

Experiments and data collection was conducted at HCR Syd WWTP to:

1. Test the feasibility of and possible performance of catalytic process to treat both the off-gas from mainstream activated sludge treatment processes and sidestream deammonification.
2. Investigate whether the existing biological odour filter has an influence on the $N_2O$ emissions, and
3. Gather data for developing a set of mathematical models for sustainability assessment decision support tool to balance variables such as effluent quality, energy consumption, cost, and $N_2O$ emissions simultaneously.

The original objectives have been broadened to include testing of catalytic process on the off-gas from a sidestream deammonification process as well.

## 4.2 Site description of HCR Syd WWTP

Hillerød Centralrenseanlæg syd (HCR Syd) is placed south of the city of Hillerød in Denmark and is the largest wastewater treatment plant operated by Hillerød Utility.
HCR Syd was built and taken into operation in 2018. It has a capacity of 65,000 PE and was loaded with approx. 57,000 PE in 2023. It consists of traditional screens followed by sand and grit removal. Pre-treatment consists of a primary filtration step (Salnes filters), followed by activated sludge treatment process consisting of a recirculation plant in three identical lines. As can be seen in FIGURE 7 each line consists of following set of tanks; selector (S), hydrolysis tank (H), denitrification tank (DN1), denitrification tank with possibility of aeration (DN2), nitrification tank (N1), post-denitrification tank (DN3), and aerated tank with possibility of nitrification and denitrification (N/DN). The primary and secondary sludge is treated by anaerobic digestion and the digested sludge is sent through a screw press for final dewatering. As a separate treatment step the reject water is treated in a deammonification step (Demon plant), where ammonium is converted through partial nitritation and anammox.

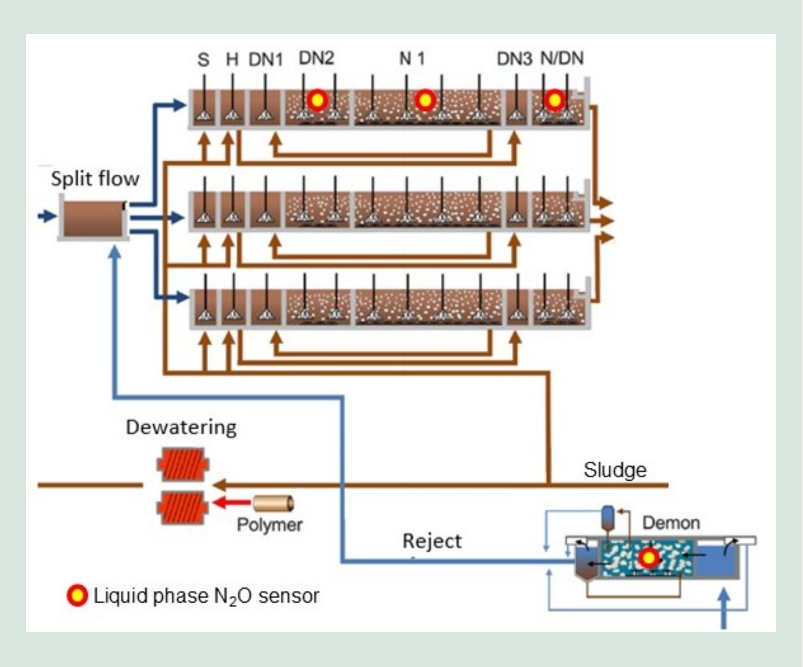


**FIGURE 7.** Placement of liquid phase $N_2O$ sensors at HCR Syd.

### 4.2.1 Historic $N_2O$ emissions (baseline)

Liquid phase $N_2O$ measurements have been collected from the activated sludge treatment tanks (DN2, N and N/DN) and the Demon tank over a nine-month period in 2023 (since mid-March). Based on these data the calculated $N_2O$ emissions resulted in an emission factor (EF) of 0.26% as kg $N_2O$-N/kg $TN_{inlet}$. As illustrated in FIGURE 8, the process step contributing most to the $N_2O$ emission is the nitrification tank (N-tank) followed by the demon plant. The emission from the nitrification follows a seasonal variation with peak emissions in May/June, relatively low emissions in the Autumn months, and a small peak in December. The emission from the Demon tank is relatively stable over the year.

What does not appear from FIGURE 8 are the concentrations of $N_2O$ in the off-gas from the mainstream process and the Demon tank. Since the air flow for aeration to the mainstream process is a lot higher than the aeration to the Demon tank, even if It is normalised by the nitrogen loading, the concentration of $N_2O$ in the off-gas is higher from the Demon tank than in the off-gas from the mainstream line, at least during the low emission period from July to December, despite the higher emission in kg $N_2O$ originating from the mainstream. This meant that the concentration observed in the mainstream off-gas had maximum peaks around 10 ppm $N_2O$, while the maximum peaks from the Demon+other ventilation was approx. 100 ppm $N_2O$.

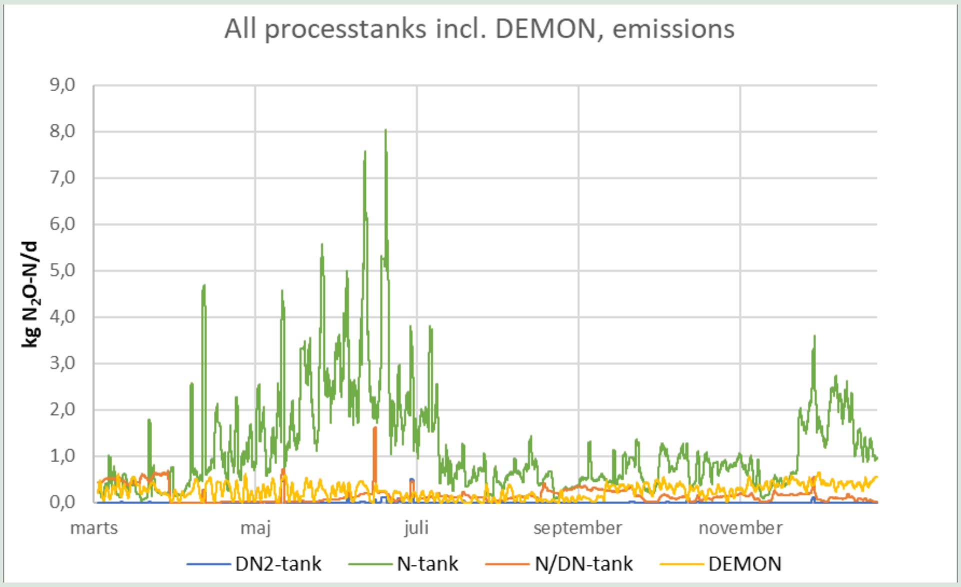


**FIGURE 8.** Daily $N_2O$ emissions during the data collection period in 2023. The blue curve is the DN tanks, the green is N tanks, the orange is N/DN tanks, and the yellow is the Demon tank. The blue shaded area indicate the time of pilot testing, and the orange shaded area the test on the biological odour treatment filter.

### 4.2.2 Test setup

The ventilation system at HCR Syd consists of two main extractions, one with air exclusively from the three mainstream process lines, and the other one which contains ventilation from the Demon tank and remaining room ventilation (other ventilation on FIGURE 9). Normally both ventilation streams are sent through the biological odour removing filters. During pilot testing the possibility of sending part of the ventilation from either of the two streams to the pilot plant was made (see FIGURE 9).

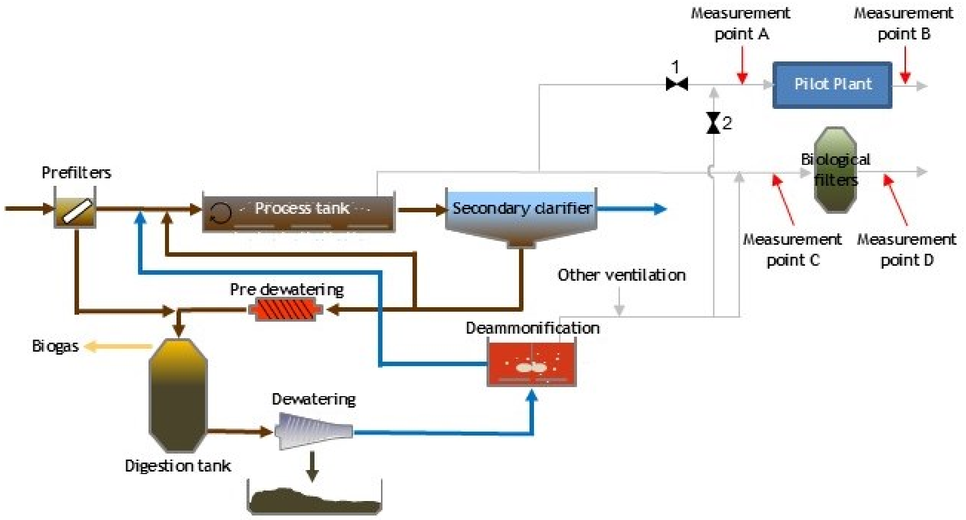


**FIGURE 9.** Flow diagram of HCR Syd with location of pilot plant and measurement points.

The $N_2O$ concentration was measured by a gas analyser at measurement points just before (measurement point A in FIGURE 9) and after (measurement point B in FIGURE 9) the catalyst. Valve 1 and 2 was installed to switch between off-gas from the mainstream and the sidestream, respectively.

**Catalyst pilot plant**

The pilot plant was installed in medio September 2023. In the first couple of weeks after installation, preliminary tests were conducted followed by testing on the ventilation from the mainstream activated sludge tanks (measurement points A1 and B1). Due to low $N_2O$ concentrations in the ventilation gas from the mainstream (below 10 ppm), the inlet to the pilot plant was changed to perform testing on the ventilation from the Demon tank + other ventilation (measurement points A2 and B2), which contained a higher $N_2O$ concentration (see timeline in FIGURE 6). This was a slight change to the original plan, in which it was intended only to test the mainstream off-gas though the pilot plant.

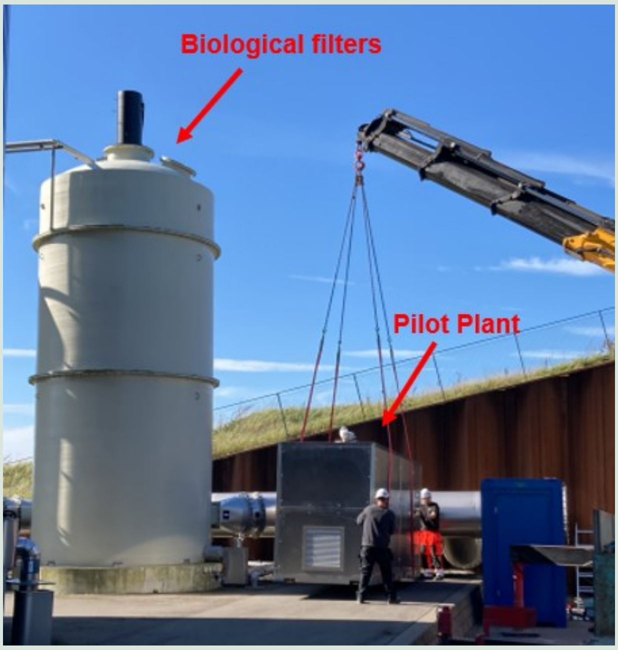


**FIGURE 10.** Installation of the pilot plant at HCR Syd.

**Biological odour filter**

During the last week of testing at HCR Syd, the removal performance of the existing biological odour filter was conducted by moving the sample lines connected to the gas analyser to measure on the mixed air going into the filters (measurement point C) and the exhaust pipe at the top of the filters (measurement point D), see FIGURE 9.

## 4.3 Results

In this section preliminary learnings are presented followed by results from test on off-gas from the mainstream process tanks and the sidestream deammonification tank.

### 4.3.1 Preliminary learnings

As HCR Syd was chronologically the first test site, a lot of practical learnings were done in the first two weeks of pilot testing. Below a sum up of these is given. This meant that $N_2O$ removal data that could be used to analyse pilot performance on, was not collected until the last half of the test period.

### Heat tracing

Heat tracing was installed, but a bit delayed on the sample tubes. Despite this, issues with condensation of the sulphur-guard were experienced, which lead to the suspected sulphur catalyst deactivation issues.

### Pilot plant stops due to low temperature

Once the pilot plant tripped due to low temperatures during night. The installation of heat tracing on the gas sample line took longer than anticipated, which could have contributed to this. The low temperature trip indicated that the gas did in fact cool quite a lot on the way from the WWTP to the pilot plant, with high risk of water condensation in the pilot plant. As mentioned previously, the water condensation likely resulted in low efficiency of the sulphur-guard increasing the risk of potential sulphur poisoning of the catalyst.
Further, it was uncertain to how low temperatures the sulphur adsorption would work satisfactory. The outside temperatures reached down below freezing during the test period.

### Sulphur deactivation

As mentioned in chapter **Fejl! Henvisningskilde ikke fundet.**, challenges with sulphur content in the off-gas were encountered, which lead to catalyst deactivation. A sulphur adsorption guard are therefore important to protect the catalyst.

### Low $N_2O$ concentrations -> Validation with handheld meter

Due to the low $N_2O$ concentrations measured by the analyser, additional measurements were done on-site with a handheld $N_2O$ analyser (Fourier Transform InfraRed spectroscopy – FTIR) for comparison (see FIGURE 11). There was reasonable agreement between the two analysers given that it was on-site test, with varying tube length, sampling times etc. The multiplexer sampling time was also evaluated, and a sampling time of approx. 3 minutes was necessary for stabilization.

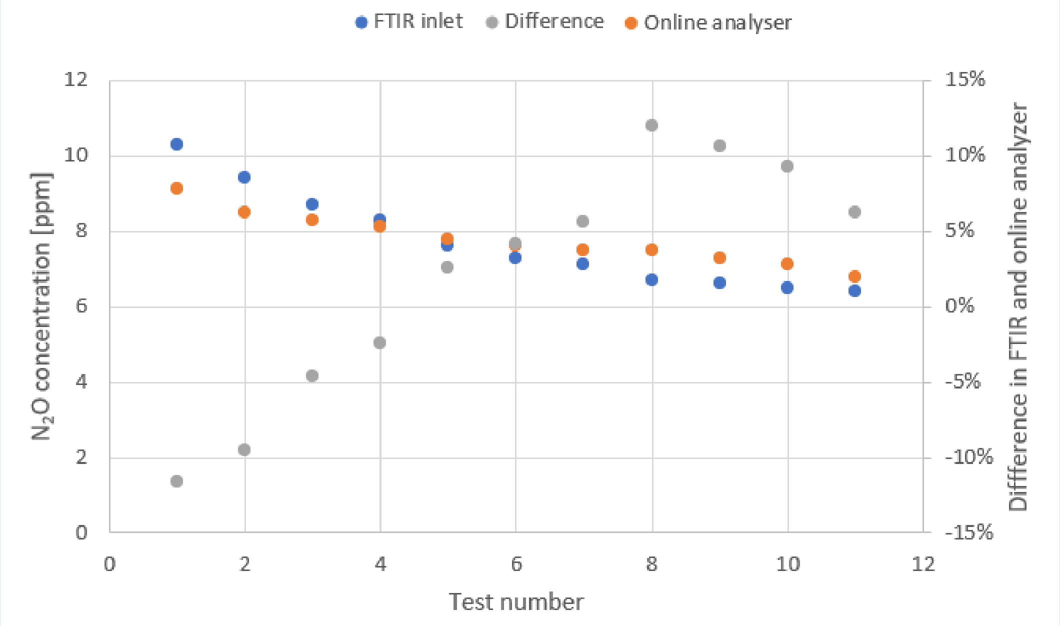


**FIGURE 11.** Comparison between online gas analyser (orange) and FTIR (blue). Left axis is ppm concentration, right axis is percent difference in the measured values.

**Sampling frequency**

When testing on the intermittently aerated Demon process, the $N_2O$ concentration varied when the aeration was turned on and off in the Demon process. Due to the varying $N_2O$ concentrations the sample time was changed down to a 2-minute sampling time, sacrificing a bit of accuracy for faster sampling.

Dynamic $N_2O$ concentrations in the inlet to the pilot plant was experienced at all three test sites, since all the biological nitrogen removing processes were operated as intermittently aerated processes.

**Methane**

Around 350 ppm of methane ($CH_4$) was measured in the off-gas from the aeration tanks by a handheld FTIR analyser.

Measurements of inlet and outlet $CH_4$ concentrations showed about 20% conversion of $CH_4$ across the catalyst. This indicates a possible competition between decomposition of $N_2O$ and $CH_4$, which can reduce the catalytic activity. Further analysis on this will be needed to get further insight on this topic.

### 4.3.2 Mainstream process tanks

The tests started in the end of September 2023.

The analyser measured peaks of up to 50 ppm $N_2O$ in the common gas to the biofilter (measurement point C and D in FIGURE 9). The pilot plant was then subsequently connected to the outlet gas from the activated sludge processes (measurement point A1 and B1 in FIGURE 9). When measuring here, the concentration had maximum value of 1.8 ppm $N_2O$ and most of the time it was below 0.5 ppm, which is too low to expect any removal on the catalyst and too low to measure difference on in- and outlet due to analyser precision. Even though it is much more difficult to remove the very last contamination catalytically, it was still a surprise that there appeared to be no difference in inlet and outlet. It was therefore discovered that the multiplexer was faulty.

Because of the low concentrations it was decided to change the sampling place from the activated sludge off-gas to the combined off-gas from Demon and building ventilation, as the $N_2O$ concentrations were expected higher.

Despite a lower emission in $N_2O$ kilo per day from the Demon tank than from the mainstream process tanks, as illustrated in FIGURE 8, a higher concentration of $N_2O$ was observed in the off-gas from the Demon tank.

### 4.3.3 Sidestream Demon and other ventilation

The combined off-gas from Demon and building ventilations contained higher $N_2O$ concentrations (measurement point A2 and B2 in FIGURE 9). The source is believed to primary be the Demon process, since this is a high-rate biological nitrogen converting process. Since the Demon is an intermittently aerated process, the $N_2O$ concentration varied, with peak values up to 120 ppm (see FIGURE 12). With the multiplexing between inlet and outlet every two minutes, it was challenging to get good estimations of the removal efficiency. To overcome this the aeration control was adjusted to obtain slightly longer aeration phases. Combined with optimization of sample timing, it was possible to get some more usable results with longer peaks with lower concentrations (see FIGURE 14).

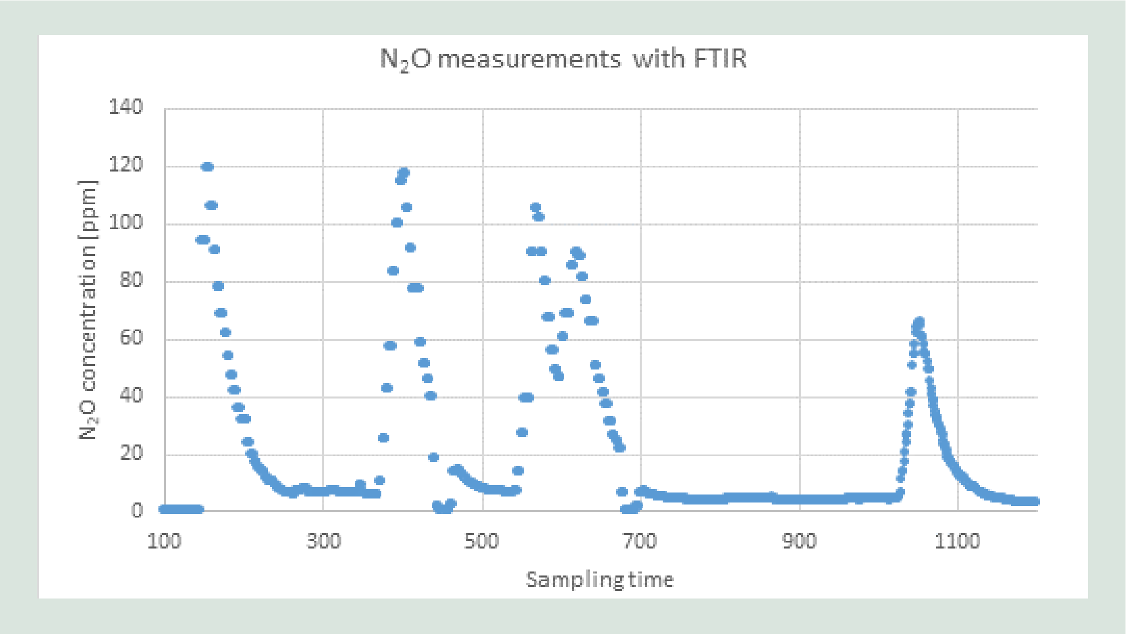


**FIGURE 12.** The $N_2O$ waves measured with the FTIR. Sampling time was 2 minutes.

To estimate the removal efficiency, the outlet from the pilot plant was measured with the handheld FTIR and compared to inlet measurements from the analyser (see FIGURE 13).

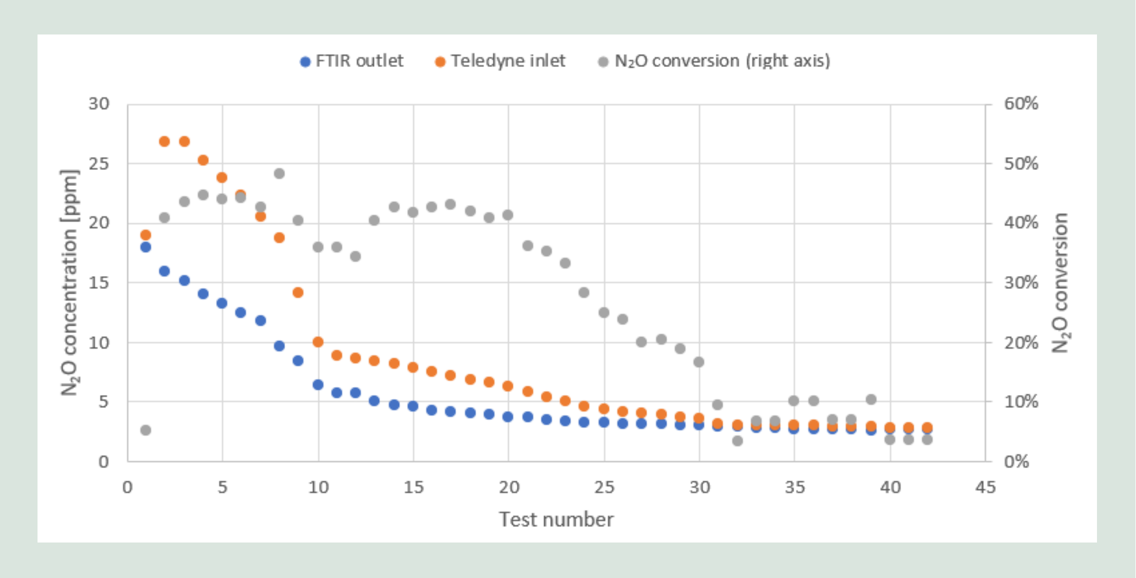


**FIGURE 13.** Estimate of catalytic conversion in mid-October 2023 using inlet analyser data (orange dots) and handheld FTIR (blue dots), to calculate removal efficiency (grey dots).

Looking at FIGURE 14, peak values around 50 ppm of $N_2O$ in the inlet were observed, and the $N_2O$ removal efficiency was around 30%. Perhaps a slight decreasing tendency in $N_2O$ conversion could be observed.
After a week of pilot-plant operation the catalytic conversion was around 20% (FIGURE 15), which is a fast deactivation of the catalyst. Catalyst poisoning, with sulphur was suspected to be the cause.

As a further test, the reactor temperature was increased, which resulted in an increase in conversion, which is an expected response from the catalytic reaction. This confirmed that the catalyst was active and functioning, but activity had been severely reduced by the sulphur poisoning.

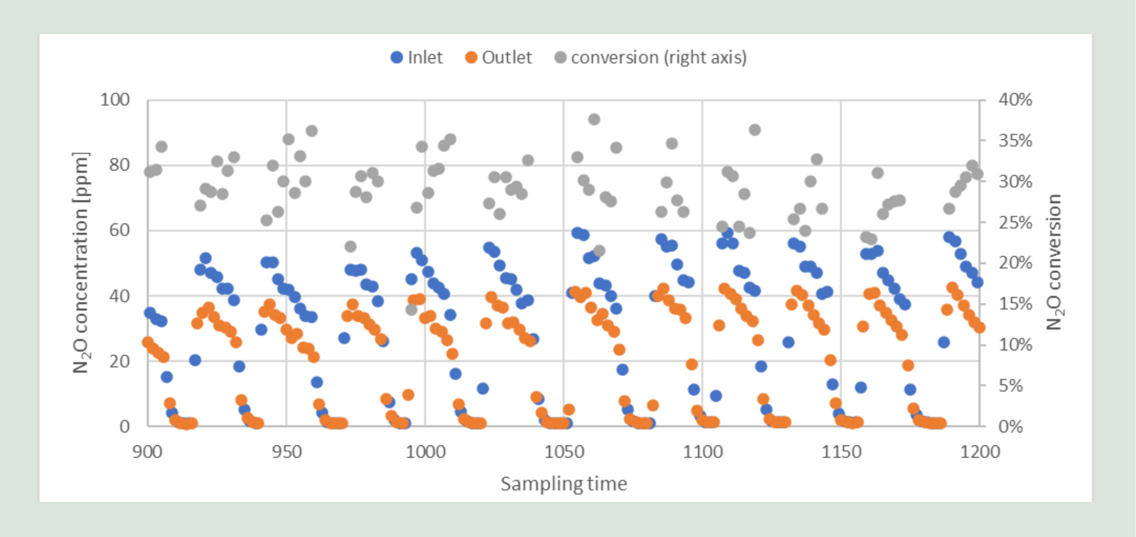


**FIGURE 14.** Catalytic N2O conversion end-October. Sampling time was 2 minutes.

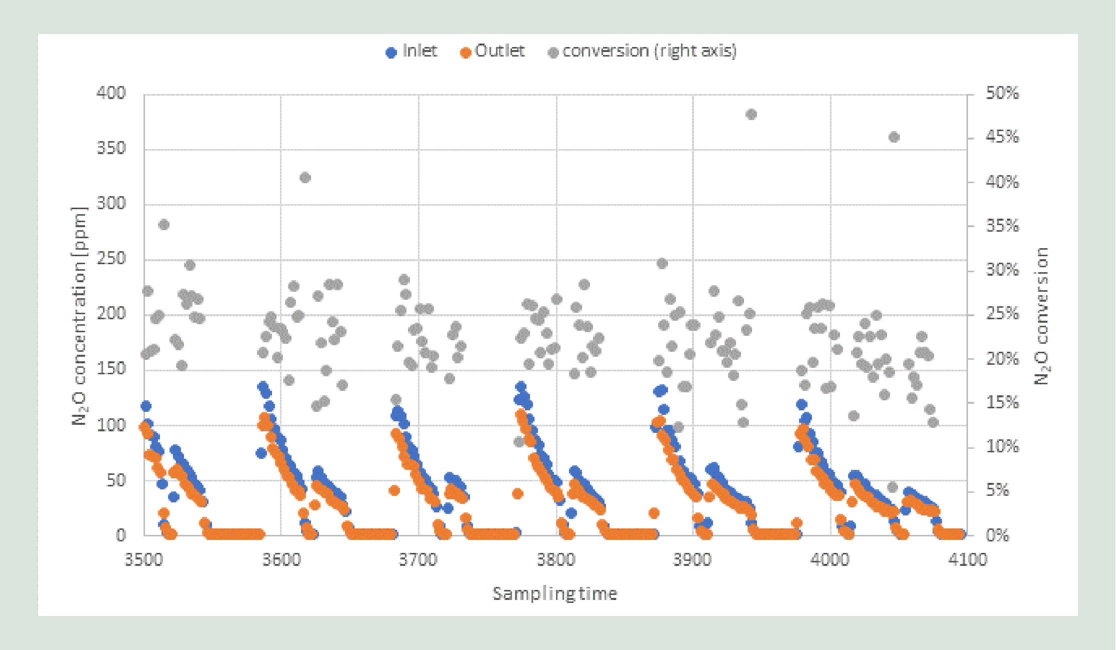


**FIGURE 15.** Catalyst activity dropped after another week of operation. Samling time was 2 minutes.

### 4.3.4 Biological odour filter

The last part of the measurement campaign at HCR Syd entailed measuring the N2O concentration at the inlet and outlet of the existing off-gas odour treatment process consisting of a biological filter (measurement point C and D in FIGURE 9). In FIGURE 16, four days of measurements can be seen. It can be visually observed, and confirmed by data processing, that the concentration measured in and out of the filter did not differ significantly from each other, indicating no removal of N2O in the filter.

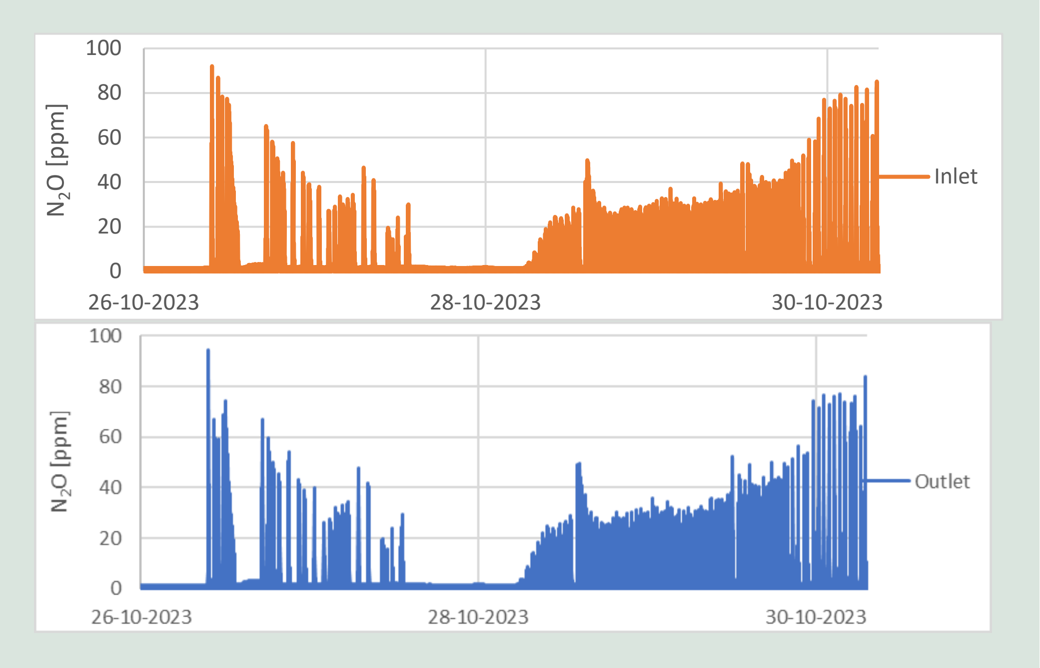


**FIGURE 16.** $N_2O$ measurements from inlet and outlet of the biological odour removing filter.

## 4.4 Discussion

In the first half of the measurement campaign at HCR Syd a lot of good practical learnings were made, but that also meant that no useful $N_2O$ removal data were collected in the two weeks of pilot operation. This was unfortunate, as it was later discovered that the catalyst was likely deactivated by sulphur poisoning. The removal efficiency and the rate of poisoning at the beginning of the test is therefore still unknown.

Still, by continuously following up on results and test conditions and being able to quickly react to the findings, the test series at HCR Syd managed to produce some useful results in terms of getting some $N_2O$ removal and efficiency decrease to understand the nature of the catalyst deactivation. The results from HCR Syd therefore indicate tendencies and overall learnings, more than exact removal rates.

It seems that the measures taken to prevent water from condensation in the sulphur guard were insufficient. It is therefore important to note that the condensation can occur at higher temperatures than expected, in the small pores of a guard or a catalyst, due to the capillary forces. More was learned about sulphur and poisoning later in the project. (See **Fejl! Henvisningskilde ikke fundet.**)

## 4.5 Conclusions

The testing and data collection at HCR Syd resulted in the following conclusions:

- Preliminary tests provided some good practical learnings, but no meaningful $N_2O$ removal results.
- Catalytic $N_2O$ removal was demonstrated on the off-gas from the sidestream deammonification + other ventilation.
- Once data could be collected removal efficiencies of approx. 30% were observed, which decreased to approx. 20% the following week.
- Catalyst deactivation caused by sulphur was observed. The sulphur guard added to the pilot plant did not work properly. The reasons are not entirely clear, but condensation of water likely to have caused issues.

- Off-gas from both mainstream process and the sidestream deammonification contained both sulphur and methane.
- Mainstream process tanks in the periods of the year with low emissions are not a fitting $N_2O$ stream to be treated by catalytic conversion.
- No $N_2O$ removal is taking place in the biological odour removing filters.

# 5. Test on sidestream deammonification at Ejby Mølle WWTP

## 5.1 Purpose

Experiments and data collection were conducted at Ejby Mølle WWTP to:

1. Test the feasibility and possible performance of catalytic process to treat the exhaust gas from a deammonification sidestream treatment process, and
2. Gather data for developing a set of mathematical models for sustainability assessment decision support tool to balance variables such as effluent quality, energy consumption, cost, and $N_2O$ emissions simultaneously.

## 5.2 Site description of Ejby Mølle WWTP

Ejby Mølle WWTP is one of the eight wastewater treatment plant facilities operated by the utility company VandCenter Syd, and it’s located in Odense (Funen), Denmark.
The Ejby Mølle WWTP has a treatment capacity of 385,000 person equivalents (PE). The incoming wastewater is mechanical treated in screens, led through sand and grit removal and pretreated in primary clarifiers where the settled organic material is pumped directly to the anaerobic digesters. Two thirds of the secondary treatment (biological treatment) consist of activated sludge system using an alternating BioDenitro process, while approximately one third consists of rock-media trickling filters. The produced biological sludge is led to anaerobic digestion for biogas production and is subsequently sent for dewatering. The reject water from final dewatering is treated in a separate deammonification treatment step (sidestream secondary treatment) before it is pumped back to the mainstream process tanks.

### 5.2.1 Sidestream process

Ammonium in the reject water from the separate deammonification treatment step is converted through partial nitritation and subsequent anammox process. The reject water stream has a high concentration of ammonium and a relatively high temperature, which is well suited for this type of process. This alternative process to conventional nitrification-denitrification provides several benefits, such as lower energy and carbon requirements, and lower sludge production.

Two Demon reactors were commissioned in 2014. The technology (Demon GmbH, Gommiswald, Switzerland) is characterized by using a pH-based aeration control and the use of hydrocyclones to selectively retain granular sludge. These reactors were first commercialized as sequencing batch reactors, but the deammonification reactors in Ejby Mølle were built as continuously stirred-tank reactors (CSTRs) with an internal settler. The two sidestream reactors are operated in parallel, and each have a volume of 320 $m^3$ and a design load capacity of 394 kg N/d.

The effluent from the reactor overflows a weir in the internal settler and it continues to the main aeration ditches (main liquid train of the WWTP). The reactors are made of stainless steel and fully covered. The exhaust gas leaves at the top through a "chimney". The aeration is provided by panel diffusers at the bottom and there is also a mixer that ensures complete mixing when the aeration is turned off. One of the characteristics that differentiates Demon reactors from other sidestream deammonification technologies is the use of hydrocyclones as external selectors. The hydrocyclone provides a way of retaining granular sludge in the reactor, the lighter stream or overflow is wasted while the heavier stream or underflow is retained.

The main control parameters that control the intermittent aeration in the reactors are pH, DO and nitrite ($NO_2^-$). The reactors have been operated since the start-up in December 2014 using pH as the main control parameter. A pH set-point and a band-width is set manually in the SCADA system. When pH reaches the set-point +50% of the band-width aeration is turned on until pH reaches the set-point -50% of the band-width which stops the aeration. Several other parameters are used in the background and can stop aeration even if the pH set-point has not been reached. These are maximum aeration time, maximum $NO_2^-$ level, maximum DO level and minimum ammonia ($NH_3$) concentration. Additionally, feeding to the tank is paused if a high $NH_3$ set-point is reached. During the experimental period, this combination of parameters was manipulated to operate the reactors under different control strategies.

### 5.2.2 Historic $N_2O$ emissions (baseline)

Nitrous oxide emissions from the mainstream and sidestream treatment steps at Ejby Mølle have been semi-continuously monitored for a decade. The accurate quantification of emissions remains a challenge for the surface-aerated activated sludge mainstream reactors. Average emissions are in the order of 1-3% of the nitrogen load (Saad 2021) and for the trickling filters emissions has up to this point, not been able to be estimated due to physical constraints. However, the sidestream deammonification reactors were early on identified as a hotspot for nitrous oxide emissions, with usual emission factors between 3-7% (Uri 2017) but can go as high as >50% under different operational conditions (Uri 2017) and have been object of optimization efforts over the past years.

Unlike the mainstream activated sludge or trickling filters, the exhaust air of the sidestream deammonification reactors can be easily captured via a ventilation pipe. Therefore, the combination of potentially high concentrations of $N_2O$ in a limited and controlled air stream makes these reactors ideal candidates for the testing of a catalytic solution.

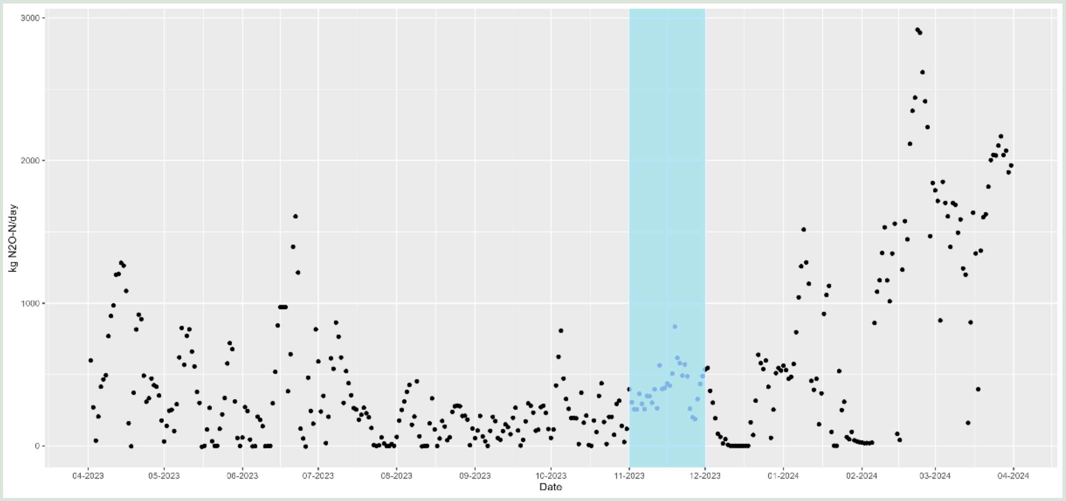


**FIGURE 17.** $N_2O$ emissions (kg $N_2O$-N/d) from the two deammonification tank at Ejby Mølle WWTP for a year. Testing period shadowed.

### 5.2.3 Test setup

The deammonification treatment reactors are covered, and the exhaust gas from the process is collected through the ventilation system. The pilot plant with the catalyser was connected to this ventilation pipe to perform testing on the exhaust gas from the deammonification. For measuring the removal performance of the catalyst in the pilot plant, $N_2O$ concentrations were measured continuously at sample points just before (inlet – measurement point A on FIGURE 18) and after (outlet – measurement point B on FIGURE 18) the catalyst.

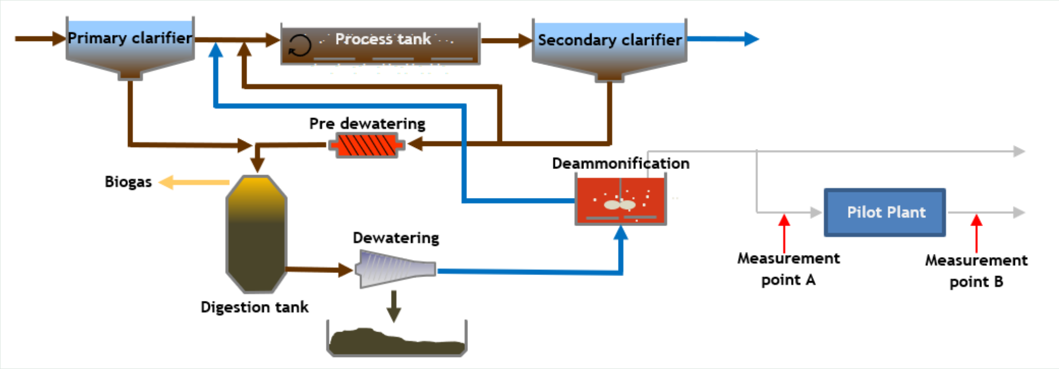


**FIGURE 18.** Test setup at Ejby Mølle.

The pilot plant was installed at Ejby Mølle at the end of October 2023. Testing of the catalyst performance on the ventilation stream from the deammonification treatment was conducted in the following weeks until the end of November 2023, (see FIGURE 6).

The pilot plant was installed next to the deammonification reactors, and a plastic pipe was inserted into the ventilation pipe at the top of one of the reactors and connected to the pilot plant (see FIGURE 19). The pipe was heat traced along with the installation of a tap for removing any condensed water at the lowest point.

**FIGURE 19.** Pilot plant and analyser unit installed next to the Deammonification at Ejby Mølle, Odense.

The $N_2O$ production in the reactor was monitored both within the reactor, using a liquid phase sensor, and in the exhaust, using a gas analyser multiplexing on the two streams (measurement points A and B). $N_2O$ in the exhaust gas was measured as the inlet to the pilot plant, and finally in the outlet of the pilot plant (see FIGURE 18). The data from the gas analyser was used to estimate the removal efficiency of $N_2O$ by the pilot plant, while the liquid sensor was used to estimate the daily $N_2O$ emission and emission factor from the deammonification reactors.

## 5.3 Results

In this section results from preliminary investigations, pilot tests as well as post analysis are presented.

### 5.3.1 Preliminary investigations

**Sulphur measurements**

A handheld sulphur analyser showed $H_2S$ concentrations of 2.1-2.4 ppm, both inlet and outlet of sulphur guard, indicating that it was not working. Condensation of water is believed to have been the cause of the malfunction. To solve this, a tap for water drainage was installed to remove any water that would appear due to condensation in the pipes and the pipes were heat traced.

On December 1st the inlet concentration of $H_2S$ to the pilot plant was measured at 4.8 ppm. The outlet after the adsorbent was measured at 0 ppm (see FIGURE 20). This clearly demonstrates that the cold $H_2S$ adsorption can efficient when inlet conditions are maintained, which for this test required heat tracing on the connecting gas pipe from the process to the pilot plant.

**FIGURE 20.** Left: Inlet $H_2S$ concentration. Right: $H_2S$ outlet from adsorption reactor.

**Methane measurements**

Methane measurements conducted with the handheld FTIR analyser, indicated a correlation between $N_2O$ and $CH_4$ levels from the deammonification process; When one is high in concentration, so is the other (see FIGURE 21). Even though removal of both compounds is observed over the catalyst, it seems that the removal efficiency of $N_2O$ is higher compared to that of $CH_4$.

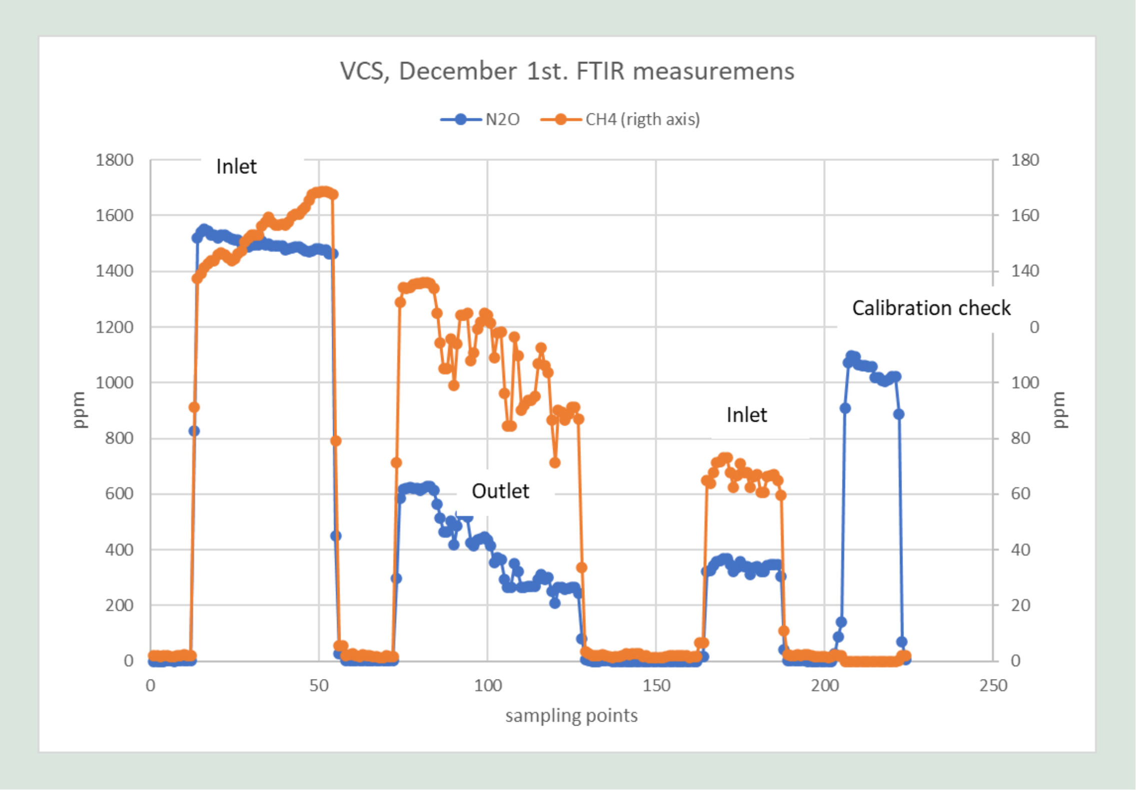


**FIGURE 21.** FTIR measurements of $N_2O$ and $CH_4$. Both Y-axis are in ppm. X-axis is sampling points (one every 20 second).

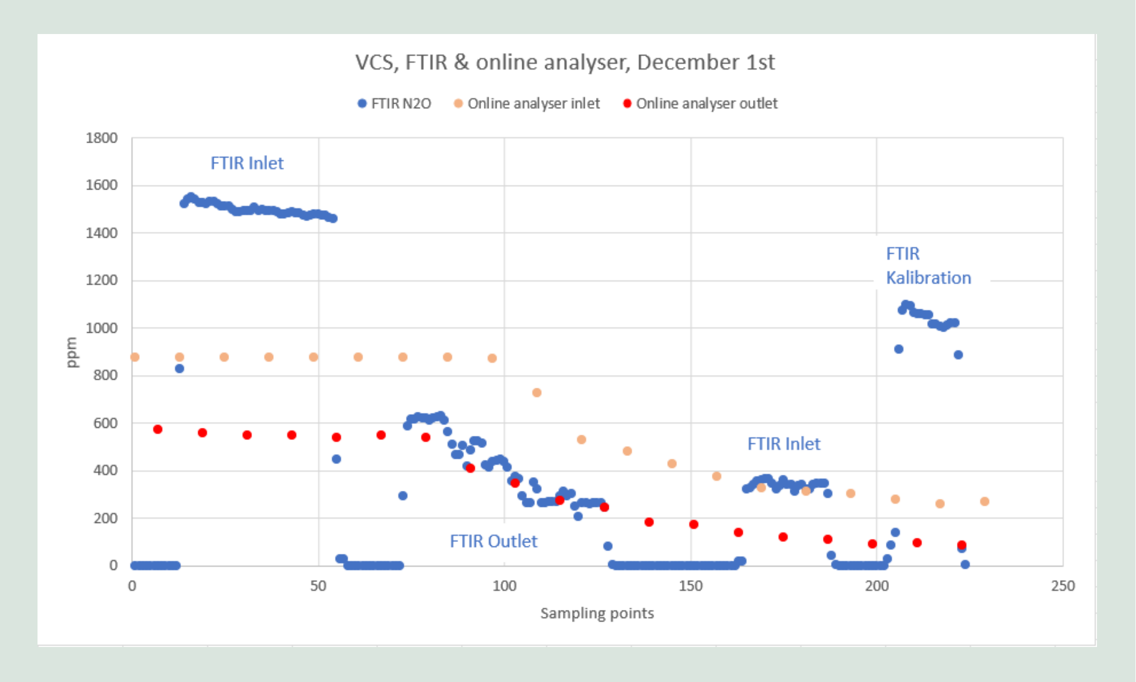


**FIGURE 22.** Comparison of handheld and online gas analysers. Y-axis is ppm, X-axis is sampling points (one every 20 second).

**Comparison of analyser and handheld $N_2O$ measurements**

Looking at FIGURE 22, the measurements from the two different analysers correspond relatively well, when comparing inlet concentrations measured in periods where the analyser was not saturated and when measuring outlet concentrations. Generally, the analysis shows a catalytic $N_2O$ conversion of around 64%.

Note that during the first FTIR inlet measurement in FIGURE 22, the online gas analyser was out of range (see later). Also, there where periods where the FTIR was measuring on surrounding air and thus the $N_2O$ drops to 0 ppm.

**Change of catalyst**

The online analyser appeared to go out of range at $N_2O$ levels of 900 ppm (see FIGURE 23 and FIGURE 24). The analyser was first calibrated using gas containing 8 ppm $N_2O$ and it was decided to recalibrate with a gas containing a higher concentration of $N_2O$. Following the recalibration, it became clear that the catalyst needed changing, since no $N_2O$ removal was observed.

A fresh catalyst was installed on November 17th and during the change it was found that the tracing on the inlet gas had never been turned on. A new sulphur guard was loaded in the adsorption unit as well and the entire unit started back up on November 20th and started treating off-gas from the deammonification tank on the 21st.

## 5.3.2 Deammonification process

After the catalyst was replaced, the gas analyser started reaching maximum on the inlet measurements once again, but not for the outlet measurements, showing the catalyst was working. During periods when the inlet did not reach maximum values, $N_2O$ removal efficiency reached an estimated 60-65% (see FIGURE 23), with an average temperature of 400°C in the catalytic reactor.

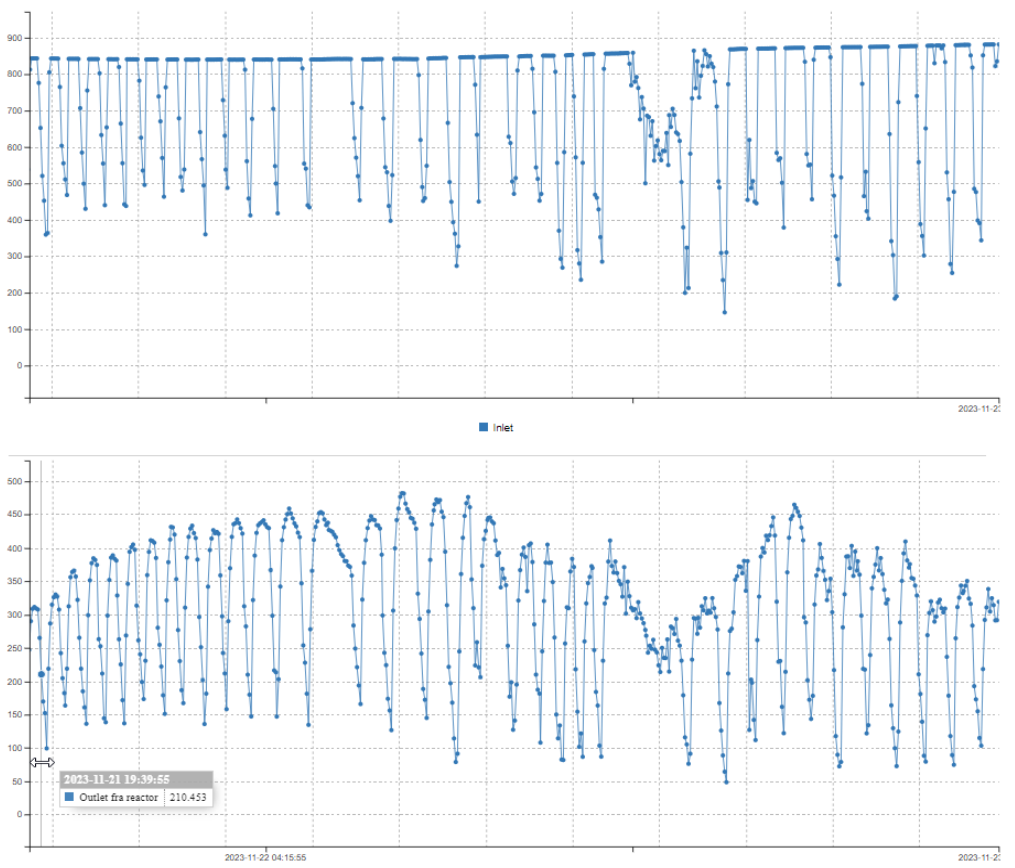


**FIGURE 23.** Gas analyser results on Nov. 22nd. Top: inlet concentration, bottom: outlet concentration. The concentration on the y-axis is in ppm $N_2O$.

To estimate peak inlet concentrations (where the analyser is saturated), a conversion of 65% was used for calculating backwards. This gives an estimated max inlet concentration around 1350 ppm $N_2O$ for the period shown in FIGURE 23.

Concurrently, operations staff at Ejby Mølle worked on optimizing the control settings for the deammonification tank to minimise the $N_2O$ peaks, as well to give longer peak periods with a concentration below the saturation limit.
On November 24th, feed to deammonification tank stopped due to an issue with the pump, but analysis on the material already in the reactor showed improved conversion (70-80%, See FIGURE 24). One theory why the conversion is higher are that methane emissions was reduced in the off gas, as methane and $N_2O$ may be competitive reactions on the catalyst. When the pump issue was solved, the conversion was 65-75%.

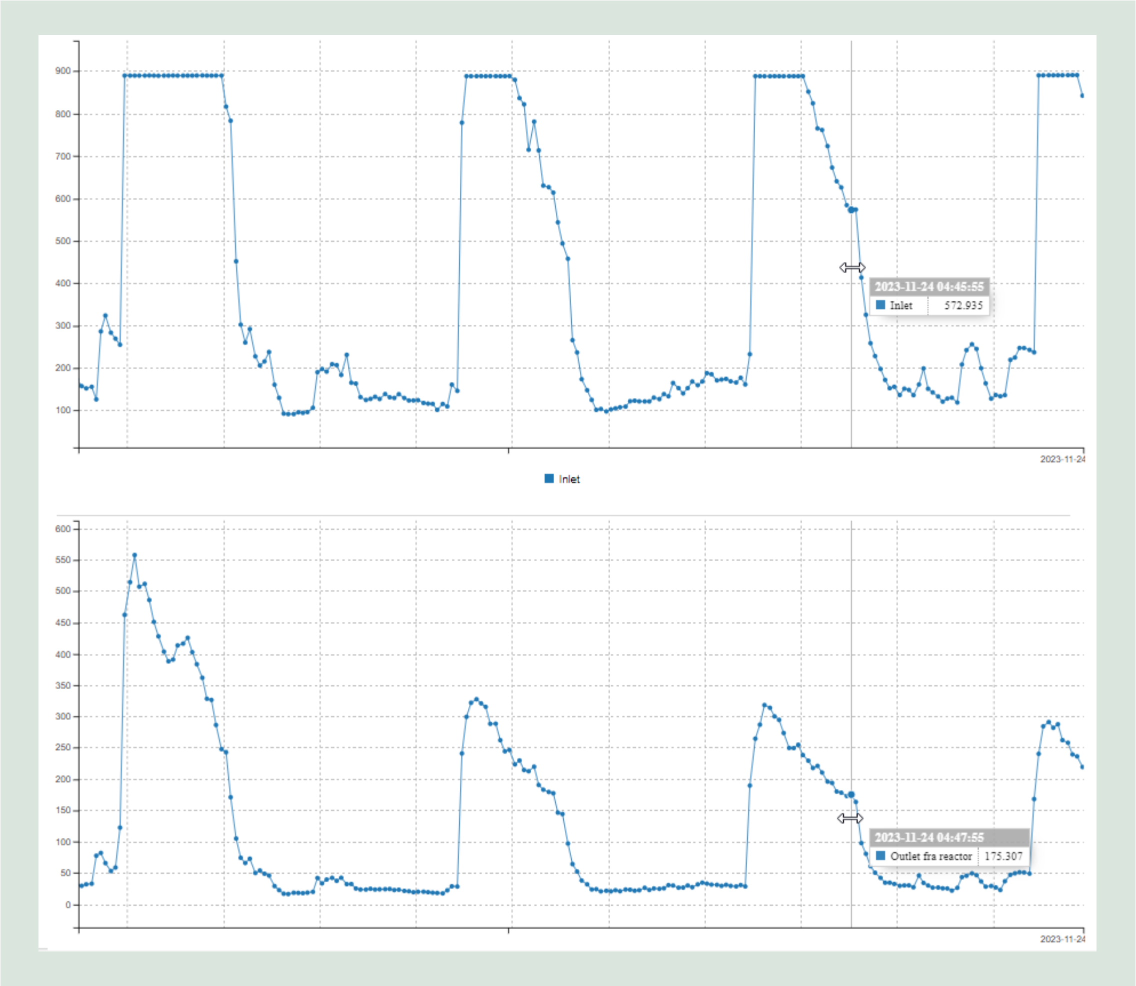


**FIGURE 24.** Gas analyser results on Nov. 24th. Top: Inlet concentration, bottom: outlet concentration. The concentration on the y-axis is in ppm $N_2O$.

Using the data from after the catalyst replacement to calculate the conversion efficiency of $N_2O$ in the pilot plant, results in large variations (see FIGURE 25), mainly due to the analyser saturation issues. Removal efficiencies of up to 80% could be observed in periods with stable operation and inlet concentration below the saturation limit. Methane conversion across the catalyst of about 55% was observed with the FTIR analyser.

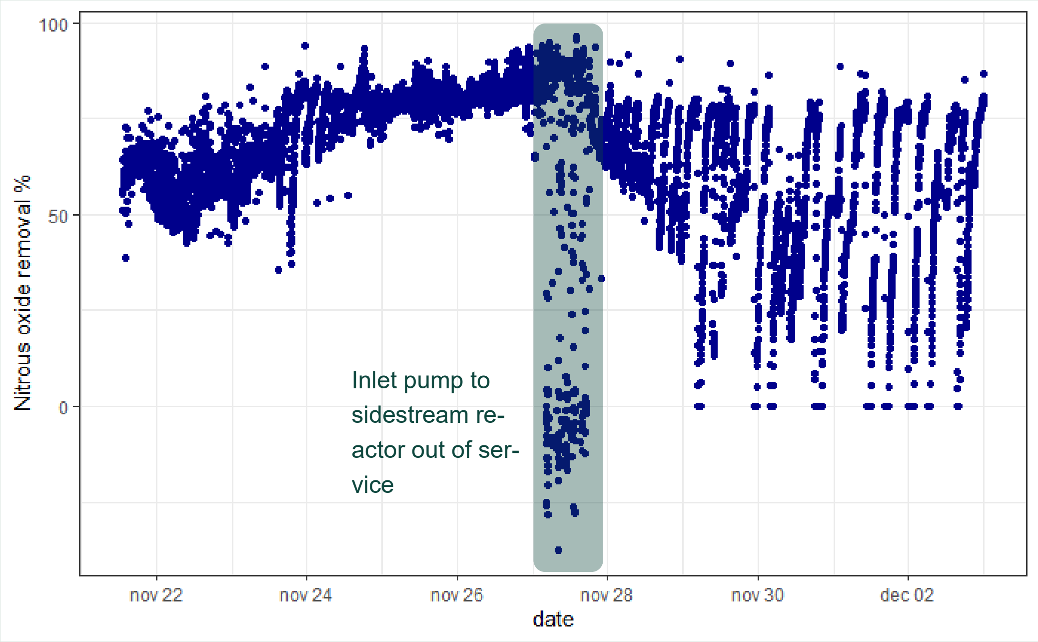


**FIGURE 25.** Calculated $N_2O$ removal efficiency in the pilot plant.

### 5.3.3 Post measurement campaign analyses

Samples of the catalyst have subsequently been analysed in the lab. An activity test on the catalyst that was replaced (i.e. it had been operating at HCR Syd and in the beginning of the Ejby Mølle campaign) confirmed that there was hardly any activity for the reaction removing $N_2O$ left.

A line scan detecting sulphur, confirms that sulphur had been adsorbed by the coat layer of the catalyst (see FIGURE 26). The red line on the left picture illustrates where the line scan was done. The same finding is indicated by the analysis of the sulphur concentration in the catalyst coat, which is not the case for the fresh catalyst. The sulphur uptake measured by the line scan, is in concentration levels where it is not surprising that it would cause complete catalyst deactivation.

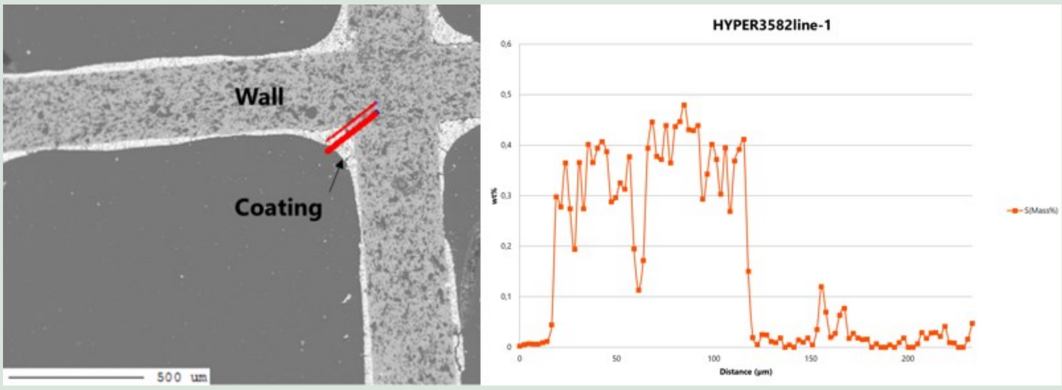


**FIGURE 26.** Left: Picture showing the line-scan passing through coat layer (the whitest part) and monolith wall (grey with darker grey spots), right: Sulphur concentration in the catalyst coating.

The analysis of the sulphur guard showed an average sulphur uptake of around 0.2 wt.%. Some sulphur had been removed by the guard, but despite the uptake, sulphur was found in the last catalyst sample as well. The sulphur uptake of the guard was below the expected capacity at these conditions. The top part of the guard had adsorbed less sulphur than the bottom, which is unusual. These observations could be the result of water condensation issues. Despite the reduced removal by the catalyst due to issues with sulphur poisoning, good learnings can be taken from these test campaigns with respect to an optimized guard and inlet configuration design.

## 5.4 Discussion

Saturation of the gas analyser and rapid changes in inlet gas concentration due to intermittent operation of the aeration made data analysis on this test site challenging.

Despite a good visual correlation between liquid phase sensor and gas analyser data, it was difficult to produce a linear regression good enough to be used for calculating inlet concentrations when the gas analyser was saturated. Comparison between handheld measurements and the online analyser showed agreement between the two types of measurements in periods with concentrations below the saturation limits.

The data points used to estimate the conversion were chosen using periods of stable operation. Removal efficiencies up to 80% were observed with conversions often being around 65%. It is difficult to conclude whether the catalyst was deactivated in this test period or not, due to the abovementioned measurement issues. The last test showing $N_2O$ conversion around 77%. Comparing this with what was observed in the first test series (before changing of guard and catalyst), where the catalyst quickly deactivated and where there was later found significant amounts of sulphur in the catalyst, it is evident that the guard worked more efficiently in the last part of test (after changing of guard and catalyst). During the last part of the test series heat tracing was always on and that is likely to have improved the performance of the guard significantly. The fact that much less water was drained from the system with the tracing on confirms this.

## 5.5 Conclusions

The testing and data collection at Ejby Mølle's deammonification sidestream treatment off-gas resulted in the following conclusions:

- Confirmation of deactivation of the catalyst from the first testing period at HCR Syd.
- Removal efficiencies in the range 60-80% was demonstrated with a fresh catalyst.
- Removal efficiencies provide an indication that this could be a fitting application of the technology with a feasibly viable business case (see Chapter **Fejl! Henvisningskilde ikke fundet.**).
- Precise removal efficiencies were challenging to calculate due to saturation of the gas analyser when inlet concentrations were above approx. 800 ppm and fast variations in the $N_2O$ concentration due to intermittent aeration of the deammonification process.
- Cold $H_2S$ adsorption demonstrated successfully, but heat tracing to prevent water condensation was essential.

# 6. Test on mainstream aeration at Tårnby

## 6.1 Purpose

Experiments and data collection were conducted at Tårnby WWTP to:

1. Test the feasibility and possible performance of catalytic process to treat the off-gas from mainstream activated sludge treatment processes
2. Investigate whether the existing activated carbon odour filters have an influence on the $N_2O$ emissions

## 6.2 Site description at Tårnby WWTP

Tårnby Renseanlæg (WWTP) is the only wastewater treatment facility operated by Tårnby Utility located just south of Copenhagen in the vicinity of Copenhagen Airport.

Tårnby WWTP has a capacity of 71,500 PE and was loaded with approx. 67,000 PE in 2017-2019. With expanding population and industrial activity in the catchment area Tårnby WWTP is approaching it capacity limit.
It consists of a single line in a plug flow recirculation configuration (see FIGURE 27). The first six zones are non-aerated followed by five zones with the possibility of aeration.

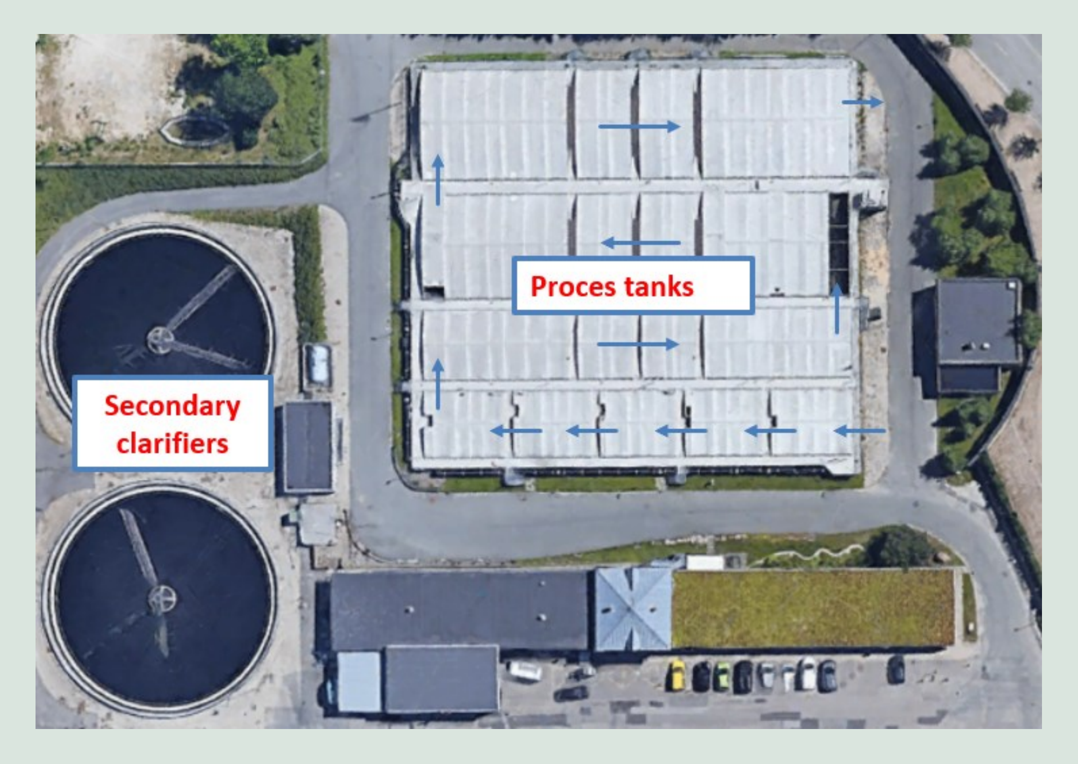


**FIGURE 27.** Overview of plant layout at Tårnby WWTP.

In 2013 the aeration tanks were covered with a cloth media on a steel construction. The air below the covering, above the water surface is extracted by a ventilation system securing vac-

uum underneath the cloth media. The extracted air mainly consists of the off-gas from the aeration but might be slightly diluted with air entering the system from cracks and openings in the covering.
Currently the plant is operated as a single sludge stage system, i.e. no primary sludge is taken out prior to the biological treatment. The dewatered secondary sludge is sent for disposal on agricultural land and the reject water from the dewatering is sent back to the inlet of the biological process tanks.

As mentioned above, Tårnby WWTP does not have separation of primary sludge, which means that the wastewater after fine screens and sand and grit removal is sent directly to the mainstream biological treatment.

### 6.2.1 Historic $N_2O$ emissions (baseline)

$N_2O$ emissions from the ventilation air from the biological tanks has been measured in the period from August 2022 to start November 2023. These measurements have resulted in an average yearly $N_2O$ emission factor of 2.38%. However, a huge variation over the year is observed with the highest $N_2O$ emission in the summer months observed in both 2022 and 2023, as illustrated in FIGURE 28. Similar patten in the variation of the emission is observed from 2022 to 2023, however there is still a shift in emission level with 2023 showing higher emissions than 2022.

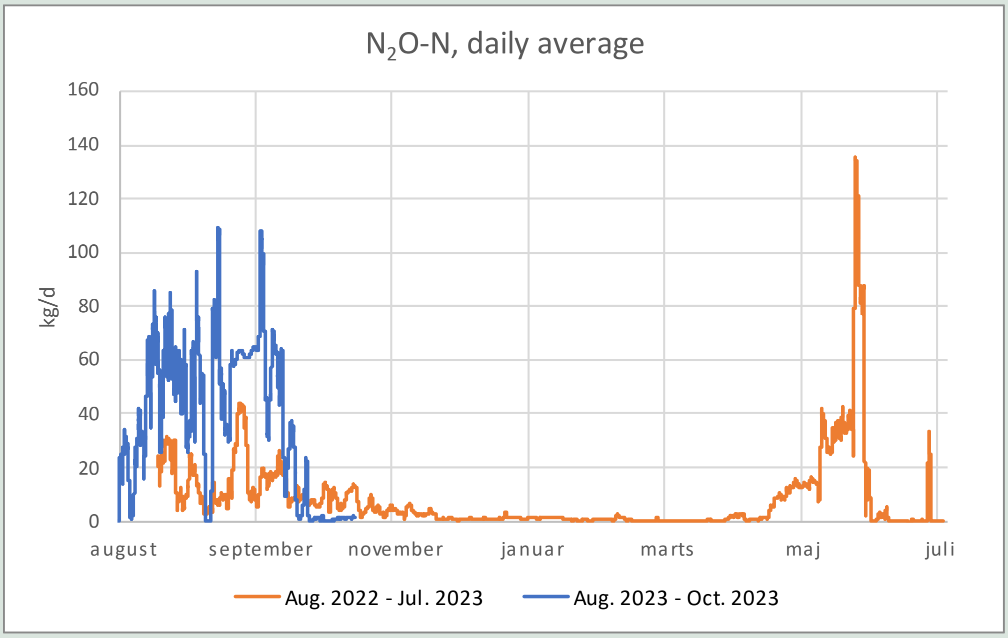


**FIGURE 28.** Daily $N_2O$ emissions from the data collecting period. The orange curve represents the first whole year, and the blue curve the colliding period (Aug.-Oct. 2023).

### 6.2.2 Test setup

At Tårnby WWTP the pilot plant was receiving ventilation air from the covered mainstream process tanks (see FIGURE 29). This stream is normally mixed with other ventilation air from pretreatment, rainwater basins, and other room ventilation. All ventilation air is subsequently sent through two parallel activated carbon filters for odor removal.
During the test only a fraction of the ventilation stream from the process tanks was led through the pilot plant, while the remaining air continued through the normal odour treatment step.
Measurement points of the $N_2O$ concentration were located just before (Measurement point A

in FIGURE 29) and after (Measurement point B) the catalyst during the pilot plant testing and at the inlet (Measurement point C) and outlet (Measurement point D) of one of the activated carbon filters for testing of the effect of this filter.

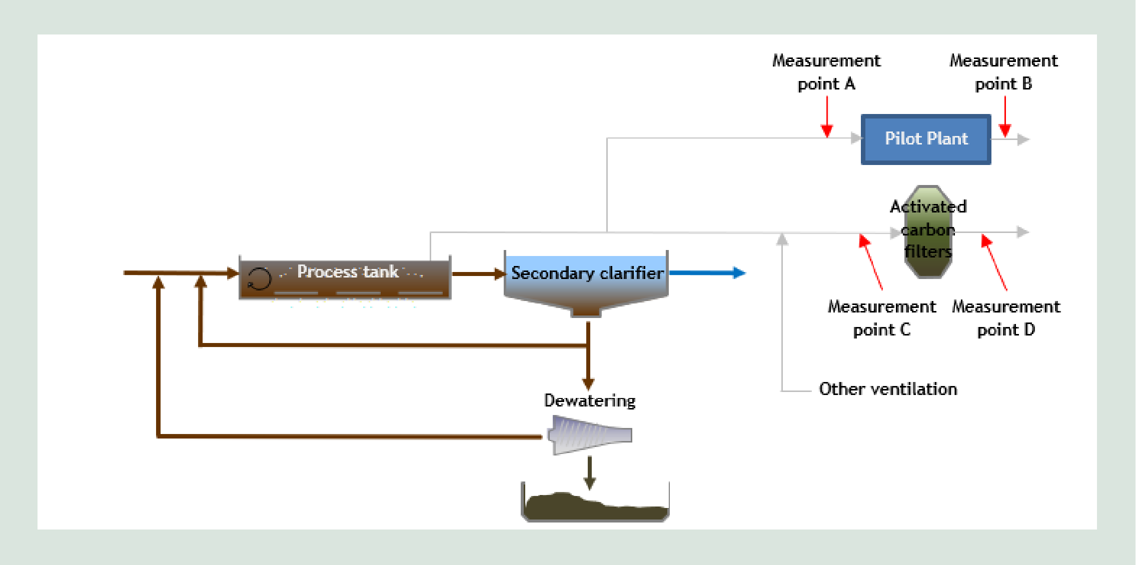


**FIGURE 29.** Test setup at Tårnby WWTP.

**Catalyst pilot plant**

Installment of the pilot plant at the wastewater treatment plant was done medio December 2023 and was run until the end of January 2024. In this period only testing on the ventilation air from the process tanks through the pilot plant was conducted.

**Activated carbon odour filter**

After the dismantling of the pilot plant, testing on the performance of removing $N_2O$ in the activated carbon filter was performed by measuring the $N_2O$ concentrations before and after a filter during the Spring of 2024 (see FIGURE 28).

## 6.3 Results

In this section results from a test campaign followed by results obtained during treatment of the off-gas from the mainstream process and a post measuring campaign are presented.

### 6.3.1 Test campaign and data

The pilot plant at Tårnby WWTP started treating off-gas from the mainstream process tanks in December 2023.
First, installation was completed and some preliminary results obtained by supplementing on the online $N_2O$ analyser with handheld measurements of $N_2O$, $H_2S$ and $CH_4$. Subsequently, tests were conducted on the off-gas from the mainstream process tanks and finally a prolonged data collection campaign were conducted on the activated carbon odour removal filter.

**Preliminary findings**

It was not possible to install a lot of heat tracing on the inlet gas pipe and the pipe could not be insulated until later. This meant an increased risk of water condensation in the pores of the sulphur guard.
It was not possible to conclude the performance of the sulphur guard during startup using the portable analyser due to low/zero $H_2S$ emissions measured. The $N_2O$ analyser showed about

2 ppm $N_2O$, which was too low to determine removal rates on the catalyst. The low concentration was confirmed by a handheld FTIR analyser, which measured 2-3 ppm $N_2O$ and around 295 ppm methane. Around 20% of the methane was converted by the catalyst.

### 6.3.2 Results from mainstream process tanks

During the test of the catalyst in the mainstream off-gas, the $N_2O$ emissions were minimal compared to during other times of the year (see FIGURE 30). Only a few peaks at the very beginning of the four-week test period were observed and could be used to estimate a $N_2O$ removal potential. Evaluating catalytic performance in this period is therefore difficult.

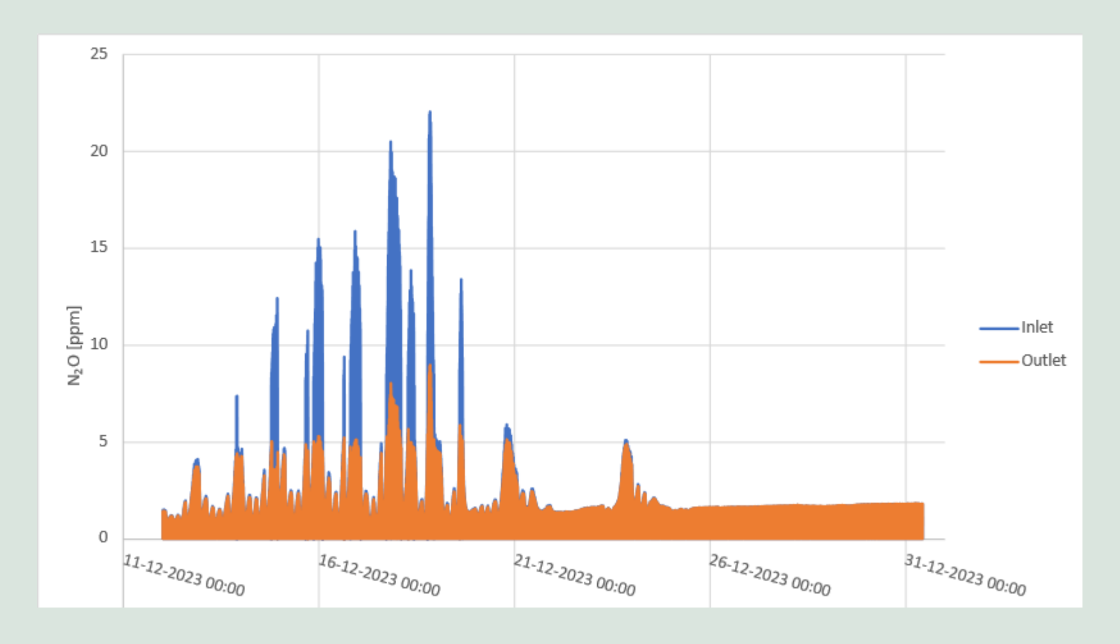


**FIGURE 30.** Two weeks of $N_2O$ measurements from inlet and outlet of the pilot plant at Tårnby WWTP.

In the period from December 7th to 22nd, there were about one $N_2O$ peak per day, with no other apparent pattern in frequency or length.
Looking at these peaks the catalytic conversion is estimated to be around 80% and drops to around 60% from the 7th to the 19th, showing a downward trend in catalytic conversion. This could be caused by catalytic deactivation; however, it should be noted that the conclusion is drawn on a limited data set.

The pilot plant tripped December 25th and was not restarted again until January 2nd. There were no measured $N_2O$ values above 5 ppm in the remaining test period, except for one peak measured on January 15th. Here the inlet concentration was just below 10 ppm inlet, and the catalytic conversion efficiency was approx. 9%, indicating severe deactivation.

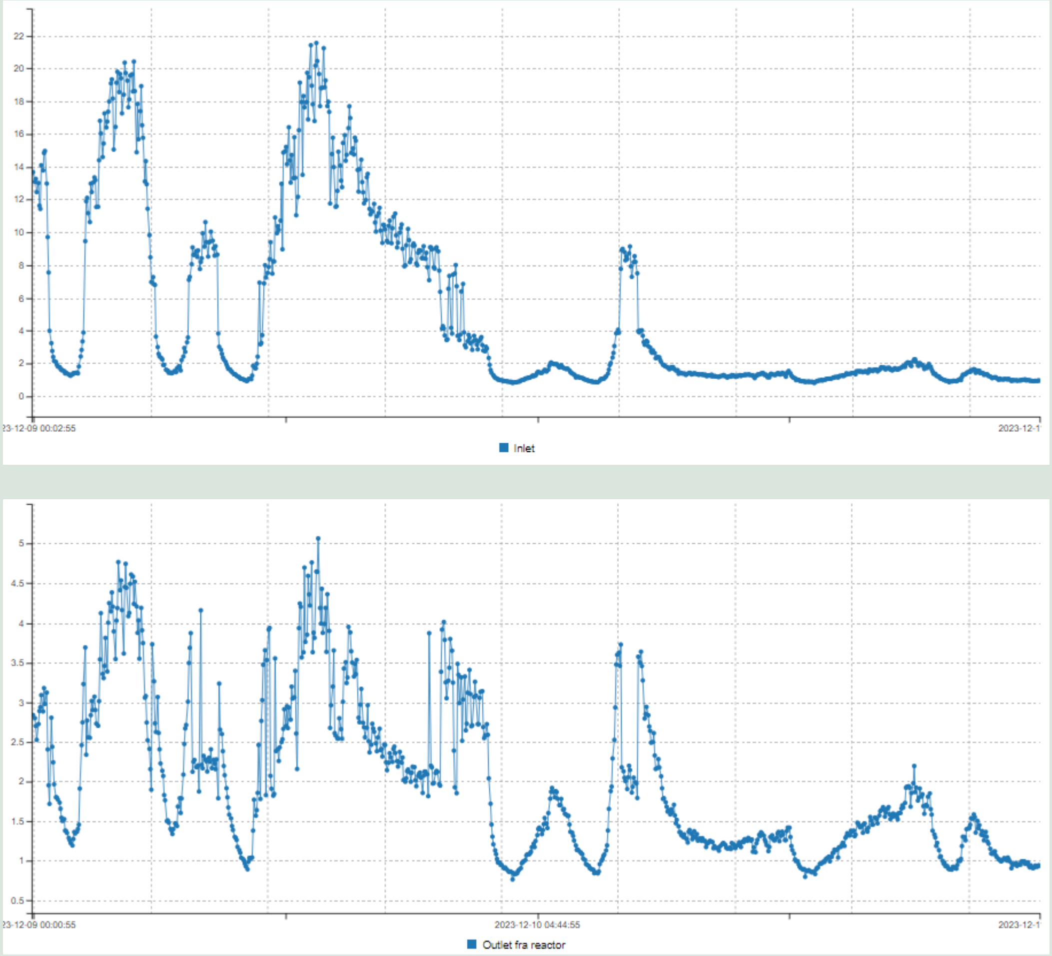


**FIGURE 31.** Measurements from December 9th to 11th. The top graph is inlet, and bottom is outlet $N_2O$ concentration (unit on y-axis is in N2O ppm - note the different scales on inlet and outlet graph). Estimating $N_2O$ removal efficiency based on these data result in approx. 80% removal.

### 6.3.3 Post measurement campaign analyses

**Sulphur-guard**

Once the test campaign on the off-gas from the process tanks was concluded, the pilot plant could be opened and allowed visual inspection of the spent sulphur-guard. Comparing it with a fresh, it is clear that it has been in use (see FIGURE 32). The guard material gets a darker greyish colour when adsorbing $H_2S$. The darker colour along the reactor walls and in an area in the right side of the guard bed, could be signs of it being exposed to condensed water, running down the walls and dripping from the inlet pipe.

**FIGURE 32.** Left: Fresh sulphur guard installed November 17th at Ejby Mølle. Right: Spent sulphur guard removed after pilot dismantling in Tårnby.

### Catalyst material

The catalyst removed from the pilot plant was evaluated in the lab and as expected based on the test campaign, it showed strong signs of deactivation (see FIGURE 33). Both samples from the top and bottom of the spent sulphur guard where heavily deactivated.

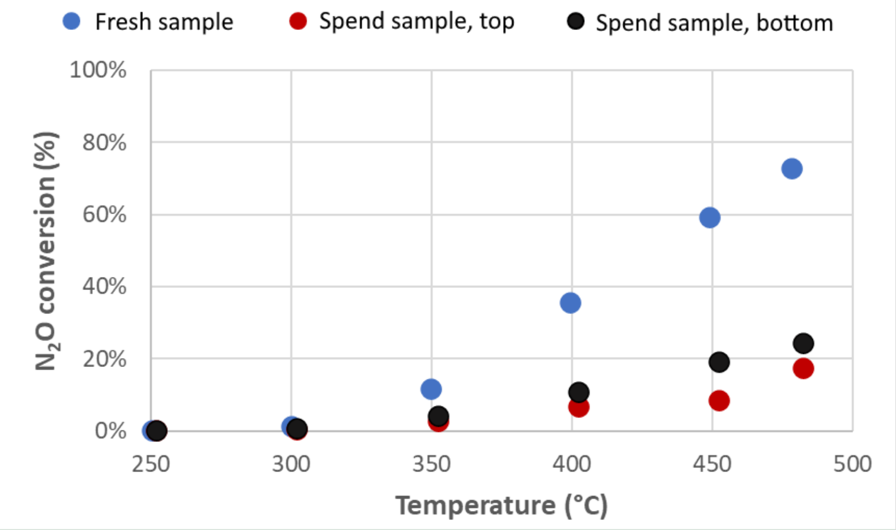


**FIGURE 33.** Lab comparison of the catalyst removed in Tårnby (black and red dots) to a fresh catalyst (blue dots). Note that the actual $N_2O$ conversion depends on several factors, including gas composition and size of catalyst. Therefore, the absolute values cannot be used, but the comparison between samples, show clear deactivation.

Another analysis method was used to compare the amount of sulphur through the catalyst samples. The amount of sulphur found in the first catalyst sample, which was changed about halfway through the Ejby Mølle test campaign, is about 4 times higher than what was found in the last catalyst sample (the one retrieved from Tårnby).

These analysis results indicates that sulphur was causing the catalyst deactivation in the test campaigns. It is likely that the process conditions of the test installation could not keep the sulphur guard dry and thus it lost the ability to adsorb the sulphur and the catalyst was poisoned. Additionally, there could also have been issues with the size of sulphur guard, as it was based on the first measurement of 0.1- 0.5 ppm sulphur.

Despite the believed bleed of sulphur through the guard and into the catalyst resulting in deactivation, it is believed that a design with a better process setup avoiding condensation and expanding the size of the guard, could result in a full functionality and protection of the catalyst from sulphur.

### 6.3.4 Results from activated carbon odour filter

As can be seen in the two graphs below (FIGURE 34), the change in $N_2O$ concentration before and after the activated carbon filters is zero to none. This applies both for situations with low inlet concentrations, as observed during February to April, and when peaks above 100 ppm $N_2O$ are observed in the inlet during May.

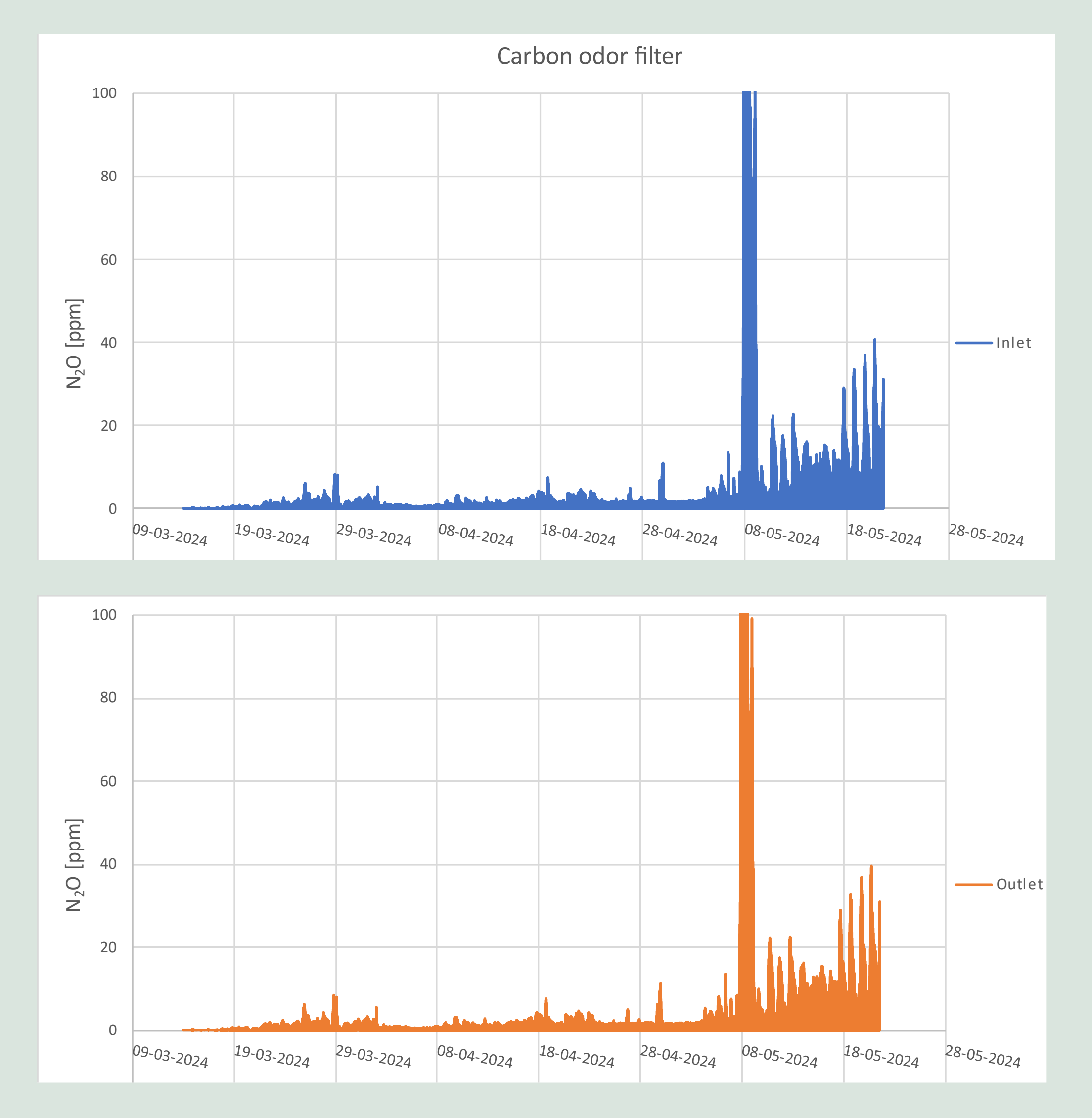


**FIGURE 34.** $N_2O$ measurements from inlet and outlet of the activated carbon odour removing filter from February to May 2024.

## 6.4 Discussion

As sulphur was found on the catalyst after the tests, it seems that the sulphur guard did not have full functionality during the tests. This was likely caused by insufficient heat tracing on the sample pipes, increasing the risk of water condensation in the sulphur guard and thus slip of sulphur to the catalyst. The $N_2O$ conversion was estimated on a limited data set to be approx. 80% at the beginning of the test and then dropping to 60%, and finally about 10% during the test in Tårnby, indicating sulphur poisoning of the catalyst.

Unfortunately, there is no data on the sulphur-guard from the beginning of the Tårnby test, so the guard might have been saturated at this point already. In addition, the capacity of the guard is reduced with temperature and the temperature was quite low during the test period.

It is believed that the sulphur removal can be designed to work much better by avoiding water condensation and having an optimal bed volume and dimensions.

## 6.5 Conclusions

The testing and data collection at Tårnby WWTP resulted in the following conclusions:

- Some high catalytic removal rates was obtained during a few peaks in the off-gas from the mainstream process tanks.
- During most of the test period, the mainstream process tanks did not prove a fitting $N_2O$ source to be treated by catalytic conversion, due to low inlet concentrations. The estimated catalytic conversion started around 80% and then appeared to drop.
- Significant methane emission from the process tanks were observed. Some conversion of methane on the catalyst was observed but could also be a competitor with $N_2O$ conversion.
- No $N_2O$ removal is taking place in the activated carbon odour removing filters, both during low and high inlet $N_2O$ concentrations.

# 7. Commercialization

## 7.1 Purpose

The aim of this chapter is to evaluate the economic viability and the environmental effect of catalytic treatment of WWT off-gas. The analysis will be based on the learnings from the test series performed as part of this project. To make an overview of potential applicability of the technology, assumptions and simplifications have been made due to uncertainty on pollutant concentrations, best process design and costs estimates.

## 7.2 Process setup

As shown in this development project, some off-gas streams from WWTPs contains potent greenhouses gases $N_2O$ and $CH_4$. It has also been shown that $N_2O$ can be removed catalytically resulting in a proof-of-concept. Catalytic treatment requires elevated temperatures and pre-treatment in the form of gas cleaning resulting in significant OPEX (operating expense). However, most of the heat for raising the temperatures can be recovered in a feed/effluent heat exchanger (F/E HEX), which uses the gas from the catalytic process to heat the gas coming to the catalytic process.  F/E HEX is included in the economical assessment.
Important insights were found regarding the need for gas pre-treatment in this project. Sulphur management is needed for the catalytic process and every off-gas stream tested in this project contained $CH_4$. These learnings are included evaluation of the potential GHG reduction and the economic assessment. $CH_4$ is the second largest contributor to global warming after $CO_2$. $N_2O$ is the third. It is therefore relevant to evaluate the possible removal of both $N_2O$ and $CH_4$. $CH_4$ measurements in this project were only conducted during a few hours, with a handheld analyser on site. Thus, there is a high degree of uncertainty related to the $CH_4$ values.

The process setup considered in the economic assessment includes a couple of modifications from the test setup based on learnings made in during the testing:

- Sulphur guard (adsorption unit) designed for the higher concentrations
- Piping design from process to adsorption unit to avoid condensation
- Inclusion of a feed-effluent heat exchanger (F/E HEX) to recover heat from the treated off-gas

In FIGURE 35, the modification from the pilot test setup in FIGURE 4 are shown.

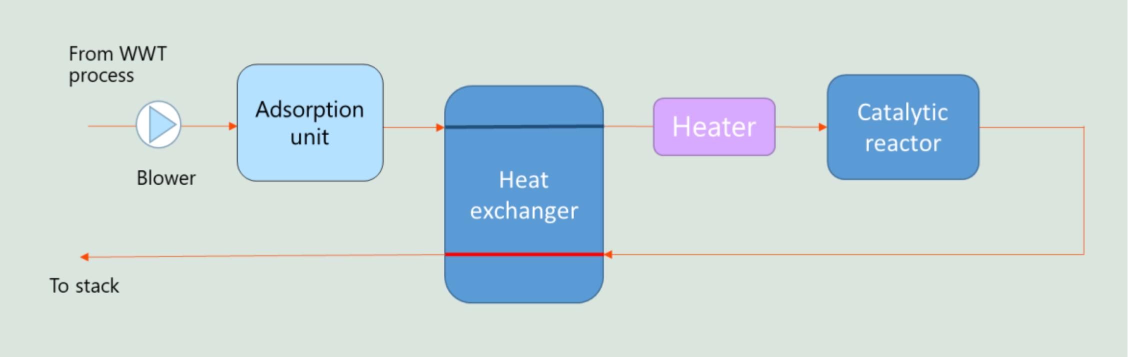


**FIGURE 35.** Proposed process setup for full-scale implementation of catalytic unit for treating $N_2O$ in WWT off-gas.

## 7.3 Catalyst process design and removal efficiencies

As seen in Chapter **Fejl! Henvisningskilde ikke fundet.**, the test at Ejby Mølle ended up with approx. 80% conversion of $N_2O$. As mentioned, the catalyst in the pilot plant was designed to not have too high conversion during testing, to better be able to follow possible decrease in performance.

For a full-scale catalytic unit to be installed at a WWTP, the target removal efficiency is off course higher. However, removing the last bit of $N_2O$ requires relatively more catalyst, and may therefore not be the best choice considering the overall economics. Typically, the most optimal removal is in the 95-99% range. For the economic evaluation in this section, the results from the Ejby Mølle test have been upscaled to a design with an estimated $N_2O$ removal of 98-99% (98.5%) at an inlet temperature of 400°C.

During the measurement campaign at HCR Syd a $CH_4$ removal of around 20% was observed. At Ejby Mølle, where the sulphur removal was working better, the $CH_4$ removal was about 55% at the end of the campaign. Therefore, an assumed 50% removal of $CH_4$ has been included in the economic evaluation for all considered scenarios.

The catalyst cost has been estimated based on products similar to the catalyst tested in the pilot, but there is of course also an uncertainty related to this cost estimate. With such a limited dataset and for a new type of catalyst, such scaling naturally comes with uncertainties.

## 7.4 Scenarios

In order, to evaluate the economical sustainability a number of scenarios have been set up covering varying concentrations of $N_2O$ and $CH_4$ as well as air flows.

### 7.4.1 $N_2O$

To create an easy-to-understand assessment of the economic feasibility of applying catalytic technology on off-gas treatment from WWTPs, several scenarios have been defined based on the test conducted during the project (see TABLE 1). In these scenarios a constant $N_2O$ concentration is assumed, which is of course a simplification of the actual process observations. The same applies for the airflow. Average values have been used to estimate the amount of $N_2O$ emitted and possibly reduced and the maximum airflow rate used for sizing the catalytic treatment technology.

**TABLE 1.** $N_2O$ scenarios evaluated.

| **Site** | **$N_2O$ concentration** | **Airflow ($Nm^3/h$)** | | **Period** | **$N_2O$ emission** | | | |
|---|---|---|---|---|---|---|---|---|
| | ppm $N_2O$ | Avg. | Max | - | g $N_2O$-N/h | Kg $N_2O$-N/day | Kg $N_2O$-N/year. | Ton $CO_2$ eq./year |
| HCR Syd mainstream aeration tanks | 40 | 2100 | 11000 | May-July | 105 | 2.5 | 230 | 99 |
| HCR Syd sidestream Demon+other ventilation | 50 | 175 | 350 | All year | 11 | 0.3 | 96 | 41 |
| Tårnby mainstream aeration tanks | 300 | 4500 | 15000 | May-Aug | 1687.3 | 40.5 | 4926.8 | 2114 |
| Ejby Mølle sidestream Demon - high emission case | 1000 | 100 | 250 | All year | 125 | 3 | 1094.8 | 470 |
| Ejby Mølle sidestream Demon - "normal" emission case | 100 | 100 | 250 | All year | 12.5 | 0.3 | 109.5 | 47 |

The $N_2O$ emissions measured in this project was close to zero from the HCR Syd process tanks and very low from the Tårnby process tanks (see Chapter 5 and **Fejl! Henvisningskilde ikke fundet.**). If these time periods were representable for the emission during the entire year, it is unlikely that it would be economically viable to operate a catalytic unit. From the baseline $N_2O$ emission measurements at each site, it is however known that parts of the year peak emissions occur. In these two cases, only emissions and catalytic treatment, during the specified periods have been considered (see TABLE 1). For both deammonification cases (HCR Syd and Ejby Mølle), the emission is relatively constant over the year. At HCR Syd, the off-gas from the Demon process was diluted by ventilation air. An estimation of the average and maximum air flow rate is therefore used in this scenario. The measurements conducted at Ejby Mølle during this period showed high emissions, which were unusual compared to previous years' observations, and caused by external factors outside of the scope of this project. For this case two scenarios were therefore considered – a high emissions case based on measurements observed during the project and a "normal" emission case based on previous observations.

### 7.4.2 $CH_4$

In TABLE 2 the $CH_4$ measurements, corresponding $CO_2$ equivalents, and concurrent $N_2O$ measurements are shown.

**TABLE 2.** Comparison of $CO_2$ equivalent emissions from $N_2O$ and $CH_4$. $CH_4$ is assumed emitted constantly the whole year.

| **Site** | **$N_2O$** | | | **$CH_4$** | | |
|---|---|---|---|---|---|---|
| | ppm $N_2O$ | ton $CO_2$eq./year | Period | ppm $CH_4$ | ton $CO_2$ eq./year | Ratio ppm $CH_4$/ ppm $N_2O$ |
| HCR Syd mainstream aeration tanks | 40 | 99 | May-July | 350 | 127.2 | 8.75 |
| HCR Syd sidestream Demon+other ventilation | 50 | 41 | all year | 190 | 5.8 | 3.80 |
| Tårnby mainstream aeration tanks | 300 | 2114 | May-Aug | 295 | 229.8 | 0.98 |
| Ejby Mølle sidestream Demon - high emission case | 1000 | 470 | all year | 220 | 3.8 | 0.22 |
| Ejby Mølle sidestream Demon - "normal" emission case | 100 | 47 | All year | 150 | 2.6 | 1.5 |

The GWP of $N_2O$ is almost 10 times higher than for $CH_4$. But further, the molar weight of $CH_4$ is just 16 g/mol, whereas it is 44 g/mol for $N_2O$. This means that per molecule $N_2O$ is almost 3 times as heavy, resulting in a higher mass flow for the same concentration. This means that for the same concentration, $N_2O$ has almost 27 times higher global warming effect than $CH_4$. All in all, this mean that generally the $CO_2$ equivalent emissions from $N_2O$ are much higher than for $CH_4$, as it is evident from TABLE 2. This clearly shows that unless $CH_4$ concentrations are very high, the focus should be on reducing $N_2O$ emissions. Only the HCR Syd process tank case has a high impact of the methane compared to $N_2O$. This is in part due to the relatively high $CH_4$ measurement and the low $N_2O$ measurement (which is also reflected in a generally low $N_2O$ emission baseline from HCR Syd).

## 7.5 Economical assessment

In general, off-gas from WWTP are very small flows compared to flows typically used for industrial catalytic solutions. Larger catalytic projects are often unique in design, tailored to fit into the specific plant and process. This approach is likely to result in too high costs when considering units for WWTPs. To reduce costs, it is considered important to keep engineering costs down, by reusing design as much as possible or even having a few specific modules to choose from.

Equipment lifetime of 10 years has been considered in the economic assessment. Likewise, OPEX for catalyst consumption are also evenly distributed in this manner. This provides a simple analysis that provides a good first assessment of the economic viability of the proposed technology.

### 7.5.1 CAPEX

The pilot test unit in the project was rented from the private vendor xpuris Aps, who have been assisting in the investment cost estimations. Economy of scale has an impact on the investment cost, since it is not the material costs that drives the overall costs, but rather the engineering work. Therefore, the smaller units have a higher cost per treated Nm$^3$ than the bigger ones. It is also evident that costs are almost the same for the 3500 Nm$^3$/h unit as for the 4700 Nm$^3$/h unit, which is in line with expectation for units of this size.

CAPEX is based on quotas made for WWT $N_2O$ off-gas treatment projects in Europe which can be seen in TABLE 3.

**TABLE 3.** Cost of xpuris units, offered for actual WWT $N_2O$ off-gas treatment projects in Europe.

| Flow | CAPEX | Quotation year |
|---|---|---|
| Nm$^3$/h | kEUR | |
| 10 | 125.0 | 2025 |
| 30 | 127.5 | 2025 |
| 735 | 236.0 | 2025 |
| 3500 | 470.0 | 2024 |
| 4700 | 485.0 | 2024 |

The prices in TABLE 3 do not include $N_2O$ sensors, sulphur guard (except the 735 Nm3/h), duct work, civil work structures or stack. Other than that, the units are turn-key and including installation. Civil works are not necessarily needed.

For all three sites where the pilot plant was placed for this project, a suitable place was found, which could likely accommodate such unit. The stack was just a small pipe on the unit and will also not add much to costs. Duct work and stack will be similar to what was also done at each site in this project. The units treating off-gas from sidestream would not be much larger than the test unit of this project. Even though the size will be larger for full scale for the process tanks, it is not expected that it will add further to the costs, than the total installed factor included.

As the cost estimates are for a turn-key unit with installation included, it is assumed that a total install cost factor of just 1.1 can cover the remaining costs. With this addition to the CAPEX, the total investment cost estimate can be seen in the blue line in FIGURE 36.

As the maximum off-gas flows for the scenarios treating the mainstream off-gas are much larger, therefore extrapolation is needed.

A common way of scaling plant or unit costs is to use the following formula:

$$Cost\ plant\ B = \left(\frac{Capacity\ plant\ B}{Capacity\ plant\ A}\right)^{e} \cdot Cost\ of\ plant\ A$$

Where the exponent *e* depends on the complexity of the scaled plant, unit or component.

To get the best fit to the xpuris cost data and a flat curve as flow increases, an exponent of 0.4 was used (see FIGURE 36). This is a rather low factor, typically used for simple equipment.

This assumes that the same or a similar unit design can be used all the way up to 15,000 Nm$^3$/h. When reaching higher flows, it will likely be necessary to utilize two similar units in parallel instead.

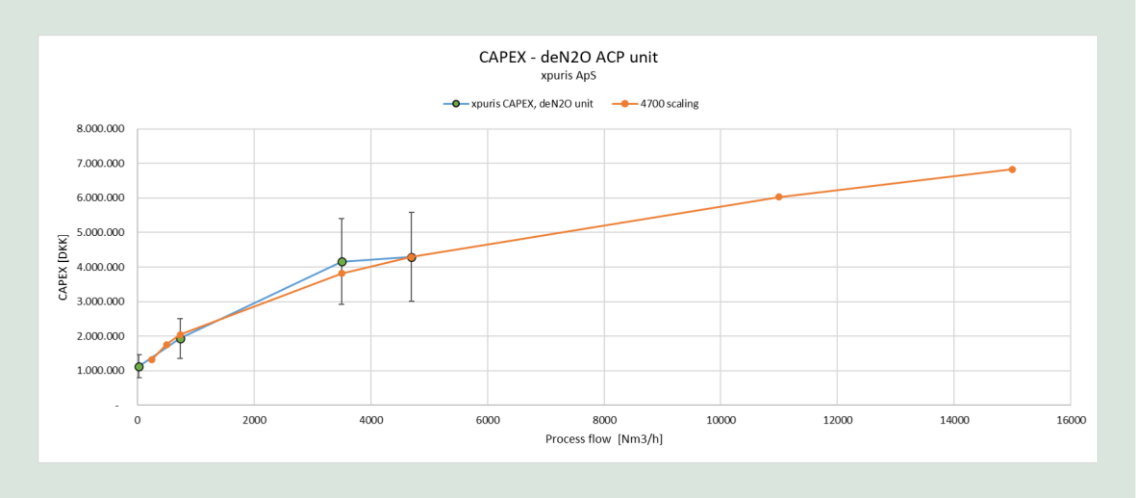


**FIGURE 36.** CAPEX estimate based on quote prices from xpuris (blue line), and extrapolation to get CAPEX for larger unit sizes (orange line).

The maximum flowrate from TABLE 1 is used as design flow to estimate unit costs. For the sidestream cases linear interpolation of the xpuris unit costs has been used. For the mainstream tank cases the extrapolation (orange curve on FIGURE 36) has been used to estimate costs.

### 7.5.2 OPEX

The operating costs are kept as simple as possible and only the major components have been included:

- Power consumption for blower and heater along with sulphur guard replacement costs and catalyst replacement costs.
- The guard is assumed to be replaced every year.
- The catalyst is assumed to have a 5-year operating time. For the sidestream treatment, the unit is expected to be operated all year. The mainstream cases are expected to be in operation 3 to 4 months per year during peak emission times (see TABLE 1). The first catalyst installation is included in the CAPEX. With an assumed lifetime of 5 years of operation time, but only operating 3 or 4 months a year, no need for catalyst replacement is expected in the first 10 years of operation for the mainstream cases and therefore not included in this economic evaluation. For the sidestream cases one replacement of catalyst is considered in a 10-year period. For simplicity these costs are distributed evenly over the 10 years, no interest included.
- The requirement of sulphur guard replacement has been estimated based on the level of measurements done at each site. For HCR Syd and Tårnby sites, an average sulphur load of 1 mg/Nm$^3$ (0.7 ppm) $H_2S$ has been assumed. At the Ejby Mølle a sulphur load of 4 mg/Nm$^3$ (2.6 ppm) $H_2S$ has been assumed resulting in a higher need for guard replacement. The average flow from TABLE 1 is used for sulphur guard consumption as the guard consumption depends on the actual flow of gas through the guard.
- The power consumption for the heater is based on compensating an approach temperature in the heat exchanger of 30°C. Any heat from catalytic reactions is neglected, but so is temperature loss in the catalytic unit.

- The power consumption for the blower depends to a high degree on the unit design and the resulting pressure drop. The blower consumption is estimated based on the blower used in the test unit, however with additional pressure drop added to account for F/E HEX and more sulphur guard and catalyst. The power consumption for the heat compensation and the blower is calculated to be 14.9 Wh/Nm$^3$.
- The power costs are assumed to be 1.2 DKK/kWh.

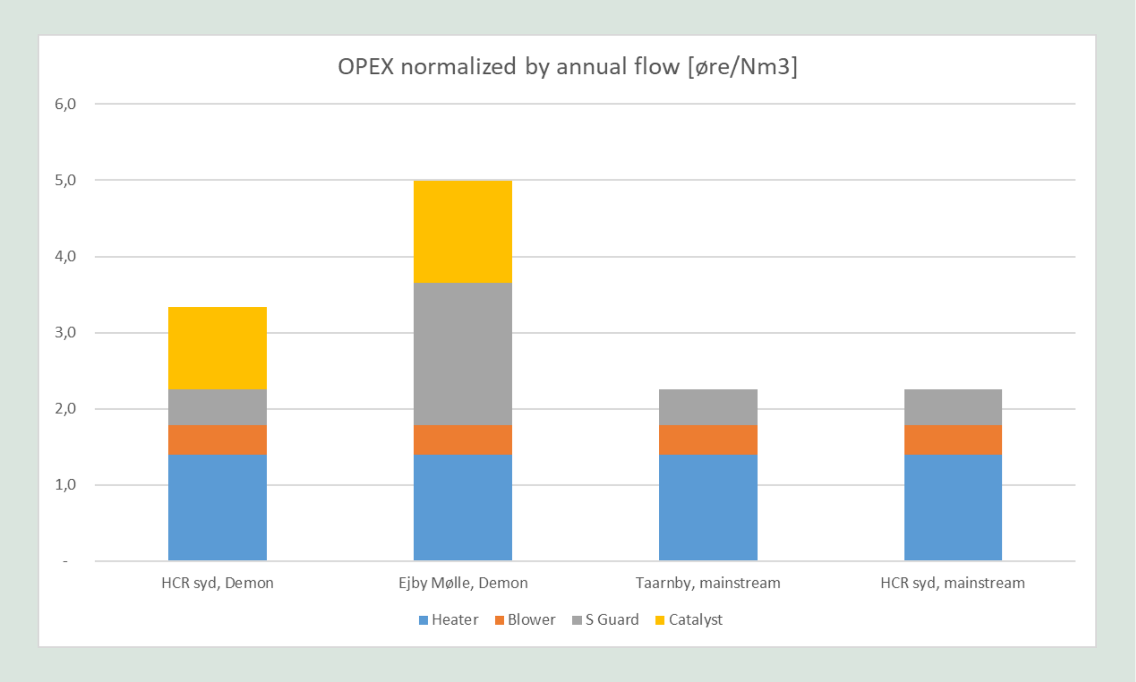


**FIGURE 37.** Opex in øre/Nm$^3$ for each site. No catalyst costs are included for the cases with only periodic operation as it is assumed that the catalyst can last the 10 years in this economic evaluation.

The OPEX for Ejby Mølle site is higher as higher sulphur concentration has been assumed. Heater and blower OPEX are the same per Nm$^3$ (see FIGURE 37). Heating is the largest contributor for three of the sites. From the Ejby Mølle scenario sulphur removal cost can contribute significantly to the OPEX. Thus, a better understanding of the actual sulphur level is important both for economic evaluations, as well as for the actual design of the sulphur removal.
Service of the unit is not included in the OPEX, but is not expected to have a major impact.

### 7.5.3 $CO_2$ saving price

For the economic assessment, a cost of 750 DKK/ton $CO_{2,eq}$ has been used, similar to what is imposed on Danish industry, (Skatteministeriet 2024). In order to consider possibly future $CO_2$ pricing, a cost of 1500 DKK/ton $CO_{2,eq}$ has also been considered and compared the calculated $CO_{2,eq}$ shadow prices.

## 7.6 Scenario assessment

The evaluation has devided into mainstream scenarios (HCR Syd and Tårnby) and sidestream scenarios (Ejby Mølle – high emission case, Ejby Mølle – “normal” emission case, and HCR Syd Demon).

### 7.6.1 Mainstream scenarios

The HCR Syd (Hillerød) scenario shows about equal GHG savings from $CH_4$ reduction as from $N_2O$ reduction. Regardless, the calculated $CO_{2,eq}$ savings in the HCR Syd scenario are far lower than the annual estimated cost of catalytic treatment. There is thus not a positive business case for treatment plants with emissions in the range observed at the HCR Syd process tanks.

The Tårnby process tanks however looks as if it could be a rather attractive case. With the assumed conditions described above, the annual $CO_{2,eq}$ related savings can be more than 1.6 million DKK/year, with annual costs estimated at just short of 1 million DKK/year (see FIGURE 38).

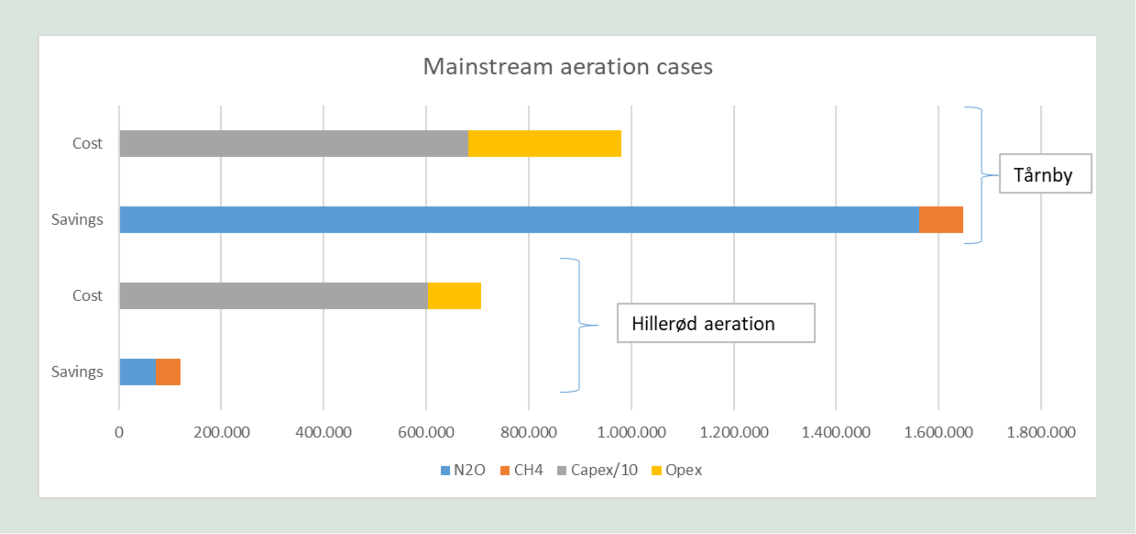


**FIGURE 38.** Annual cost and savings in DKK for the mainstream scenarios.

As can be seen the majority of the cost is based on the CAPEX. There is not a lot of difference of the CAPEX of the two cases, even though the maximum flow is 36% higher in the Tårnby case. This is due to the rather flat shape of the cost curve at higher costs in FIGURE 36. For Tårnby, the OPEX are almost one third of the CAPEX cost, whereas for HCR Syd they are almost down to one sixth of the costs.

Looking at FIGURE 37 the OPEX per treated Nm3 is the same for the two cases. Still the OPEX for the Tårnby case are much higher than for HCR Syd. The reason for the difference is because Tårnby has a higher average flow compared to maximum flow than HCR Syd, and one more month of peak emissions per year where the catalytic treatment will be operating (as per TABLE 1). The higher average flow and longer operating time also increases the $CO_{2,eq}$ savings for the Tårnby case, but most importantly the higher $N_2O$ emissions compared to HCR Syd is the main driver of the high $CO_{2,eq}$ savings expected at Tårnby.

### 7.6.2 Sidestream scenarios

The “Ejby Mølle – high emission” scenario shows a positive business case, whereas the other two do not (see FIGURE 39). Costs are relatively similar between Ejby Mølle and HCR Syd, but the lower $N_2O$ concentrations in the HCR Syd and the Ejby Mølle “normal emission” scenarios, means that $CO_2$ savings are much lower than the annual cost of the catalytic unit.

It is also evident that the $CH_4$ contribution to the savings is almost neglectable compared to $N_2O$.

The annual CAPEX contributes significantly more than the OPEX to the costs. About three quarters of the annual costs are from CAPEX.

An important note here is that for the HCR Syd Demon, the off-gas is mixed with other ventilation gas. The ratio between the flow of the two is unknown. The other ventilation air is not expected to contribute with any $N_2O$. Thus, it would make much more sense to add the catalytic unit only to the Demon off-gas. This is certain to improve the business case of a catalytic solution considerably, but still uncertain if it would become positive.

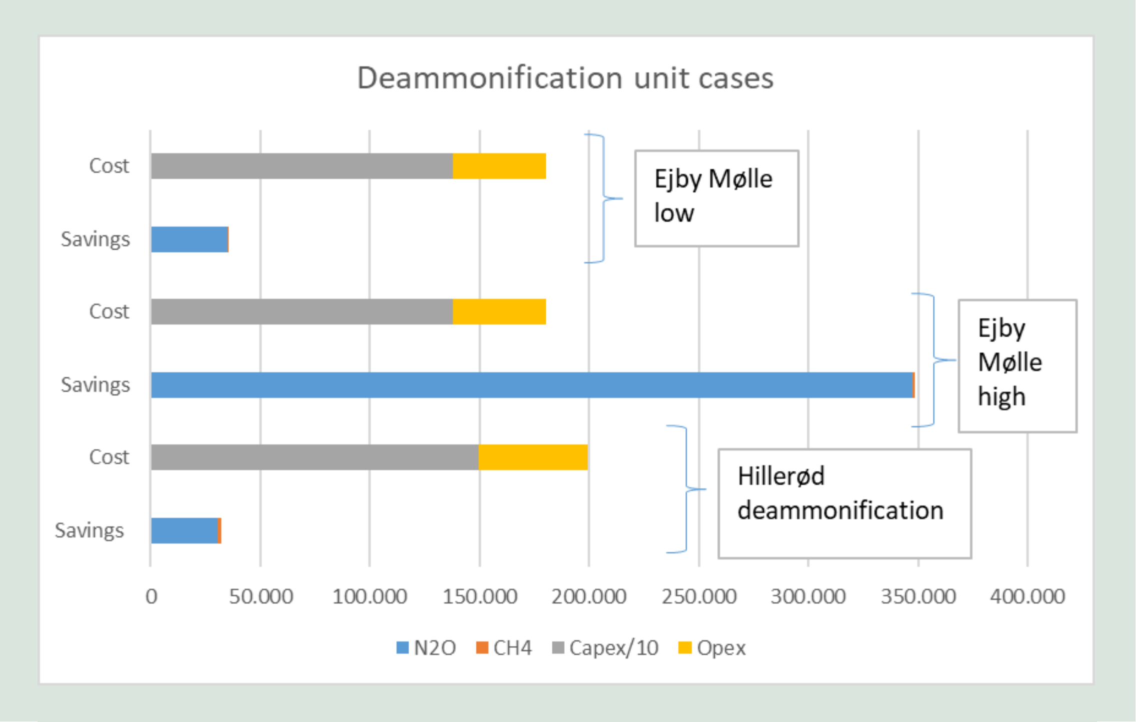


**FIGURE 39.** Annual cost and savings in DKK for the sidestream scenarios.

The CAPEX estimate comes with an estimated tolerance of +/- 30% (TABLE 3). Since the CAPEX is the largest cost contributor it makes sense to evaluate the effect of these tolerances. This is relatively simply done by looking at FIGURE 38 and FIGURE 39. Increasing or decreasing the CAPEX with 30% does not change any of the cases in terms of whether they result in a positive or negative business case.
The factors which have the largest impact on the feasibility of a project is the $N_2O$ emission and the period in which it is emitted.

### 7.6.3 $CO_2$ shadow price

Looking at the $CO_{2,eq}$ abatement cost of each case (FIGURE 40), there is a huge variability. As concluded above only Tårnby aeration and Ejby Mølle high cases looks attractive, with a $CO_2$ price below 750 DKK/ton. Even if a future cost of twice the currently expected, i.e. 1500 DKK/ton, would be implemented, it does not change the attractiveness of the other cases. But it is clear that the Ejby Mølle low case, comes a lot closer when having one larger unit for both lines.
The actual lifetime of such a catalytic unit is likely to be 30 years or more and not just the 10 years of this evaluation. Therefore, the actual abatement costs of the $CO_2$ will be much lower than estimated in FIGURE 40.

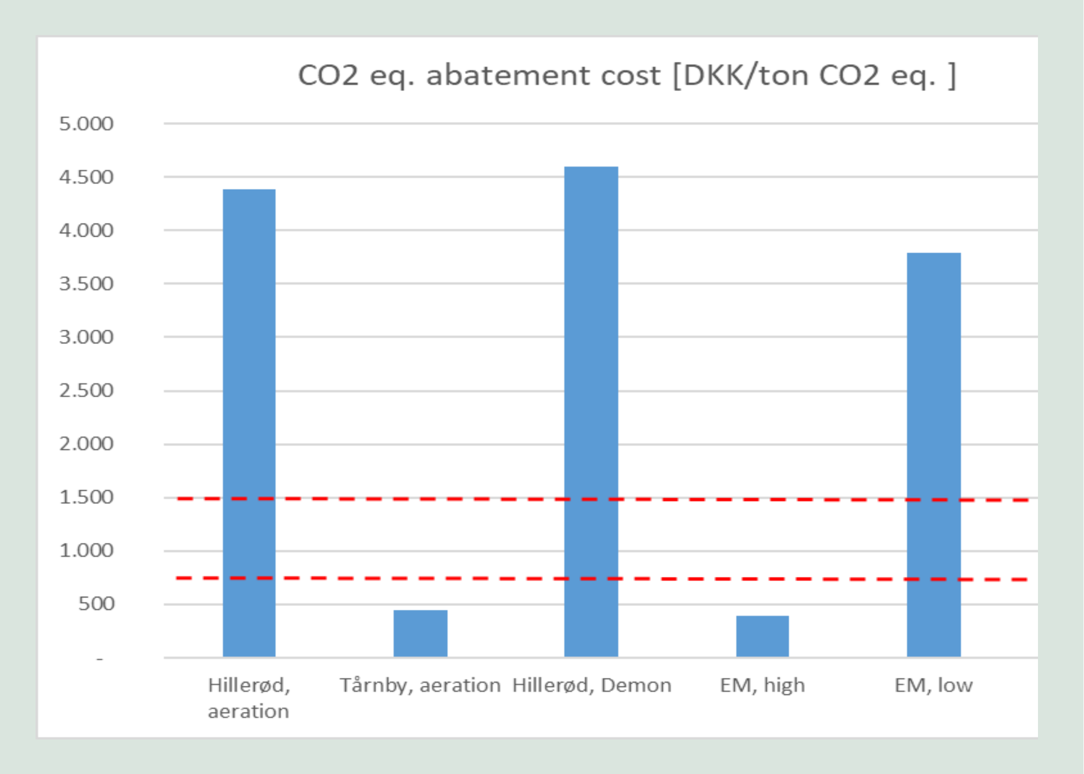


**FIGURE 40.** Estimated abatement cost. A case with one catalytic unit for both EM deammonification units at low concentration has been added. The dotted lines represent 750 DKK/ton and 1500 DKK/ton.

## 7.7 Discussion

It is very important to note that there are still large uncertainties on the estimation used in this economic assessment, which of course impacts the conclusions.

The CAPEX distributed over 10 years lifetime is the major component of the cost. This may, at least partly, be explained by the maximum flow determining the plant size and therefore cost, whereas the OPEX and savings are determined by the average flow. If CAPEX could be reduced, it would have a relatively big impact on the business case of implementation of catalytic $N_2O$ abatement. As mentioned earlier, cost per unit could potentially be reduced by serial production. This means that the capacity will not necessarily fit the specific site, but on the other hand, plant costs should be lowered by economics of scale. This could potentially make the technology feasible for more sites.

It is clear from above results, that the economic feasibility varies enormously from site to site. It would be beneficial to get more and better data to be able to evaluate the feasibility more accurately. But it appears, that there are sites where catalytic abatement is attractive and sites where it is not.

Out of the five cases, there are two that appear positive. Interestingly, one is for deammonification, and one is for mainstream aeration tanks. Illustrating that attractive cases can be found in both segments.

Deammonification units are much less widespread in use than mainstream aeration tanks. The result of this study indicates that catalytic treatment for mainstream aeration could indeed be attractive for plants with high peak emission levels. This would mean a much larger market than only sidestream deammonification units.

In a nutshell, it is the actual $N_2O$ emission from each site that determines economic feasibility.

Since the start of this project, possibilities of alternative catalyst has emerged. This could mean that the sulphur removal can be avoided. Looking back at FIGURE 37, it is clear that this would have a significant impact on the OPEX of the catalytic unit.

## 7.8 Market potential and international outlook

Biological nitrogen removal at WWTP is widely applied in Denmark as >90% of all wastewater treated has demands for nitrogen levels. With increasing focus and tightening regulations on nutrient discharges (e.g. the revised urban wastewater treatment directive from the European Union), the application of biological nitrogen removal processes is only expected to increase. This is expected to increase the formation of $N_2O$ at WWTP, which can then serve as a point source to be treated instead of a diffuse source in the receiving water bodies. The need for technologies to treat $N_2O$ is therefore expected to increase over the coming years as nitrogen removal gets implemented to a larger extent than currently.

In regions where process tanks are already covered, this technology could serve as an interesting application to reduce carbon footprint. This could be areas where treatment plants are placed underground (e.g. in Norway, Sweden, and Finland due to the local topography), or where they are covered due to odour reduction in built-up areas.

Assessing the economic sustainability have shown that the viability is completely dependent of the $N_2O$ emissions at a given site. For sites with high peak emissions even though it might only be during a couple of months per year, can have a positive business case.
The starting point of assessing the market potential must therefore be to get a better understanding of the $N_2O$ emissions and the extent of “high emission” sites. As there was 2 out of 5 cases (40%) in this project that was relevant, it is believed that there will be a significant number of interesting cases in the European market. It is however, not expected that the 40% can be completely extrapolated to apply to all nitrogen removing WWTPs, but to a significant amount of WWTPs, somewhere between 10-30%.
As was found here not all sidestream treatments based on biological deammonification have significant emissions in the range where the business case becomes positive. This might be related to the rate and efficiency of the biological processes and a mapping and understanding of these two values could provide insights that allowed identification of “high risk” emission sites.

This chapter highlights the importance of and need for political and legislative action to reduce emissions from wastewater treatment plants – otherwise the mitigation technologies might not be implemented to any significant extent. Economic incentives like $CO_2$ taxes are important but must be carefully designed to avoid harming industry and to drive improvements where they matter most. Achieving climate goals requires swift legislation on emission limits or incentivized emission reduction.
Collaboration between governments, industry, and society is essential, not only to cut emissions but also to promote long-term sustainability and resource efficiency.

# 8. Modelling and holistic assessment

## 8.1 Purpose

The purpose of the "Modelling and Holistic Assessment" section within the NACAT project is to develop and apply advanced simulation tools and sustainability assessment frameworks to quantify and reduce $N_2O$ emissions from WWTPs. The aim was to create digital twins of selected WWTPs to integrate real-time operational data with mathematical models, enabling accurate prediction of effluent quality, operational cost, and GHG emissions under varying operational strategies.

By incorporating detailed process modelling, including biological nutrient removal, physico-chemical speciation, and gas-liquid mass transfer, the project evaluates both source specific and plantwide dynamics of $N_2O$ generation and emission. Coupled with techno-economic analysis and life cycle assessment (LCA), this serves as a decision-support system to assess trade-offs between competing objectives, such as effluent quality improvement, energy optimization, cost control, and carbon footprint reduction.

The overall goal is to identify practical emission abatement strategies and provide scientific evidence for the feasibility of emerging technologies, particularly catalytic $N_2O$ removal, in full-scale wastewater operations.

To this end, a modelling framework was developed to simulate the integration of catalytic off-gas treatment into wastewater treatment lines (mainstream, sidestream, or both), and to evaluate its cost-effectiveness using scenario-based analysis, annualized investment and operating costs, and dynamic GHG mitigation indicators.

This modelling approach allows utilities and policymakers to compare catalytic treatment options with other mitigation strategies and supports evidence-based decision making on investment in climate-relevant technologies.

## 8.2 Methods

### 8.2.1 The “NACAT” Activated Sludge Model (ASM)

The NACAT Activated Sludge Model is based on the widely used ASM2d (Henze 2006), extended with additional functionalities described by (K. F.-A. Solon 2017) and (Massara 2018). These extensions enable the model to simulate not only biological carbon (C), nitrogen (N), and phosphorus (P) removal processes, but also chemical and biological mechanisms related to sulphur (S), iron (Fe), deammonification activity, and nitrous oxide ($N_2O$) production and emissions.

Three key biological pathways for $N_2O$ production are explicitly included:

- $NH_2OH$ oxidation (NN pathway): $N_2O$ is formed via the reduction of NO to $N_2O$ by the enzyme *or* in ammonia-oxidizing bacteria (AOB), coupled with hydroxylamine oxidation to nitrite ($NO_2^-$) (Pocquet 2016).
- AOB nitrifier denitrification (ND pathway): $N_2O$ is produced through the sequential reduction of $NO_2^-$ to NO and then to $N_2O$ by AOB. These reactions are lumped into a single process as per Pocquet et al. (2016).
- Heterotrophic denitrification (DEN pathway): $N_2O$ is an intermediate formed by ordinary heterotrophic organisms (OHO) or polyphosphate-accumulating organisms (PAO) during denitrification (Hiatt 2008).

Incorporating all three pathways allows for a more comprehensive understanding of $N_2O$ generation under dynamic conditions and different operational strategies.

The model also includes a generalized aqueous-phase chemistry framework that dynamically calculates pH and ion speciation at every simulation step (X. M. Flores-Alsina 2015) (K. F.-A. Solon 2015). Ionic strength corrections are performed using the Davies approach (K. F.-A. Solon 2017), and weak acid-base equilibria are fully accounted for. This is critical for accurately predicting substrate availability for nitrifiers, particularly free ammonia (FA, $NH_3$) for AOB and free nitrous acid (FNA, $HNO_2$) for nitrite-oxidizing bacteria (NOB), which are pH-sensitive.

Gas-liquid mass transfer is modelled for key gas components, $CO_2$, $O_2$, NO, $N_2O$, and $N_2$, based on Fick's first law. Transfer rates are determined by the difference between gas saturation concentrations (from Henry's law) and dissolved concentrations in the liquid phase. The mass transfer coefficients for each gas are calculated using diffusivity ratios relative to oxygen, scaled with respect to the reference transfer coefficient for $O_2$ (Lizarralde 2015). This enables reliable prediction of both dissolved and emitted $N_2O$.

### 8.2.2 The "NACAT" Holistic Assessment Model (HAM)

To support integrated analysis, the NACAT Holistic Assessment Model (HAM) is based on the IWA Benchmark Simulation Model No. 2 (BSM2). This plant-wide dynamic model includes primary and secondary treatment processes, biological nutrient removal, anaerobic digestion, sludge management, and biogas production. The BSM2 is widely accepted as a reference framework for evaluating operational strategies, control systems, and performance indicators in WWTPs.

For this project, the BSM2 was extended to incorporate:

- The NACAT ASM for both mainstream and sidestream (reject water) modelling.
- The IWA Anaerobic Digestion Model No.1 (ADM1), modified to include phosphorus and sulphur dynamics, representing sludge stabilization processes more realistically.
- Advanced sustainability metrics covering effluent quality, operational cost, and GHG emissions.
- A set of equations to estimate produced airflow from the water / reject water line
- A methodology based on shadow prices to estimate the feasibility of catalytic treatment.
- An economic module to compute total annualized costs for catalytic systems, including capital expenditures, energy use, and consumables.
- Scenario-based configurations for catalytic treatment applied to the mainstream, sidestream, or both, enabling integration of emission mitigation technologies into the plant-wide evaluation.

The assessment focused on four key performance indicators (KPIs):

- EQi - Effluent Quality Index
- OCi - Operational Cost Index
- GHGi - Greenhouse Gas Emission Index
- Shadow prices

These indices were computed dynamically across various operational scenarios, including reject water recirculation, addition of PN/ANX (partial nitritation/anammox) systems, and P recovery units. The catalytic treatment module was used to simulate abatement configurations and compute associated shadow prices per ton of $CO_2$-equivalent removed, enabling cost-effectiveness comparisons. This comprehensive model framework enables simultaneous assessment of water quality, resource recovery, and environmental impacts, making it suitable for evaluating trade-offs and synergies among competing goals in real wastewater treatment scenarios.

## 8.3 Results

### 8.3.1 Ejby Mølle case study

The first case study focused on testing and validating the NACAT ASM for simulating and mitigating $N_2O$ emissions in PN/ANX granular-based reactors treating reject water at Ejby Mølle.

The proposed methodology combined data pre-processing, mechanistic process modelling, control strategy simulation, and key performance indicator (KPI) analysis to assess system performance under real operational conditions. Two full-scale datasets (D1 and D2), collected over a four-month period (September–December 2023), served as the basis for model calibration and validation (Flores-Alsina, et al. 2025a).

High-frequency sensor and laboratory data were first processed to address signal noise, data gaps, and inconsistencies. Advanced data science techniques were applied to:

- Filter noise from key input variables such as $NH_x$ and $PO_4^{3-}$
- Interpolate missing data and extrapolate daily measurements to sub-daily resolution
- Adjust ion loads to align with recorded pH values via the aqueous speciation module.

These steps significantly improved model stability and simulation fidelity. FIGURE 41 illustrates the impact of pre-treatment on raw and processed sensor signals.

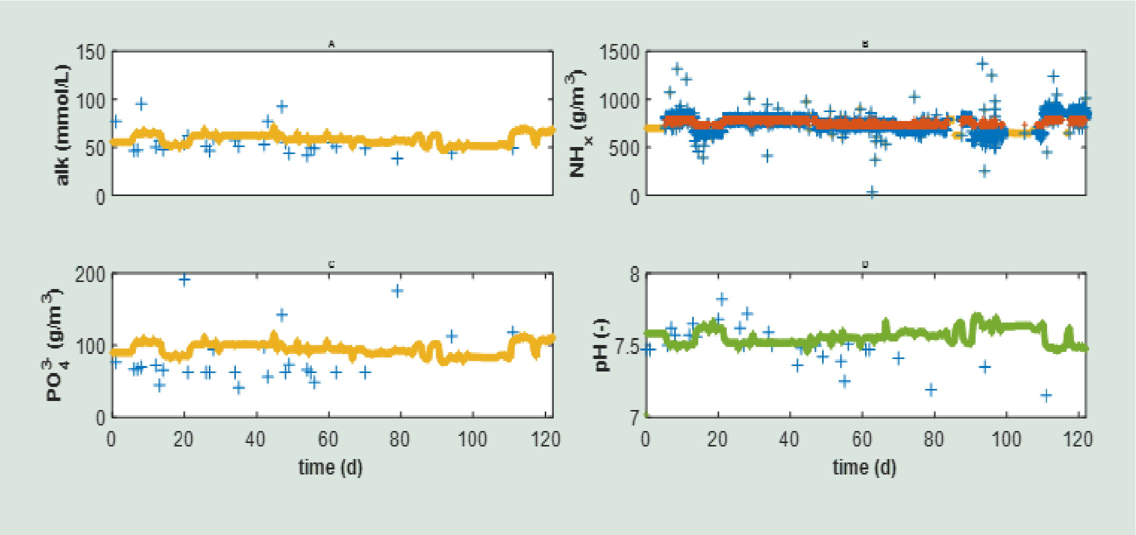


**FIGURE 41.** Plant measurements + (+ blue) and results of data -pretreatment: filtered + (+ red) / extrapolated + (+ yellow) / calculated from estimated ionic composition +.

Using the pre-treated data, simulations demonstrated that the model could accurately reproduce the observed effluent profiles and internal dynamics of the reactor. The model successfully predicted:

- Dissolved oxygen (DO) fluctuations,
- Ammonium ($NH_x$) and nitrite ($NO_2^-$) concentrations,
- $N_2O$ emissions, and
- pH variations.

Snapshots of dynamic simulations (FIGURE 42) show strong alignment between model predictions (solid red lines) and measured data (blue crosses) across different time segments (e.g., days 26.0-26.3, 35.0-35.3, and 47.0-47.3). For further details please see (Flores-Alsina, et al. 2025a).

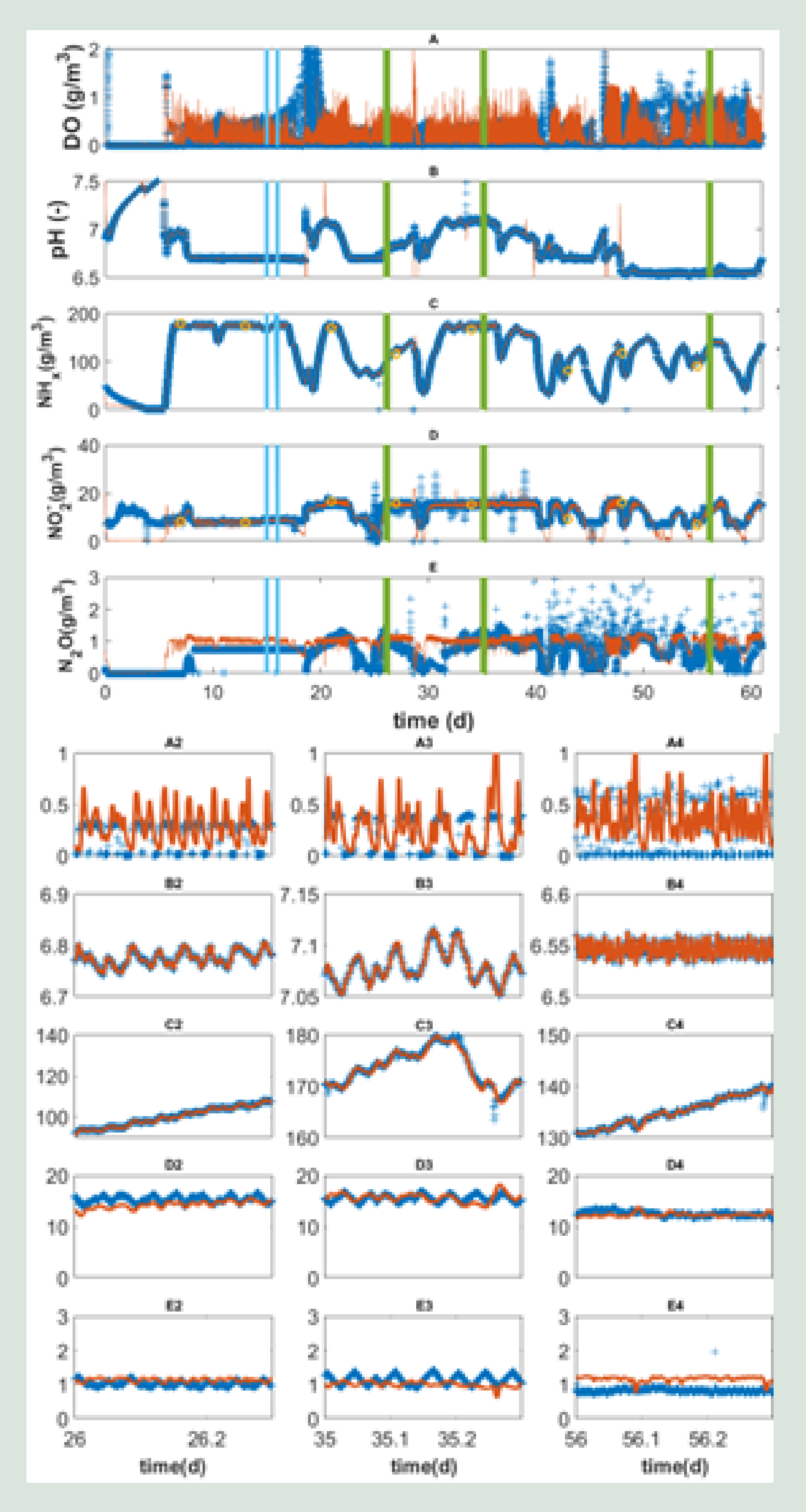


**FIGURE 42.** Three different snapshots showing plant (+) and simulation results (red-solid lines) for #D1. Green lines represent different amplified section of the time series (= snapshots). Snapshot 1= 26.0-26.3, snapshot 2= 35.0-35.3, snapshot 3= 47.0-47.3. Blue lines indicate the part of the time series amplified in FIGURE 45 to compare control strategy performance.

Microscale model outputs revealed that ammonium oxidation occurred predominantly in the outer layers of the granules, while the inner core remained largely inactive due to diffusion limitations. ANX bacteria occupied central regions, while AOB and OHO were mainly located near the surface at low concentrations.

Substrate gradients ($NH_x$ and $NO_2^-$) confirmed ANX activity, with nitrate ($NO_3^-$) being generated in the granule core. $N_2O$ was primarily produced via the AOB nitrifier denitrification (ND) pathway. The conditions were not favourable for the NN pathway due to insufficient DO levels, and the low presence of biodegradable organics and minimal OHO activity indicated negligible contribution from heterotrophic denitrification (DEN). FIGURE 43 visualizes these intra-granular distributions.

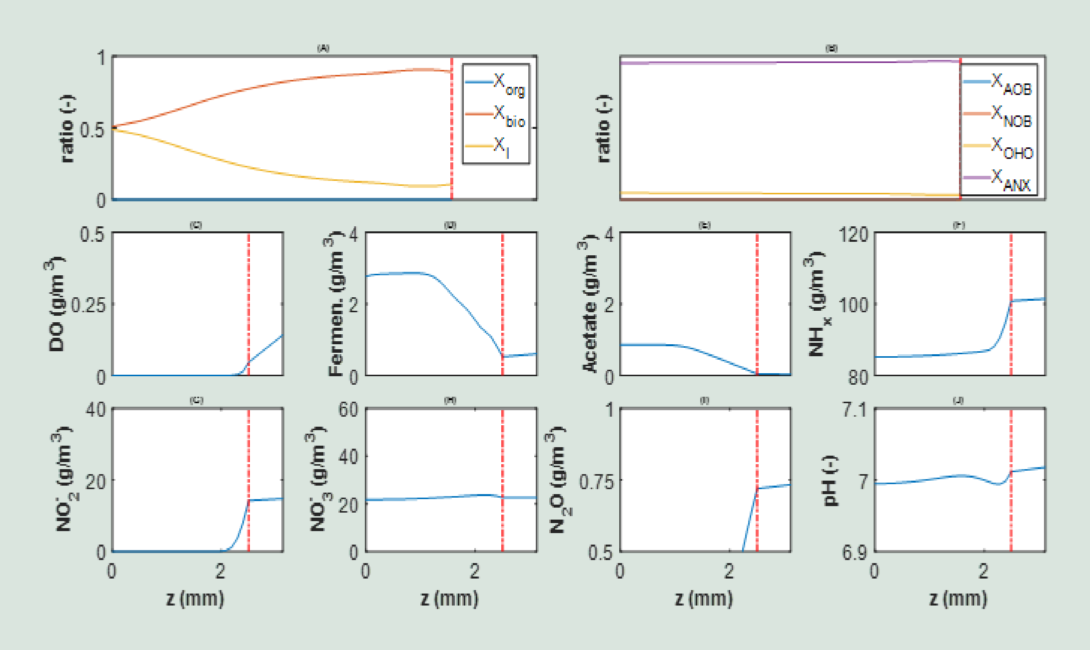


**FIGURE 43.** Intra-granule model prediction of COD distribution, bacterial composition, and gradients (#D1).

To align model outputs with plant data, the maximum granule size parameter (z_max) was increased (>2 mm), reflecting enhanced mass transfer limitations under suboptimal operating conditions. This adjustment improved prediction accuracy for both $NO_2^-$ and $NO_3^-$ dynamics.

The $N_2O$ prediction model achieved satisfactory validation results, with normalized root mean square errors (nRMSE) below 1 for key variables. FIGURE 44 presents input/output nitrogen loads and emission factor calculations for both the calibration and validation periods.

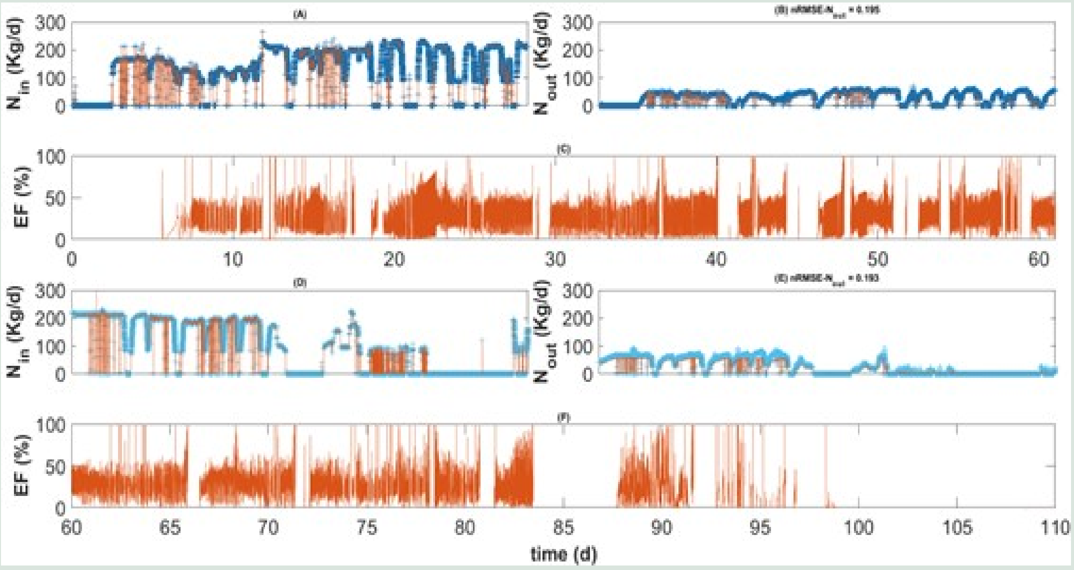


**FIGURE 44.** Input (A, D) and output (B, E) N load. Calibration (A, B) and validation (D, E) plant data sets (+) are represented in dark and light blue respectively. Simulation results (red-solid lines). Emission factors are calculated from the transfer model and based on the N₂O measurements. X-axis units for A and B are the same for C. X-axis units for D and E are the same for F.

Based on the calibrated model, different control scenarios/strategies were tested. This resulted in a control strategy based on $NO_2^-$, which showed the best $N_2O$ reduction potential yielding a reduction of emissions to 25% of the original emission. This control strategy being the most promising is consistent with the observation that ND is the dominant $N_2O$ production pathway.

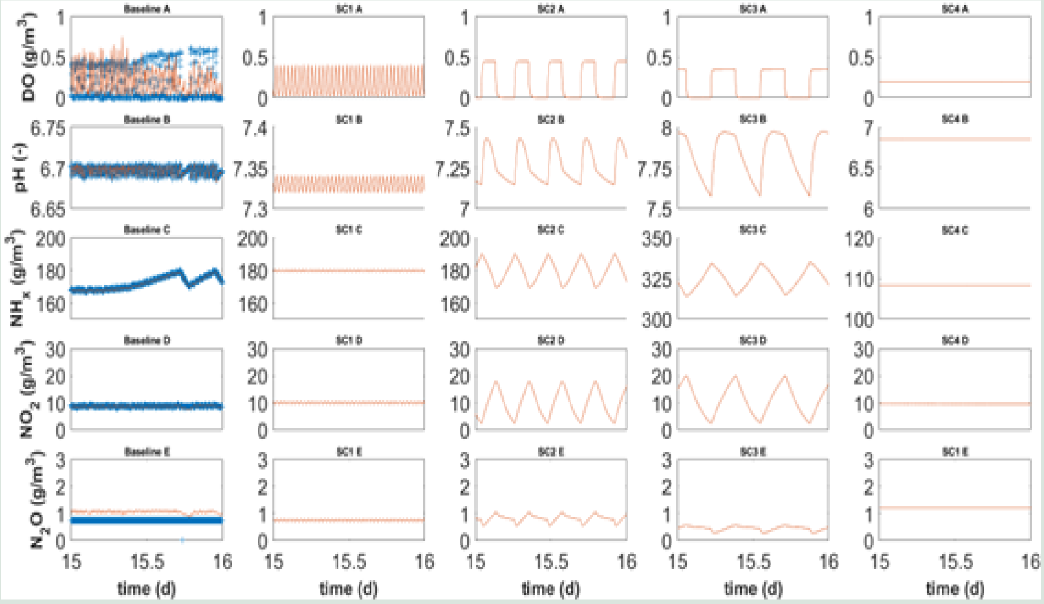


**FIGURE 45.** Snapshots extracted from #D1 showing plant (+) and simulation results (red-solid lines) (column 1) (see FIGURE 3, blue lines). The results of implementing the control strategies summarized in FIGURE 46.

Additional simulations with an improved biomass profile (i.e., lower z_max and higher VSS concentrations) yielded emission factors (EFs) more consistent with literature values for similar systems (see FIGURE 46). Comparative plots show how emission factors correlated with nitrogen loads for different configurations and scenarios.

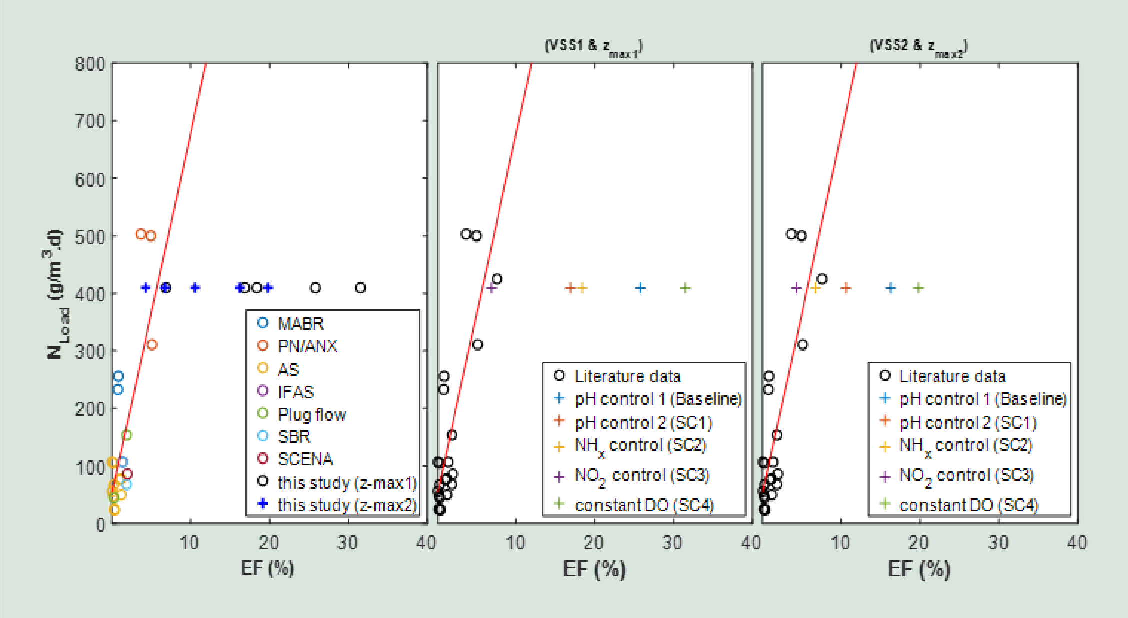


**FIGURE 46.** Comparison of the correlation between emission factors and N load for literature data and the results obtained in this study (column 1 = detailed literature data + results in this study, column 2 = literature data + first set of simulations, column 3 = literature data +second set of simulations).

## 8.3.2 BSM2 case study

**Generation of scenarios**

The second case study aimed to evaluate the plant-wide implications of different reject water (RW) management strategies using the NACAT Holistic Assessment Model (HAM), an extended version of the IWA Benchmark Simulation Model No. 2 (BSM2) (Jeppsson 2013). This study assessed how operational changes, and technological upgrades affect effluent quality, operational costs, and GHG emissions (Flores-Alsina., et al. 2025b).

Four reject water handling strategies were compared through dynamic simulations:

- A0 - Baseline scenario (conventional BSM2 configuration),
- A1 - RW Storage (ST): storing reject water during the day and releasing it at night,
- A2 - PN/ANX Reactor Addition: incorporating a partial nitritation/anammox unit,
- A3 - P Recovery (SPU): integrating a struvite precipitation unit for phosphorus recovery

Results indicate that the RW storage strategy (A1) had a marginal impact, with less than 5% improvement across most key performance indicators (KPIs) relative to the baseline. In contrast, the PN/ANX configuration (A2) significantly improved nitrogen and phosphorus removal, leading to over 10% reduction in effluent total nitrogen (TN) and total phosphorus (TP).

These improvements were primarily due to reduced nitrogen load returning from the sludge line, which benefited PAO activity by limiting $NO_x$ availability and thereby reducing competition from OHO during phosphorus uptake.

However, the PN/ANX scenario also led to substantial increases in $N_2O$ emissions, attributed to high $NO_2^-$ concentrations and low DO levels - conditions favouring the AOB ND pathway. The total carbon footprint (GHGi) nearly doubled compared to the baseline scenario, highlighting a critical trade-off between nutrient removal and GHG emissions.

The P recovery scenario (A3) achieved moderate improvements in effluent quality while keeping operational costs (OCi) and GHG emissions at baseline levels. The recovery of phosphorus as struvite, coupled with minimal chemical consumption (Mg and NaOH), made this an attractive circular economy option.

**TABLE 4.** Calculated KPIs for all evaluated reject water management strategies.

| | **Baseline (A0)** | **BSM2+ ST (A1)** | **BSM2+ PN/ANX (A2)** | **BSM2+ SPU (A3)** | **Units** |
|---|---|---|---|---|---|
| TKN | 5.3 | 5.1 | 3.9 | 5.6 | $g/m^3$ |
| TN | 12.9 | 12.9 | 9.1 | 12.8 | $g/m^3$ |
| TP | 2.9 | 3.2 | 2.3 | 1.4 | $g/m^3$ |
| **EQi** | **12 575.3** | **13 017.8** | **10 063.5** | **9 586.7** | **kg/d** |
| Econsumption | 5638.9 | 5653.7 | 5496.6 | 5545.1 | kW.h/d |
| Eproduction | 5814.2 | 5830.6 | 5781.3 | 5877.7 | kW.h/d |
| BIOdiposal | 3964.2 | 3939.4 | 4025.5 | 3812.1 | kg/d |
| CHEMconsumption (Mg) | 0.0 | 0.0 | 0.0 | 227.8 | kg/d |
| CHEMconsumption (NaOH) | 0.0 | 0.0 | 0.0 | 575 | kg/d |
| CHEMproduction (struvite) | 0.0 | 0.0 | 0.0 | 218.9 | kg/d |
| Bio GHG | 0.68 | 0.68 | 1.50 | 0.68 | $kgCO_{2eq.}/m^3$ |
| Sludge processing GHG | 0.21 | 0.21 | 0.21 | 0.21 | $kgCO_{2eq.}/m^3$ |
| Energy credit GHG | 0.00 | 0.00 | 0.00 | 0.00 | $kgCO_{2eq.}/m^3$ |
| Chemicals GHG | 0.00 | 0.00 | 0.00 | 0.01 | $kgCO_{2eq.}/m^3$ |
| Sludge disposal GHG | 0.20 | 0.20 | 0.15 | 0.20 | $kgCO_{2eq.}/m^3$ |
| **GHGi** | **1.19** | **1.19** | **1.95** | **1.19** | **$kgCO_{2eq.}/m^3$** |

This case study reinforces the importance of using plant-wide models like HAM to explore multi-dimensional trade-offs between effluent quality, operating cost, emissions, and resource recovery.

**Estimation of the produced airflow**

To estimate the airflow required for aeration, the daily oxygen demand for carbon oxidation and nitrification was determined using values generated by the activated sludge model based on influent COD and nitrogen loads.

This oxygen demand was then converted into the amount of oxygen to be supplied by the aeration system, accounting for the effective oxygen transfer efficiency (OTE) under field conditions. An OTE of 25% was assumed to reflect realistic operational conditions. The mass of air needed to deliver this oxygen was estimated using the proportion of oxygen in air and the density of air, allowing the conversion of the oxygen requirement into a daily and hourly volumetric airflow for the treatment process. Gases produced during treatment, including nitrogen, nitrous oxide, nitric oxide, and carbon dioxide, were also considered as they contribute to the total off-gas volume leaving the reactor. Including these components enables a more accurate estimation of total airflow and off-gas management needs (see TABLE 5).

**TABLE 5.** Estimation of the generated airflow**.**

| | **Baseline**<br>**(A0)** | **BSM2+ ST**<br>**(A1)** | **BSM2+ PN/ANX**<br>**(A2)** | **BSM2+ SPU**<br>**(A3)** | **Units** |
|---|---|---|---|---|---|
| Airflow (Mainstream) | 4577.9 | 4591.6 | 4186.1 | 4489.9 | $m^3/h$ |
| Airflow (Sidestream) | | | 347.1 | | $m^3/h$ |

These airflow estimates were subsequently used to calculate the operational costs for treatment and to assess potential greenhouse gas emissions from nitrous oxide abatement, supporting the evaluation of both economic and environmental implications of the generated scenarios within the wastewater treatment plant (see FIGURE 37).

**Assessment of Cost-Effectiveness for Catalytic Treatment Scenarios**

To quantify the potential climate and economic benefits of catalytic off-gas treatment, the BSM2 plant-wide model was used to simulate GHG emissions under different scenarios. Using site-specific emission factors and techno-economic assumptions from Chapter 7, the associated shadow price (750 DKK per ton $CO_2$-equivalent) was calculated for each scenario. TABLE 6 presents a comparative overview of annual GHG reduction, associated investment costs (CAPEX) (see FIGURE 36), and resulting cost-effectiveness metrics. This integrated approach enables prioritization of catalytic treatment options based on both technical potential and economic viability.

**TABLE 6.** Estimation of emissions, calculation of shadow prices and potential saving once applied catalytic treatment.

| | **Baseline**<br>**(A0)** | **BSM2+ ST**<br>**(A1)** | **BSM2+ PN/ANX**<br>**(A2)** | **BSM2+ SPU**<br>**(A3)** | **Units** |
|---|---|---|---|---|---|
| $N_2O$ (Mainstream) | 3945 (13.2) | 3923 (13.1) | 2630 (8.8) | 3967 (13,3) | $kgCO_{2eq.}$/ d ($kg N_2O/d$) |
| $N_2O$ (Sidestream) | | | 17993 (60.3)* | | $kgCO_{2eq.}$/ d ($kg N_2O/d$) |
| **COST (Shadow price)** | **2958** | **2942** | **15475** | **2975** | **DKK/d** |
| COST (abatement) (Mainstream) | 2527 | 2534 | 2310 | 2477 | DKK/d |
| COST (abatement) (sidestream) | | | 416.4 | | DKK/d |
| **New COST (Shadow price + abatement) **** | **2571** | **2578** | **2959** | **2522** | **DKK/d** |
| **Savings (daily)** | 387 | 364 | 12516 | 453 | **DKK/d** |
| **Savings (yearly)** | 141 | 133 | 4569 | 165 | **K DKK/y** |
| $CO_2$ removal cost (main) | 650 | 656 | 892 | 634 | DKK/ t $CO_2$ |
| COST removal cost (sidestream) | | | 24 | | DKK/ t $CO_2$ |

*The model predicts an emission factor of 18 (kg $N_2O$ $_{emitted}$/kg N $_{influent}$). This can drastically be reduced by operating the reactor in a different manner (see Flores-Alsina et al., 2025)
** New costs (DKK/d) were calculated as daily abatement cost + reduced $CO_2$eq (kg/d), assuming 98.5% catalytic efficiency.

The techno-economic assessment of catalytic off-gas treatment integrated into the BSM2 plant-wide model highlights the importance of targeted application in areas with high emission potential. TABLE 6 presents a comparison of annual greenhouse gas (GHG) abatement and associated cost-effectiveness across different configurations: mainstream, sidestream, and combined configurations

The results confirm that sidestream applications offer the most cost-effective solution, with an abatement cost of approximately 24 DKK/t$CO_2$-eq. This value is obtained by dividing the daily abatement cost of 416 DKK/d (TABLE 6) by the avoided $N_2O$ emissions of 17,7 t$CO_2$-eq/d (calculated as 0,985 × 17.993 kg$CO_2$eq/d ÷ 1000). The cost-effectiveness is driven by the high $N_2O$ concentration in the sidestream and the relatively low airflow requirements, which reduce the operational burden of catalytic treatment.

In contrast, catalytic treatment of the mainstream line results in substantially higher costs, ranging from 634 to 892 DKK/t$CO_2$-eq depending on the configuration (A0, A1, A2, A3). These values are obtained by dividing the daily abatement costs of 2.310–2.534 DKK/d by the avoided $N_2O$ emissions of 2,6–3,9 t$CO_2$-eq/d (TABLE 6). The high abatement cost is explained by the much larger gas volumes to be treated (TABLE 5), which increase the heating and handling requirements. Furthermore, mainstream treatment scenarios are associated with higher capital expenditures (approx. 4 M DKK, see FIGURE 36), which would further increase the cost per ton if included.

From a strategic standpoint, the findings suggest that deployment of catalytic systems should prioritize sidestreams with elevated $N_2O$ levels and limited airflow, such as sidestream treatment processes. Such targeted implementation ensures higher returns on investment, reduced operational complexity, and alignment with emerging regulatory and carbon pricing framework.

### 8.3.3 Other case studies

Beyond the two main cases of Ejby Mølle and BSM, the NACAT tools were also applied to additional case studies to further evaluate their robustness and transferability across different wastewater treatment configurations. These applications demonstrated the versatility of the NACAT modelling framework in capturing both long-term and high-frequency process dynamics, including $N_2O$ emissions, in real-world scenarios. The other case studies are the mainstream treatment at HCR Syd, which is an integrated part of the NACAT project and the Novonesis Industrial WWTP, which was investigated in parallel and therefore included in this final report.

**HCR Syd (Mainstream application)**

At HCR Syd, the NACAT models were deployed to simulate system-wide behaviour across multiple treatment units. The model accurately reproduced key operational variables at different process stages, including:

- Influent flow rate (Q),
- Ammonium ($NH_x$), nitrite and nitrate ($NO_x$),
- Orthophosphate ($PO_4^{3-}$),
- Total suspended solids (TSS).

FIGURE 47 illustrates the predicted profiles across critical locations: after primary clarification, anoxic and aerobic reactors, and final effluent. The model's ability to reflect spatial variability in nutrient concentrations and flow dynamics supports its use for full-plant diagnostics and process optimization.

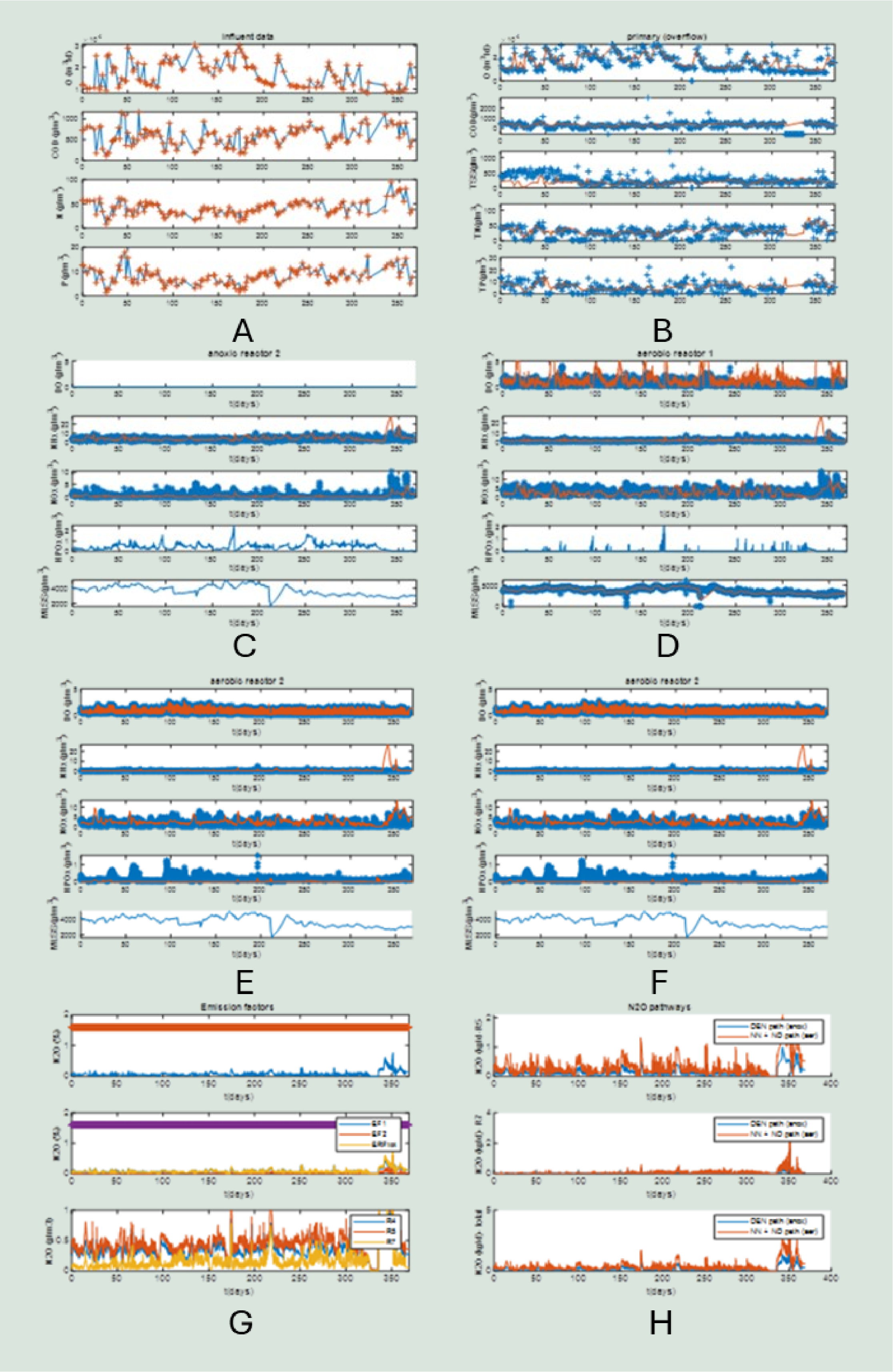


**FIGURE 47.** Plant and predicted dynamic profiles at different plant locations: (A) influent flowrate, (B) after the primary, (C) anoxic reactor 2, (D) aerobic reactor 1, (E) aerobic reactor 2, (F) anoxic reactor 2, (E) effluent, (G) emission factors, and (H) identified pathways.

**Novonesis industrial WWTP (Kalundborg, Denmark)**

Although not originally included in the NACAT project proposal, the model was successfully implemented at the Novonesis industrial WWTP in Kalundborg. This facility treats complex industrial streams with varying organic loads and nitrogen content (Lei 2025).

Despite the challenging wastewater matrix, the model achieved high prediction accuracy for:

- Ammonium, nitrite, and nitrate concentrations
- Dissolved oxygen and airflow rates
- $N_2O$ concentrations in both the liquid and gas phases

FIGURE 48 shows the alignment between model outputs (blue solid lines) and on-line sensor measurements (black crosses) for dataset D2 under baseline operating conditions. The model could capture both short-term dynamics (minutes to hours) and longer-term operational trends (days to weeks), making it suitable for both process control tuning and emission factor estimation.

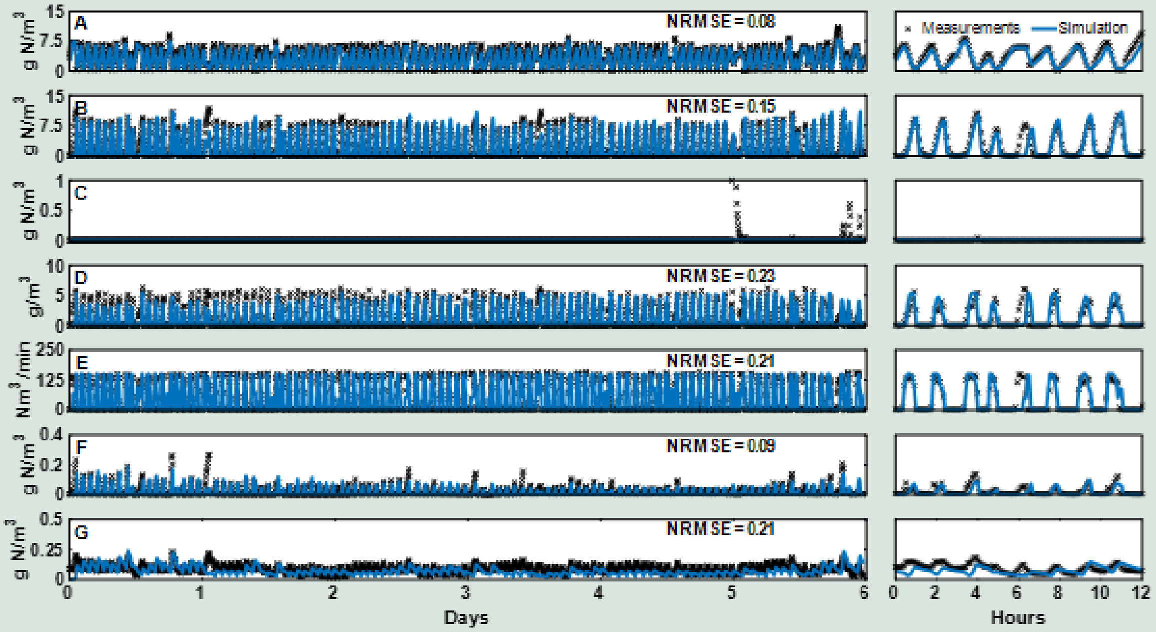


**FIGURE 48.** High resolution dynamic model prediction (blue solid lines) and on-line sensor measurement data (black crosses) comparison with A: NHx, B: $NO_2^-$, C: $NO_3^-$, D: DO, E: Airflow, F: Dissolved $N_2O$ concentration G: Gas $N_2O$ concentration in #D2 Baseline.

## 8.4 Discussion

The results from this work package underscore the strength of combining mechanistic modelling, high-resolution data processing, and plant-wide assessment to evaluate GHG emissions, specifically $N_2O$, from WWTPs. Through the development of the NACAT Activated Sludge Model (ASM) and the Holistic Assessment Model (HAM), the project demonstrated the feasibility and relevance of using digital twins as tools for emission forecasting, operational control, and environmental performance evaluation.

At the process level, the Ejby Mølle case study revealed how granule structure and operational conditions govern microbial stratification and substrate gradients, directly affecting $N_2O$ pathway activity. The ability to identify dominant pathways (ND > DEN > NN) under dynamic conditions validated the model's biological realism and its utility for scenario testing. Importantly, these insights would be difficult to obtain without such an integrated approach, as conventional monitoring cannot resolve microscale gradients or mechanistic bottlenecks.

At the plant-wide level, the BSM2 simulations highlighted the limitations of conventional reject water management (e.g., storage) in reducing N loads or emissions. In contrast, technological interventions such as PN/ANX and P recovery showed clear environmental benefits but introduced trade-offs. For example, while the PN/ANX unit significantly reduced effluent N concentrations and improved effluent quality indices (EQi), it also increased $N_2O$ emissions, negatively impacting the GHG index (GHGi). Conversely, the struvite precipitation unit offered a more balanced profile across cost, effluent quality, and emissions.

The integration of catalytic off-gas treatment into the BSM2 framework provided a quantitative basis to assess its environmental and economic implications. Simulation-based calculations, in combination with techno-economic data from pilot trials, demonstrated that sidestream applications (sidestream line) can achieve greenhouse gas (GHG) abatement at a significantly lower cost (~24 DKK/t $CO_2$-eq) compared to mainstream line treatment (~634 - 892 DKK/t $CO_2$-eq). This difference is primarily due to higher $N_2O$ concentrations and lower airflow requirements in the sidestream. While the main line high operational and capital costs reduce its cost-effectiveness. These findings highlight the value of combining dynamic modelling with site-specific techno-economic indicators to support evidence-based investment decisions in climate mitigation technologies

Additional applications at HCR Syd and Novonesis confirmed that the NACAT tools are transferable to other full-scale systems, including industrial wastewater treatment. These case studies demonstrated accurate prediction of N species, dissolved oxygen, and $N_2O$ concentrations across varying timescales and operational modes. They also highlighted the importance of model-driven pathway attribution to support control strategies and design upgrades tailored to specific emission sources.

Overall, this work pack illustrates how digital modelling, and holistic assessment can bridge the gap between empirical monitoring and actionable insight - enabling proactive, cost-effective, and climate-aligned decision-making in WWTPs.

## 8.5 Conclusions

- A digital twin approach combining mechanistic and hybrid models enables accurate prediction of $N_2O$ emissions under real operational conditions.
- Data pre-treatment (e.g., filtering, interpolation, pH correction) is essential for reducing noise, filling gaps, and enabling high-quality simulation inputs.
- In granular sludge systems, granule size and mass transfer limitations significantly affect the distribution of microbial populations and associated $N_2O$ pathways.
- The nitrifier denitrification (ND) pathway was the dominant $N_2O$ source under low-DO, high-$NO_2^-$ conditions, while the NN pathway remained negligible.
- Model-based identification of pathway-specific emissions enables targeted mitigation strategies beyond trial-and-error plant optimization.
- The NACAT modelling tools are adaptable to various WWTP configurations, including industrial systems, supporting both long-term planning and real-time control.
- Holistic assessment of cost, effluent quality, and emissions supports multi-objective decision-making under future regulatory and carbon taxation scenarios.
- In the BSM2 framework catalytic off-gas treatment is most cost-effective when applied to sidestreams with high $N_2O$ concentrations and low airflow volumes, achieving abatement costs below 24 DKK/t $CO_2$-eq.

- In the BSM2 framework mainstream treatment provides higher GHG reductions in absolute terms, but with significantly higher costs per ton abated, limiting its practical viability under current economic conditions.
- Dynamic simulation combined with techno-economic modelling enables robust evaluation of emission control strategies, allowing utilities to prioritize investments where climate and financial benefits align best
- This work has contributed a validated, open-access modelling framework that can be used by utilities, researchers, and regulators to reduce the climate impact of wastewater treatment.

# 9. Final conclusions

Several conclusions have been reached throughout the duration of the NACAT project, the main conclusions are summarized in this section.

Proof of concept of catalytic process implementation and $N_2O$ abatement results:

- Catalytic treatment is demonstrated in pilot-scale for both mainstream activated sludge and sidestream deammonification processes with a 60-80% conversion.
- An increase in TRL (technology readiness level) from 5 to 7 have therefore be obtained.
- A deactivation of the catalyst was observed yielding valuable input to full-scale design of catalyst for a specific conversion efficiency.
- Catalyst inhibition was observed, concluding that a sulphur guard is necessary and correct pipe design to avoid condensation is essential.
- Beside conversion of $N_2O$ in the catalytic process, conversion of $CH_4$ was also observed with a 20-55% conversion. This can be an advantage in some cases since $CH_4$ is also a GHG, however the conversion of $CH_4$ might lower the capacity to treat $N_2O$ in the off-gas.
- No $N_2O$ abatement is observed in existing the biological odour removing filters or in activated carbon odour removing filters.

Commercialization and $CO_2$ shadow price calculation results are summarized below.
Several business cases were made based on the three test sites to assess the economic feasibility of catalytic treatment implementation on off-gasses from WWTPs. These gave the following findings:

- Two out of the five scenarios result in a positive business case considering a value of 750 DKK/ton $CO_{2,eq}$. Interestingly, the two positive cases were one mainstream application and one sidestream application. Among the negative business cases were also both mainstream and sidestream applications.
- The $CO_{2,eq}$ shadow price varied between 400 and 4,500 DKK/ton $CO_2$ for the assessed business case scenarios.
- The main factor impacting the business case was the $N_2O$ concentration to be treated in the off-gas, which indicates that an economic assessment should be made on a case-by-case level, since $N_2O$ emissions vary greatly from site to site, highlighting the importance of $N_2O$ measurements and baseline generation.
- CAPEX was the major contributor to the cost estimate.
- Heat and sulphur guard were the main contributors to the OPEX.

Modelling development results:

- A digital twin approach combining mechanistic and hybrid models enables accurate prediction of $N_2O$ emissions under real operational conditions.
- The modelling tool made in the NACAT project has shown to be applicable for various WWTP’s tested in this project. The modelling tool is an open-access tool utilities can use to reduce the climate impact of processes.
- The nitrifier denitrification (ND) pathway was the dominant $N_2O$ source under low-DO, high-$NO_2^-$ conditions, while the NN pathway remained negligible.
- Simulations of catalytic treatment in the BSM2 framework indicated that it is a cost-effective technology for sidestreams with high emissions and less cost-effective when applied to not high emitting mainstreams. This is in line with the conclusions in the economic assessment, where the site-specific $N_2O$ emission is decisive for the business case outcome.

# 10. Perspectives

**Role of catalytic destruction in $N_2O$ mitigation**

In this project, treatment of off-gas from various covered biological process tanks were investigated – mainly by a catalytic process, but also by existing odor removing filters. The role of catalytic treatment should be seen in context with other potential $N_2O$ mitigation strategies. In an overview of possible strategies made by (Lake, Vellacott og Ye 2024). seen in FIGURE 49, it is apparent that avoiding and reducing $N_2O$ emissions, if possible, should come prior to removing $N_2O$. Assessment of the economic and environmental cost of various mitigation strategies should be the deciding factor on most suitable mitigation strategy. The project partners agree on this approach.

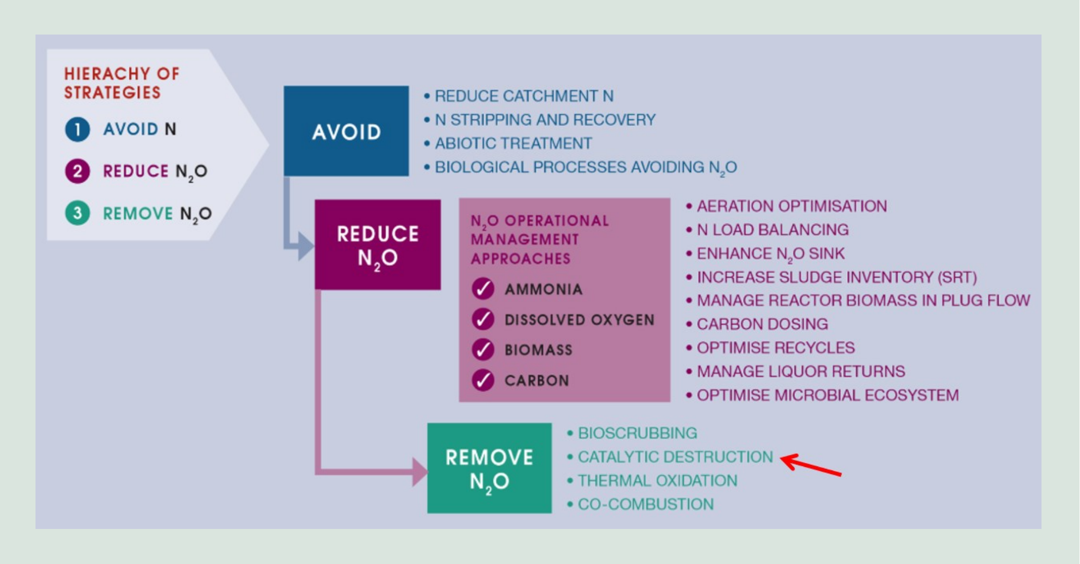


**FIGURE 49.** Potential mitigation measures. Red arrow indicating catalytic destruction. From **(Lake, Vellacott og Ye 2024)**.

Several of the reduction mitigation measures cover implementing or extension of advanced online control at WWTPs, which in comparison to building physical installations often require less investments. The modelling results in this project support that mitigation strategies by adjustment of control strategy is, in some cases, possible without affecting other operational objectives (effluent quality and operational costs) significantly.

However, for WWTPs operating close to or above their treatment capacity, there might not be operational range to achieve reduction of $N_2O$ and an extension of the process capacity by new tank volumes could be required. In these situations, end-of-pipe removal technologies might prove an attractive alternative to $N_2O$ mitigation. In this project, this observation is supported by the positive business case for Tårnby, which operates close to its capacity limit. This further underlines the need to identify $N_2O$ hotspots, as emissions vary greatly from site to site, but might often occur in places where high-rate nitrogen conversion takes place.

Alternative end-of-pipe $N_2O$ removing technologies include thermal destruction and dedicated biological conversion. Of these, thermal destruction is beginning to be implemented at industrial chemical production sites as well as sludge incineration facilities. Pure thermal destruction has a higher energy demand than catalytic treatment, which on the other hand consumes catalytic material. Depending on availability of local energy sources one technology might be more favourable than the other. Dedicated biological conversion remains to be demonstrated in bigger scale and removal efficiencies can prove challenging.

**Drivers for mitigation**

As the business case in this project is built around an assumption that $CO_{2,eq}$ reduction has a value corresponding to the taxes that have been implemented in Danish production industry, it is essential that a similar taxation is put into force for this type of technology to be implemented in full-scale.

The $CO_2$ shadow price for implementation at a given site, compared to a possible taxation of $CO_{2,eq}$ emission will decide whether mitigation is relevant at a given site and which mitigation strategy is the most attractive. The lowest shadow price found in the project was approx. 400 DKK/ton $CO_{2,eq}$, which is in the same range as shadow prices reported in the ARES project looking into $N_2O$ reduction by control (Miljøstyrelsen 2024a), a bit higher than the ones found by simple operational changes in the VARGA project (Miljøstyrelsen 2023) and within the wide range reported in the recent MST report looking into possibilities for regulatory methods to reduce $N_2O$ emissions from WWTPs (Miljøstyrelsen 2024b).

Alternatively, legislation setting limits for $N_2O$ emissions could be driving the implementation. The final formulation of the legal framework on this is underway in Denmark and will be decisive for how mitigation technologies will be implemented.

From the business case assessment, high emission scenarios result in a positive business case, whereas low/normal emission cases result in negative business cases, which might lead to promoting higher emissions from process tanks as a starting point, which is conflicting with ensuring a reduction of GHG to the atmosphere.

**Further investigations**

Future further investigations after the finalisation of this project could cover a complete assessment of the embodied carbon in the construction of a full-scale catalytic treatment plant as well as considering the $CO_{2,eq}$ cost of sulphur guard and catalyst replacement, which is needed to keep an efficient process running.

A possible future optimization of the catalytic treatment itself could include aeration of gas recirculation, as the off-gas treated in the catalytic unit still has a very high oxygen concentration. The gas can only be recirculated to a certain extent, leading to a bleed flow being extracted and fresh air in the same quantity added. Assuming a recirculation of around four times would, from a catalytic treatment point of view, have an enormous advantage, since the flow to be treated would be reduced to ¼, leading to a much smaller design. This reduces CAPEX, but also OPEX are reduced as blower and heater consumption will decrease which will lead to an improvement of the currently prepared business case.

# 11. Dissemination

Results from the project has been presented at relevant conferences around the world and furthermore led to four publications, all showed in TABLE 7.

**TABLE 7.** Dissemination list for NACAT.

| Conference/Journal | Title | Author |
|---|---|---|
| IWA WWC&E 2022 | $N_2O$ abatement from WWTPs by catalytic treatment | Hillerød Forsyning |
| Dansk Vand conference 2022 | $N_2O$ Abatement from WWTPs by Catalytic Treatment - NACAT | VCS |
| Nordiwa 2023 | Reducing emissions by catalytic treatment of $N_2O$ – the NACAT project | Envidan |
| Water Valley Denmark Workshop 2023 | Klimaopgørelser og -reduktioner '- overblik over initiativer i vandsektoren | Envidan |
| IWA WWC&E 2024 | Reducing emissions by catalytic treatment of $N_2O$ – the NACAT project | Envidan |
| Dansk Vand conference 2024 | NACAT – skal vi bare polere $N_2O$ væk? | Envidan |
| IWA Large WWTPs 2024 | Abatement of $N_2O$ in exhaust gas from full-scale WWTPs | VCS |
| IWA NRR24 | Holistic assessment of management strategies and technological solutions handling reject water. | DTU |
| IWA NRR24 | Quantifying, predicting, and mitigating nitrous oxide emissions in a full-scale partial nitration/anammox reactor treating reject water. | DTU |
| IWA ICA25 | Assessing control concepts in a full-scale partial nitration-anammox aerobic granular sludge reactor treating reject water | DTU |
| Nordiwa 2025 | Should we polish for $N_2O$ instead of reducing it in the biological treatment? Catalytic Reduction of $N_2O$ (NACAT) | Envidan |
| Water Research 2025 | Quantifying, predicting, and mitigating nitrous oxide emissions in a full-scale partial nitritation/anammox reactor treating reject water | DTU |
| Chemical Engineering Journal | Holistic assessment of management strategies and technological solutions handling anaerobic digester supernatants in wastewater treatment plants | DTU |
| Water Research | A plant-wide model describing GHG emissions and nutrient recovery options for water resource recovery facilities | DTU |
| Water Research | Dynamically predicting nitrous oxide emissions in a full-scale industrial activated sludge reactor under multiple aeration patterns and COD/N ratios. | DTU |

Beside conferences and publications an open house event was held at Ejby Mølle 27th of November 2023 for everyone who was interested to come and see the technology and learn more about the catalysator used at the NACAT project.

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**NACAT**
**N2O Abatement by Catalytic Treatment**
**MUDP-project**

The purpose of the N2O Abatement by Catalytic Treatment (NACAT) project is to demonstrate the potential for catalytic treatment of N2O from wastewater treat-ment plants (WWTP) to reduce greenhouse gas (GHG) emissions.

In the project, a pilot plant containing an adsorption guard, blower, and reactor with the catalyst was tested at three Danish WWTPs - on two mainstream off-gas streams and two side-stream deammonification off-gas streams.

The project shows good results for catalytic treatment of N2O, but the economic feasibility of the technology has to be assessed at a case-by-case level and seems to demand high emissions of N2O. Modelling efforts with a digital twin approach showed good results in predicting N2O emissions.

The Danish Environmental
Protection Agency
Lerchesgade 35
DK - 5000 Odense C

**www.mst.dk**