



Project No 327341, ACT 3 – Accelerating CCS Technologies

# SCOPE

Sustainable OPEration of post-combustion  
Capture plants (SCOPE)

Final report (D5.4)

01.10.2021-31.12.2024


Acknowledgement: This project is funded through the ACT programme (Accelerating CCS Technologies, Horizon2020 Project No 691712). Financial contributions made by the Research Council of Norway (RCN), Rijksdienst voor Ondernemend Nederland (RVO), Department for Business, Energy & Industrial Strategy UK (BEIS), Forschungszentrum Jülich GmbH, Projektträger Jülich (FZJ/PtJ) Germany, Department of Energy (DoE) USA and Department of Science and Technology (DST) India are gratefully acknowledged.

Written by:	Hanne Kvamsdal (SINTEF) (Coordinator and WP5-leader), Peter van Os (TNO) (WP1-leader), Peter Moser (RWE) (WP2-leader), Anna Korre (Imperial) (WP3-leader), + some input from all other partners	Date: 03.01.2026
Checked by:	Initial version checked by Andreas Grimstvedt (SINTEF)	Date: 28.02.2025
Issue date:	03.01.2026	



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Version	Authors	Partner	Date	Status
1	WP-leaders	SINTEF, TNO, RWE, IMPERIAL	22.01	Draft
2	Hanne Kvamsdal, Karl Anders Hoff	SINTEF	27.01	Still missing some input
3	WP-leaders + others	All	03.02.2025	Still missing some input
4	Hanne Kvamsdal + some input from others	SINTEF	28.02.2025	Still missing some input, especially on WP3
5	Anna Korre	Imperial	03.01.2026	Completed WP3 input and additional tables, updated financial information

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## 1 Identification of the project and report

Project title	SCOPE: Sustainable OPERATION of post-combustion Capture plants
Project ID	327341
Coordinator	Hanne Marie Kvamsdal (SINTEF IND)
Project website	www.scope-act.org
Reporting period	01.10.2021-31.12.2024

### Participants

Organisation	Main contact(s) + E- mail	Role in the project
SINTEF Industry (SINTEF IND)	Hanne M. Kvamsdal, Hanne.Kvamsdal@sintef.no	Coordinator
SINTEF Ocean (SINTEF OC)	Bjørn Henrik Hansen, BjornHenrik.Hansen@sintef.no	Researcher involved in WP3
NORGES TEKNISK-NATURVITENSKAPELIGE UNIVERSITET (NTNU)	Hanna Knuutila, Hanna.Knuutila@ntnu.no	Researcher involved in WP1
NEDERLANDSE ORGANISATIE VOOR TOEGEPAST NATUURWETENSCHAPPELIJK ONDERZOEK (TNO)	Peter van Os, peter.vanos@tno.nl	WP1-Leader and national project contact person for the Dutch partners
Imperial College (IMPERIAL)	Anna Korre, a.korre@imperial.ac.uk	WP3-Leader and national project contact person for the UK partners
RWE Power Aktiengesellschaft (RWE)	Peter Moser, Peter.Moser@rwe.com	WP2-Leader and national project contact person for German partners



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TotalEnergies EP Norge AS (TEPN)	Stephane Jouenne, stephane.jouenne@totalenergies.com	Researcher and industrial representative in WP1, 3 and 4
University of Sussex (SPRU)	Abigail Martin, abigail.martin@sussex.ac.uk	Researcher and WP4-Leader until 31.05.2024
Heriot-Watt University (HWU)	Susana Garcia, s.garcia@hw.ac.uk	Researcher involved in WP1, 2, and 4
Norsk institutt for luftforskning (NILU)	Maria Dusinska, mdu@nilu.no	Researcher involved in WP3
Technology Centre Mongstad (TCM)	Kotewara Putta, koteswara.putta@tcmda.com	Industrial representative in WP1, 2, 3 and 4
Herøya Industripark (HIP)	Christian Brekken, christian.brekken@sintef.no	Industrial representative in WP1, 3 and 4
Hovyu (Hovyu)	Diego Pinto, diego.pinto@hovyu.com	Researcher in WP1 and 4
Twence B.V. (Twence)	Mathijs Vos, m.vos@twence.nl	Industrial representative in WP2 and 4
HVC energie en hergebruik (HVC)	Jan Peter Born, j.born@hvcgroep.nl	Industrial representative in WP2 and 4
Linde GmbH, Linde Engineering (Linde)	Torsten Stoffregen, torsten.stoffregen@linde.com	Industrial representative in WP2 and 4
OGT Simulation Software (OGT)	Jeff Weinfeld, jeff.weinfeld@ogtrt.com	Researcher involved in WP1
Guru Gobind Singh Indraprastha University (GGS IPU)	Professor N.C. Gupta, ncgupta@ipu.ac.in	Researcher involved in WP1, 2, 3, and 4 and national project contact for the Indian partners
National Energy Technology Laboratory (NETL)	Michael S. Matuszewski, Michael.Matuszewski@netl.doe.gov	Researcher involved in WP1 and national project contact for the American partners



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Environment Agency (EA)	Mark Bourn, mark.bourn@environment-agency.gov.uk	Researcher involved in WP3 and 4
Indian Institute of Technology Kharagpur (IITKGP)	Aditya Kumar Patra, akpatra@mining.iitkgp.ac.in	Researcher involved in WP1, 2, 3, and 4
Microfilt India Pvt. Ltd. (MIPL)	Purvil Khakharia, dr.purvil@microfiltindia.com	Researcher involved in WP1, 2, 3, and 4
Cambridge Environmental Research Consultants Ltd. (CERC)	David Carruthers, david.carruthers@cerc.co.uk	Researcher involved in WP3
Aker Carbon Capture (ACC) Now slb Capturi (slbc)	Ricardo Wanderley, ricardo.wanderley@akercarboncapture.com	Researcher and industrial representative in WP1, 3 and 4


## 2 Executive summary

### 2.1 Main achievements for each WP

#### 2.1.1 WP1 Effective emissions management tools for large scale deployment

- Vapour Liquid equilibrium experimental data from loaded amines at water wash concentrations made available to the consortium for validation of models. This was an important step in the start of the project to inform partners working on the models (to make them better) and for the partners performing measurement campaigns (to better understand and interpret the data).
- ACEMS emission monitoring instrument upgraded and framework for techno-economic assessment of different emissions mitigation strategies for a range of industries agreed upon. Also, this work was done in the first part of the project. It paved the way to demonstration at Tiller and, at the very end of the project, at RWE.
- An Aerosol model was made and validated with data from RWE, HVC and Twence. This was pioneering work (such models didn't exist). The model performed quite well with the data from WP2 which will help us to better understand aerosol emissions, how they behave and how they can be mitigated.
- The CESAR1 VLE model in ProTreat has been upgraded using data from the TCM and RWE campaigns. This will increase the accuracy and quality of the process simulations in the commercial ProTreat software package which will become available to the users of ProTreat.
- There has also been work on the ASPEN+ CESAR1 model using validation data from TCM and RWE.

In Work Package 1 also the techno-economical framework was developed that was used in the project. This is an extensive piece of work that took a couple of years and many meetings to discuss the boundary

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conditions, assumptions used and the cost models. When used properly it is very valuable to compare different process solutions. The framework will be made public. It can be a good successor of the EBTF (European Benchmark Technology Framework) that was developed in the past and referenced a lot in TEA work.

Several use cases were analysed in work package 1 using the TEA framework. The overall conclusion is that emissions can be mitigated at costs that are below 5% compared to the base case (single WW) - if we exclude the WtE with BDU case. Refinery and power plant showed increases up to 3 €/tCO<sub>2</sub>. The WtE case varied a little more: from 5 to 10 €/tCO<sub>2</sub> increase (with BDU + double WW being responsible for the highest cost). This means that there are no technical showstoppers that block the large-scale implementation of CO<sub>2</sub> capture plants.

In WP1 the “Recommendations for Emission Control” was written. One of the most important public deliverables in the project, since it brings together the results of project in a comprehensive set of recommendation for the world to use.

### 2.1.2 WP2 Demonstration of emission management technologies at capture pilot plants

- Testing campaigns at four different sites with different use cases have been carried out using four different solvents (TWENCE at Hengelo, Waste-to Energy, MEA and CDRMax; RWE at Niederaussem, lignite-fired power plant, CESAR1; HVC at Alkmaar, Waste-to-Energy, MDEA/PZ; SINTEF at Tiller, CESAR1) to investigate the emission behaviour of the capture plant and to evaluate the performance of a wide range of mitigation systems for volatile and aerosol-based emissions, comprising water wash (benchmark), double water wash, acid wash, dry bed, Brownian demister two different flue gas pre-treatment technologies, wet electrostatic precipitator, and lean loading tuning.
- The effects of solvent aging (after 1,000, 5,000 and 28,000 operating hours), elevated oxygen content in the flue gas (5-16%), elevated CO<sub>2</sub> capture rates up (90-98%) and of elevated solvent regeneration temperatures (130°C) on the emissions have been investigated.
- Comprehensive sets of capture plant operating data (comprising not only stationary plant operation to provide high quality data for different plant configurations, but real-world operation, load changes and start-stop tests) and solvent analyses as well as samples from the campaigns (comprising samples using ACEMS, aged solvent, water wash liquid, droplets between water wash and demister) have been provided to WP1 for laboratory experiments and further optimisation and validation of simulation tools, for the techno-economic analysis of the most promising emission mitigation technologies and to WP3 for the simulations of the distribution of emitted components and analysis of the environmental impact
- Liquid CO<sub>2</sub> has been analysed by TWENCE using a CARBOSCAN system to confirm the compliance with EIGA specification of the CO<sub>2</sub> from the amine-based capture process and by RWE ordering an external laboratory to quantify the amine concentrations.

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### 2.1.3 WP3: Environmental quality standards, impacts and risk assessment


- Reviewed internationally approved criteria for defining persistence, bioaccumulation and ecotoxicity of chemicals and used them to classify amines, solvents, and their degradation products.
- Reviewed the impact of various amines on micro- and macro-organisms and their potential biodegradability in the ecosystem (freshwater and marine water fish, aquatic invertebrates, algae, cyanobacteria, bacteria, and terrestrial plants in terms of acute and chronic toxicity effects).
- Provided a comprehensive review of occupational health and safety issues, associated with exposure to amines and their by-products, focused on acute and chronic airborne and drinking water exposure and human health risk assessment.
- Updated the amine chemistry module within the ADMS Gaussian-type plume dispersion model to model multiple sources and multiple amines within the same setup, also incorporated additional effects into the amine chemistry module, including accounting for the uptake of amines into liquid water droplets present within the plume.
- Developed a methodology for human health risk assessment from PCC emissions, integrating a detailed air dispersion modelling process to estimate ground level amine degradation product concentrations and a location specific human health risk assessment process, considering the human chronic residential and occupational exposure to the substances via the inhalation pathway.
- Implemented the integrated emissions dispersion and human health risk assessment methodology developed in region specific case studies in the UK, Norway, Germany and the Netherlands.
- Based on method development, hazard and risk assessment testing and case studies, proposals for environmental and health standards for emissions have been made.

### 2.1.4 WP4: Mapping state support, market readiness and civil society concerns to promote the legitimacy of amine-based CCUS

- Completed study on state promotion of amine-based CCS, including analysis of historical trajectory of industrial policy and regulations up to present day, in the UK, Netherlands, Germany, Norway, and India.
- Mapped CCS value chains to analyse chain structure, key components & configurations impacting value creation & risk management
- Preliminary results of a study on investigating public support for CCS/CCUS/amine-based capture in UK.
- Arranged 6 meetings of the Stakeholder, Policy, Research & Industry Network (SPRINT) to transfer SCOPE knowledge and with key stakeholders (of which one webinar).

### 2.1.5 WP5: Project management, dissemination, and exploitation


- Established Consortium Agreement with 24 partners from six countries and three continents.

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- Organised 7 project meetings at various locations in Europe hosted by some of the partners and 20 meetings (by TEAMS) in the Project Management team.
- Established project website (<https://www.scope-act.org/>) and social media accounts (Twitter and LinkedIn) and posted news about events, public deliverables and publications.
- Four journal publications, ten conference papers, 26 presentations at conferences and workshops, and arrangement of 6 dissemination events (SPRINT events).

## 2.2 Main outcomes from the project

- There have been numerous advances in terms of model validation and improved input data, including:
  - (i) validation of the model of a solvent-based carbon capture process in Aspen Plus for improved prediction of solvent-based amine emissions to enable better design of emission mitigation strategies;
  - (ii) important improvements to monitoring equipment (ACEMS),
  - (iii) demonstration of key variables such as: the effect of WESPs as a contributor to aerosol-based emissions for different flue gases and solvents; the mitigating effect of BDU, dry bed and flue gas pre-treatment (turbulent pre-scrubber) on aerosol-based emissions; the mitigating effect of dry bed, acid wash, and double water wash on volatile emissions and,
  - (iv) confirmation that the liquid CO<sub>2</sub> quality at Twence's capture plant complies with the EIGA (European Industrial Gases Association) standard for the components analysed.
- An advanced Framework had been defined to perform the techno-economical assessment of the emission mitigation technologies studies in SCOPE with the possibility to have a fair comparison and good estimation of costs.
- A public report on recommendations for emission mitigation has been written with the main conclusion that that currently available technologies allow for controlling and monitoring emissions from amine-based CO<sub>2</sub> capture plants within desired limits (set by permit authorities). Emissions control represents around 5% of the CO<sub>2</sub> capture costs. Therefore, emissions control and monitoring are not seen as a barrier for the large-scale implementation of amine-based CO<sub>2</sub> capture.
- Reviewed the principles and methodologies of environmental risk assessment (ERA) and collated reliable data on degradation, bioaccumulation and ecotoxicity of amines, solvents, and degradation products relevant for carbon capture technologies.
- Produced a comprehensive review of health-related scientific information on the status of occupational health and safety issues associated with potential exposure to amines and their by-products which has been presented as a publicly available report.
- Improved upon the Gaussian type plume air dispersion model ADMS, used to model the air quality impact of existing and proposed industrial installations, and updated the amine module functionality,

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improving versatility in modelling, allowance for multiple sources and more than one amine in each source, as well as allowance for hygroscopic particulate emissions.

- Developed a methodology for human health risk assessment from PCC emissions, integrating the detailed air dispersion modelling process and a location specific human health risk assessment process. The integrated methodology has been used to assess the chronic residential and occupational human exposure via the inhalation pathway in four region-specific case studies in the UK, Norway, Germany and the Netherlands. Based on method development, hazard and risk assessment testing and case studies, proposals for environmental and health standards for emissions have been made.
- Nationally-specific strategies for ensuring CCS innovation and adoption have been identified for the UK, Norway, the Netherlands, Germany, and India, which enables cross-national comparison for the purpose of generating CCUS ethical governance insights and represents one of the three key components of the WP4 Multi-Sectoral Framework for Societal Acceptance.
- All six SPRINT events have been successfully implemented for the project. Each of them with a different focus and different approach. One of them was in the form of a webinar. Participation of partners and audience was very good, and a lot of information was collected on the various aspects that were addressed. Two discussion rounds were organised with experts in the field. All public information has been shared and a public summary report was written.

### 3 Role and contributions of each project partner

#### 3.1 SINTEF Industry (SINTEF IND)


SINTEF IND has been the coordinator of the project, WP5-leader and contributed to some tasks in the project (Task 1.1, Task 2.2, Task 2.3, Task 3.2, Task 3.3, Task 4.5, Task 5.1, and Task 5.2).

More specifically this means the following work has been conducted:

Task 1.1: Closing knowledge gaps on emissions' prediction, control and monitoring

1. Development of a dynamic model of the water-wash sections to study the effect of volatile emissions. Combined with the results from the Tiller pilot this model can be used to distinguish between aerosol-based and volatile based emissions.
2. Further improvements of the ACEMS (Absorber Continuous Emission Monitoring System) prototype with focus on obtaining reliable measurements through high quality gas sampling and analysis. The improved sampler is tested as part of WP2. The results of this work are described in D1.3.

Task 2.2: Emission mitigation at RWE's capture plant at the lignite-fired power plant Niederaussem

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As part of the test campaign at the Niederaussem pilot, the ACEMS prototype was tested. The results are described in D2.4.

Task 2.3: Analysis of emission mechanisms at SINTEF IND’s capture plant at the CO<sub>2</sub> Lab at Tiller and Niederaussem capture plant.

Before testing at the Niederaussem pilot, the ACEMS prototype was tested in a short test campaign using spent solvent from the Niederaussem pilot. As part of this campaign, particle dosing was used to mimic aerosol forming flue gases. The results are described in D2.2.

In both Task 3.2 and Task 3.3 the role of SINTEF IND has been a discussion partner in meetings, especially on providing input to the environmental assessment based upon experience on capture plant operation and emission characterization as well as earlier work on environmental impact assessment of amines.

Task 4.5: Has been part of the planning of the SPRINT events, presented the SCOPE project, and contributed to the discussion during the events.

#### Task 5.1: Project Management


As the Coordinator, SINTEF IND has been active in all management activities related to e.g. planning and monitoring of progress, reporting to ACT, Quality Assurance, establishment of the Consortium Agreement and arrangement of meetings. Furthermore, SINTEF IND is the national contact person for the Norwegian partners (8) and thus responsible for the technical and financial monitoring and reporting to the national funding agency. Together with the other WP-leaders, progress is reported in D5.1, D5.2, D5.3, D5.4 (final report) in addition to mid-term report and quarterly TLRs.

#### Task 5.2: Dissemination and exploitation

SINTEF IND has together with IMPERIAL been the coordinators of all dissemination end exploitation activities. More specifically SINTEF IND has contributed to the strategy for these activities and promoted such activities whenever possible.

### 3.2 SINTEF Ocean (SINTEF OC)

SINTEF OC has worked within WP3 in collaboration with WP-lead IMPERIAL to describe relevant methodologies of environmental risk assessment (ERA) in the context of amine-based CO<sub>2</sub> capture plant emissions, including underlying laboratory methods to address persistence (P), bioaccumulation (B) and ecotoxicity (T) of chemicals. SINTEF OC collected, summarized and categorized PBT data for amines, solvents and relevant degradation products. Due to the scarcity of marine ecotoxicity data, SINTEF OC also performed laboratory studies assessing the toxicity of selected amines to marine algae, microcrustacean and fish. The summary report “PNECs and degradation data for amines and amine degradation products (Deliverable D3.1) was the main deliverable for SINTEF OC in the SCOPE project, but results were also presented at the SETC Europe meeting in Seville, Spain in 2024:

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- Hansen, B.H.; Wielogorska, E.; Altin, D.; Korre, A.; Farkas, J.; Da Silva, E.F.; Hoff, K.A.; Kvamsdal, H.M.; Sørensen, L.; Brakstad, O.G. 2024. Marine ecotoxicity of amines used as solvents in carbon capture processes: Species sensitivity distributions and additive toxicity aspects. Presentation. SETAC Europe 34th Annual Meeting, Seville, Spain. May 5<sup>th</sup>-9<sup>th</sup> 2024.

### 3.3 NORGES TEKNISK-NATURVITENSKAPELIGE UNIVERSITET (NTNU)

NTNU has contributed mainly to Task 1.1 in the project. NTNU has measured vapour-liquid equilibrium experiments of loaded amines relevant to wash water systems. The data was used to improve models. The NTNU aerosol model was improved by implementing a class-based aerosol model and used in the modelling of WP2 pilot campaign runs.

In total, NTNU work has contributed to 3 journal publications and one conference publication:

- Journal publication '[Experimental VLE data for the AMP/PZ/H<sub>2</sub>O system under relevant water wash conditions for carbon capture applications](#)' is a work performed in collaboration with Heriot-Watt University
- Journal publication '[Demonstrating the effect of solvent aging on the volatile and aerosol-based emissions of the AMP/PZ-based solvent CESAR1 after 1,000 h and 30,000 h operation](#)' describes results from RWE's WP2 pilot campaign. NTNU contributed in the discussions and performed laboratory experiments related to the volatility and physical properties of the aged and fresh CESAR1 one.
- Journal publication '**Understanding aerosol growth and emissions: CO<sub>2</sub> capture in the RWE Niederaussem pilot plant using CESAR1**' uses the NTNU's aerosol model and is under review for publication.
- Conference publication 'Vapor-liquid equilibria and pH of aqueous amines for better understanding of amine emissions' was presented in TCCS-12 conference.


### 3.4 NEDERLANDSE ORGANISATIE VOOR TOEGEPAST NATUURWETENSCHAPPELIJK ONDERZOEK (TNO)

TNO has led WP1 and Task 4.5 and contributed to several tasks of the project (Task 1.1, Task 1.2, Task 2.1, Task 2.2, Task 2.4, Task 4.5, Task 5.1, and Task 5.2). The specific work is described below:

TNO has organised monthly meetings in WP1 to keep track of the progress and to detect possible issues in time for corrective actions.

Task 1.1: Closing knowledge gaps on emissions' prediction, control and monitoring

- TNO has, together with HVC and Twence, assessed emissions in the WtE sector by defining the use cases, performing multiple emission measurement campaigns (in WP2) and process the data in a way that it could be used in the various models, techno-economical evaluations and the recommendations
- TNO discussed with MIPL and IITKGP about the conceptual process design for the case in India.

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- TNO was responsible for D1.5. Recommendations for emission control, where the results in the project came together in a set of clearly described recommendations. This is a public deliverable.

#### Task 1.2: Techno-economic analysis of emission control strategies

- TNO worked together with Hovyu and HWU on the techno-economic framework. The task was led by HWU and has led to a set of tools for Techno-economic analysis that makes it possible to compare different solution on the same bases. This framework will be published and could be a new standard.
- TNO worked out the WtE use case together with the involved partners.

#### Task 2.1: Emission mitigation at Twence’s capture plant at the Hengelo Waste-to-Energy plant

- TNO has performed multiple campaigns at Twence with their emissions measurement equipment (FTIR, ELPI+ and various test columns). Support by Twence was very good, making it possible to test a variety of setting, leading to valuable data for the modelling and emission assessment. One of the focus points in the Twence campaign was the assessment of the BDU. D2.1 Emission mitigation technologies for MEA, was prepared by TNO.
- TNO supported Twence by discussing the measurements performed on CO<sub>2</sub> quality.

#### Task 2.2: Emission mitigation at RWE’s capture plant at the lignite-fired power plant Niederaussem

- TNO has supported the testing at RWE in Task 2.2 and have made their equipment (EPLI+) available for longer term testing of various setting at the RWE plant.


#### Task 2.4

- TNO has performed multiple campaigns at HVC with their emissions measurement equipment (FTIR, ELPI+ and various test columns). Support by HVC was very good, making it possible to test a variety of settings, leading to valuable data for the modelling and emission assessment. One of the focus points at HVC was the influence of the WESP on the emission behaviour. The findings have led to a change in the settings for the capture plant at HVC, leading to lower emissions and a more stable plant. D2.6 Emission mitigation technologies for MEA and MDEA/PZ, was prepared by TNO.

#### Task 4.5

TNO was in charge of all the SPRINT events. For all events, the program and agenda were prepared by TNO. All the events (besides the event in India) were led by TNO and all discussions were moderated by TNO. Deliverable D4.5 Summary of all SPRINT events, was written by TNO.

#### Task 5.1 Project Management

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- TNO was WP1 leader and managed SPRINT. As WP2-leader TNO has been active in all management activities (progress meetings, aligning the work, monitoring progress, reporting etc.). TNO was the national contact for the Dutch partners (TNO, Hovyu, Twence, HVC).

#### Task 5.2 Dissemination and exploitation

- Together with the project partners TNO has published journal articles and presented the project and results of SCOPE at conferences (TCCS12, GHGT16 and GHGT17 and several national events).

### 3.5 Imperial College (IMPERIAL)

Imperial has led WP3 and interacted with nearly all SCOPE project partners in order to carry out the integrated modelling that has brought together PCC emissions specifications, facilities specifications, scaling of emissions for scenario analysis, software modules development, regulatory assessment, atmospheric dispersion and degradation modelling, reviews of human health and ecological risk assessment methodologies and compilation of several project deliverables. Imperial has also been responsible for the project communication and dissemination and has contributed to project management efforts, on behalf of the UK partners and as a member of the project management board (Task 3.1, Task 3.2, Task 3.3, Task 4.5, Task 5.1, and Task 5.2).


Imperial contributed to deliverable D3.1 PNECs and degradation data for amines and amine degradation products; carried out a critical and editorial review of Deliverable 3.2 Assessment of the Impact of Various Amines on Micro- and Macro-organisms and their Potential Biodegradability in the Ecosystem; prepared deliverable D3.3 Human health hazard assessment strategy for amine emissions around PCC facilities and was responsible for the deliverables D3.3-3.5 reporting on the four regional case studies on the emission dispersion and degradation and the human health risk assessment. Early on in the project produced the SCOPE project Communication and Dissemination Strategy deliverable 5.6.

Together with the SCOPE project partners, Imperial has contributed to and led the production of several publications have been produced during the project period as reported in section 8 of this report.

### 3.6 RWE Power Aktiengesellschaft (RWE)

RWE Power has led WP2 and Task 2.2 and contributed to several tasks of the project (Task 1.1, Task 1.2, Task 2.1, Task 2.2, Task 2.3, Task 3.3, Task 4.5, Task 5.1, and Task 5.2). The specific work comprised:

Task1.1: Closing knowledge gaps on emissions' prediction, control and monitoring

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- Support of the optimisation of models (Aspen, ProTreat) regarding volatile emissions of a capture pilot plant using the CESAR1 solvent by providing comprehensive sets of operating data and solvent analyses.
- Contributing solvent samples and analysis data of fresh and very aged CESAR1 for laboratory experiments on differences of the properties which might determine the formation of volatile and aerosol-based emissions.
- Macroscopic amounts of solid aerosol-nuclei have been sampled upstream of the CO<sub>2</sub> absorber at the capture pilot plant at Niederaussem using an ELPI+ system and confirmation that the particles, which are important for the formation of aerosol-based emissions, mainly consist out of Na<sub>x</sub>S<sub>y</sub>O<sub>z</sub> using SEM/EDX measurements.
- Comprehensive data sets from the testing of dynamic capture plant operation (load changes, start/stop) dynamic testing have been provided for further developing a Machine Learning model to gain a better understanding of the emission peaks and to forecast future emission levels. Additionally, the operating data have been used to test a Large Language Model for the more accurate prediction of the emissions during dynamic capture plant operation.
- Construction and use of a sampling system for droplets falling down from the demister to the water wash and entrained droplets following the flue gas flow from the water wash to the demister to analyse the droplet composition and to validate an aerosol model, together with analysis data of the water wash liquid (CO<sub>2</sub> loading, amine and NH<sub>3</sub> content), and operating data for different plant configurations (high and low number concentration of aerosol nuclei generated in the flue gas by a wet electrostatic precipitator, fresh and very aged solvent, single water wash, dry bed). Additionally, measurements of the particle number concentration with ELPI+ up and downstream of the water wash and upstream of the CO<sub>2</sub> absorber, and for different operating voltages of the wet electrostatic precipitator have been carried out.
- RWE Power assisted the definition of one of the use-cases (lignite-fired power plant) of the TEA by providing the power plant-relevant information and supported the development of recommendations for capture plant operators how to control emissions.

#### Task 1.2: Techno-economic analysis of emission control strategies

- RWE Power supported the up-date of the economic models developed within the ALIGN-CCUS project and the estimation of the marginal cost of emission mitigation technologies for amine-based capture plants.

#### Task 2.1: Emission mitigation at Twence's capture plant at the Hengelo Waste-to-Energy plant

- RWE Power ordered an external laboratory to analyse liquified CO<sub>2</sub> from the capture pilot plant at Niederaussem and confirmed the high purity of 99.978% and concentration of H<sub>2</sub>O, O<sub>2</sub>, NO<sub>x</sub>, amines (PZ, AMP), and NH<sub>3</sub> below the requirements from Northern Lights specifications.

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#### Task 2.2: Emission mitigation at RWE’s capture plant at the lignite-fired power plant Niederaussem


- RWE Power has realised testing campaigns with long-time aged CESAR1 (after 40 months without exchange of the solvent inventory and 24/7 operation), middle-aged (5,000 operating hours) and fresh solvent (1,000 operating hours) regarding the performance of more than 20 configurations of emission mitigation technologies for aerosol-based and volatile emissions. The test program comprised repeat measurements and data sets (particle number concentrations and size distribution, amine and ammonia emissions, concentration of amines in the water wash inventory, solvent analyses) have been provided for the validation and optimisation of the emission models in WP1.1. The results have been presented in D2.5.
- The emission behaviour and the effect of more than 20 configurations for emission mitigation technologies have been tested for capture rates between 90% and 98%. 30 repeat measurements with just the water wash have been carried out to provide data for analysis and simulation of this benchmark. The results have been presented in D2.3.
- A testing campaign on dynamics of capture plant emissions at Niederaussem and the effect on the performance of emission mitigation tools have been tested. 25 different tests were realised (ramp down to 50 and 70% for 2hr, ramp down to 50% for 15min, load following, shut-down / start up, shut-down / ramp start-up. The performance of single water wash, acid wash, double water wash, dry bed, dry bed + acid wash, and dry bed + double water wash was tested and comprehensive process data for the further analysis and simulation have been provided. The results are presented in D2.9.
- At Niederaussem the effect of increasing the O<sub>2</sub> content and reducing the CO<sub>2</sub> content in the flue gas (mimicked off-gas of a natural gas-fired plant: CO<sub>2</sub> content was reduced from 15% to 4% by adding air to the flue gas). The performance of single water wash (benchmark), acid wash, double water wash, dry bed with double water wash, dry bed with acid wash, and dry bed with single water wash have been assessed. The results are presented in D2.8.

#### Task 2.3: Analysis of emission mechanisms at SINTEF IND’s capture plant at the CO<sub>2</sub> Lab at Tiller and Niederaussem capture plant

1. RWE Power organised the transport of ca. 900 kg very aged CESAR1 solvent from Niederaussem to the Tiller test facility for comparative plant operation with the same inventory.
2. A measurement campaign at Niederaussem with the ACEMS system has been carried out and operating data have been provided for the validation of the performance of ACEMS. The results will be presented in D2.4.

#### Task 3.3 Development of Environmental and Health Quality Standards for critical emissions

1. RWE Power contributed results from the testing campaigns at Niederaussem to the simulation of emissions of CESAR1 and basic data for the German use case that was investigated in WP3.

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Task 4.5 Knowledge transfer through the Stakeholder, Policy, Research and Industry NeTwork critical emissions (SPRINT)

1. SPRINT Event #5 and the local workshop “Emission mitigation technologies for post-combustion capture plants” was hosted by RWE combined with a project meeting and a site visit in Niederaussem. Additionally, the results and conclusions of WP2 have been presented in Event #6 Global symposium “SCOPE: Project results and recommendations for future research and policy initiatives”.

Task 5.1 Project Management

1. As WP2-leader RWE Power has been active in all management activities (aligning activities, monitoring progress, reporting). Furthermore, RWE Power has been the national contact for the German partners.

Task 5.2 Dissemination and exploitation


1. Together with the project partners RWE Power has published journal articles (4, 2 submitted) and presented project the content and results of SCOPE at conferences (PCCC6, PCCC7, TCCS12, UTCCS-7, GHGT17).

### 3.7 TotalEnergies EP Norge AS (TEPN)

The contribution of TotalEnergies EP Norge and its affiliate TotalEnergies OneTech in SCOPE has been mainly to bring an industrial perspective concerning the work done in the different WPs. Several researchers from the R&D team working on the development of solvent technology for anthropogenic carbon capture were involved. They participated to regular progress meeting of WP 1, 3 and 4 and played a role of challenging the work in progress. The Laboratoire of Air Quality in Lyon, France followed WP3 since TotalEnergies will be a future end-user of solvent capture technology on its sites. Indeed, how to measure emission, mitigate them and evaluate their risk and impact is central in our actual studies. One refinery of TotalEnergies was proposed as application case in Task 1.2 related to the Techno-economic analysis of emission control strategies. The study was transposed as a journal article. TotalEnergies participated actively to the review process.

### 3.8 University of Sussex (SPRU)

SPRU was the WP4 leader until end of May 2024 when they pulled out of the consortium. SPRU was responsible and only partner working in Task 4.1 to Task 4.4, while the results were discussed in project meetings with the other partners. SPRU pulled out as they could not provide another expert to fulfil their obligations to complete all remaining work and finalise D4.1, D4.2, D4.3, and D4.4 when the principal

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investigator left the university. However, a separate deliverable is issued based on presentations in the meetings.

### 3.9 Heriot-Watt University (HWU)

HWU contributed to WP1 and WP2 and led Task 1.2 in WP1, based on their experience in modelling amine-based carbon capture plants and their integration into power and industrial plants, amine degradation, modelling energy conversion systems, process dynamics and techno-economic evaluation. In WP1, HWU improved the available thermodynamic models for CESAR1 in AspenPlus by using the obtained data within SCOPE and supported CCS12 to extend the available steady state AspenPlus Process model to CESAR1. HWU led Task 1.2 on techno-economic analysis of emission control strategies and in WP2, HWU assisted the experimental campaign at Niederaussem to evaluate dynamics of emission mitigation (Task 2.2) and developed Machine Learning models to predict amine emissions.

### 3.10 Norsk institutt for luftforskning (NILU)

NILU contributed to WP3, especially to task 3.1 ‘Methods and guidelines for environmental and health risk assessment’. Our main involvement was in the subtask 3.1.2 ‘Health-related hazard assessment’ where NILU was responsible for the deliverable 3.3 ‘Human Health hazard assessment strategy for amine emissions around PCC facilities’. NILU participated in reviewing existing human related toxicology data utilizing also its knowledge from the previous CO<sub>2</sub>-capture projects where NILU investigated cytotoxicity and genotoxicity of several nitrosamines and nitramines. An association between exposure to nitrosamines and nitramines and adverse health effects in humans has been assessed through the analyses of biomarkers of effect. The D3.3 was submitted in M12. This deliverable was updated, and the updated version was submitted in M36. The review of existing knowledge showed that most of nitrosamines and nitramines were found to have genotoxic/mutagenic potential. Directly acting mutagens can be associated, even at very low doses, with a mutagenic effect and therefore pose a carcinogenic risk. However, the level of risk may depend upon the exposure. Therefore, NILU performed pilot in vitro experiments with the substance CESAR1 using advanced three-dimensional (3D) in vitro respiratory model that provides the opportunity to use exposure scenarios more relevant for the in vivo situation. Cytotoxicity and genotoxicity of the CESAR1 compound was tested in an air-liquid-interface (ALI) lung model, culturing human alveolar A549 cells on the apical part of a support membrane, and human endothelial EA.hy926 cells on the opposite side of the membrane, to feature the air–blood barrier in the alveoli of the lower respiratory tract. Cytotoxicity was performed by the Alamar blue assay. For genotoxicity testing, the comet assay was used to detect DNA strand breaks and oxidized purine lesions (with lesion specific enzyme formamidopyrimidine DNA glycosylase). Preliminary results suggest that, up to a 250x dilution, CESAR1 is non-cytotoxic and non-genotoxic in the ALI lung model, which closely replicates the physiological conditions of the lung. However, cytotoxicity was found in standard in vitro

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culture at this concentration, and there is an indication that a 100x dilution may be cytotoxic and genotoxic in endothelial cells (EA.hy926 cells) within the ALI lung model. The confirming experiment is ongoing and the separate report from the toxicology studies is under preparation.

### 3.11 Technology Centre Mongstad (TCM)

TCM has participated in the SCOPE project as Industrial advisory and contributed to WP1, WP2, WP3 work packages and WP4 for knowledge transfer network and stakeholder meetings. TCM brought industrial perspective concerning the work done in the different WPs and shared TCM practical experience whenever and wherever required. Three researchers from the TCM Technology team working on the development of solvent technology testing, environmental permits development and reporting, process model development and validation for amine-based carbon capture were involved. They participated in regular progress meetings of WP 1, 3 and 4 and played a role of challenging the work in progress.

The contributions are specifically:

Task 1.1: Closing knowledge gaps on emissions' prediction, control and monitoring

- Support of the process simulation model development and validation (Aspen Plus) regarding volatile emissions of a capture pilot plant using the CESAR1 solvent by providing operating data used by NETL.
- TCM collected the environmental permits for real industrial projects and provided the project to develop the basis for emission limits.
- Participated in monthly update meetings and involved in discussions


Task 1.2: Techno-economic analysis of emission control strategies

- TCM worked together with TNO, HWU and Hovyu on techno-economic framework development. HWU led the task and a set of tools for design considerations for column sizing, Techno-economic analysis to compare different solutions on the standard was developed. Detailed working sessions were held together with partners.
- TCM helped Indian partners on the discussions related to simulation and technoeconomic analysis of emission mitigation scenarios for CO<sub>2</sub> capture from fertilizer industry using 30 wt% MEA solvent. Provided TCM operational insights and configurations suitable for the industrial case considered.

Task 2.2: Emission mitigation at RWE's capture plant at the lignite-fired power plant Niederaussem

- Supported HWU on planning and brainstorming the dynamic capture plant testing at RWE. TCM provided advice regarding different operational scenarios and relevant cases.

Task 3.1.4 Method and guidelines for integrated emission monitoring, modelling and risk assessments.

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- TCM shared the knowledge and experience of monitoring related to emissions from CO2 capture plants.

#### Task 3.2 Case studies around facilities - emissions modelling and risk assessment

- TCM collaborated with ICL and provided the required information for executing the emission modelling and risk assessment for Norwegian case study. TCM participated in Technical due diligence discussions related to results analysis and the impact.

#### Task 4.5 Knowledge transfer through the Stakeholder, Policy, Research and Industry NeTwork critical emissions (SPRINT)

- The first SPRINT event on “Regulations, Permitting and a Review of the Guidelines for Emissions Control” was hosted by TCM together with project meeting in Bergen, Norway.
- TCM helped TNO on survey questionnaire preparation and also by providing the answers from TCM permitting process experience.


### 3.12 Herøya Industripark (HIP)

HIP has contributed with discussions in project meetings and reviewed publications and deliverables. HIP organised and hosted the project meeting in Porsgrunn, Norway in 2023 which included a field trip to the capture plant in Brevik and a workshop with invited speakers outside the consortium.

#### Hovyu (Hovyu)

Hovyu was involved in WP 1 where it participated in discussions for model improvement and validation of refitted model (more specifically the new CESAR1 model implemented in ProTreat). A model of the eNRTL activity coefficient was developed in Python, and parameters regressed to fit the experimental data. Results showed a good accuracy of the model.

With the novel data generated by NTNU (VLE data under water wash conditions), OGT implemented a refitted thermodynamic model in ProTreat which improved the predictions of VLE. By collaborating closely with RWE and OGT, Hovyu was able to test and validate the model using RWE pilot plant data. For that Hovyu built a digital twin of RWE pilot plant in ProTreat. Then, the data was sorted into input parameters and output parameters. The input parameters were fed to the simulation sheet and results from the simulation were compared to the experimentally measured output parameters. The results showed that the predictions of the new model were improved compared to the older version (previously implemented in ProTreat). The capture rate was estimated more accurately. The findings were presented at conferences (GHGT and IcheaP).

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Hovyu led the TEA task and was responsible for the deliverable D1.4 where it also performed the simulations and cost estimation of CO<sub>2</sub> capture plant with different emissions mitigation strategies in a refinery. The simulations were performed using ProTreat software using a gas provided by Total Energies. The full-scale plant was optimized for two solvents: MEA and CESAR1. Several parameters were investigated, like packing heights, use of inter-cooler, etc, resulting in several simulations performed. The optimal case for each solvent, the ones presenting the lowest reboiler duty, were selected for economic analysis.

Hovyu used a template spreadsheet provided by HWU. However, such spreadsheet was developed for a power plant case which is significantly different from the refinery case. To adjust it to the refinery case, Hovyu needed to modify the spreadsheet. Once the framework was validated by TotalEnergies, Hovyu proceeded with the analysis.

Besides being the leader of the tasks (and Deliverable responsible), Hovyu also simulated the case of Power Plant using MEA (which responsibility was from HWU). Due to technical difficulties, HWU could not perform the simulations using MEA solvent. To avoid leaving this case out of the scope of the analysis, Hovyu performed the simulations and delivered the results to HWU.

Collaboration with HWU, TNO and TEOT was crucial for the progress of this activity.

### 3.13 Twence B.V. (Twence)

Twence has contributed to several tasks in WP1 and WP2.

The specific work comprised:


Task1.1: Closing knowledge gaps on emissions' prediction, control and monitoring

Twence has together with TNO and HVC assessed emissions in the WtE sector by defining the use cases, performing multiple emission measurement campaigns (in WP2) and process the data in a way that it could be used in the various models, techno-economical evaluations and the recommendations.

Task 2.1: Emission mitigation at Twence capture plant at the Hengelo Waste-to-Energy plant

TNO has performed multiple campaigns at Twence with their emissions measurement equipment (FTIR, ELPI+ and various test columns). Support *was provided* by Twence *in preparation, design of measurement/testing protocols, on site activities in interaction with Twence facilities, evaluating results and dissemination of outcomes*.

One of the focus points in the Twence campaign was the assessment of the BDU. D2.1 Emission mitigation technologies for MEA, was prepared by TNO and supported by Twence.

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Another focus point was the investigation of the quality of liquid CO<sub>2</sub> produced from CO<sub>2</sub> captured by a pilot plant operating MEA as a solvent to capture CO<sub>2</sub>. An extended measurement campaign was performed using advanced analysis equipment installed at the Twence pilot plant. This equipment was also made available to all consortium partners for analysis of CO<sub>2</sub> produced at other pilot plants present in the consortium. D2.7 Report Guidelines “CO<sub>2</sub> Greenhouse quality” was prepared by Twence and publicly disseminated by the consortium.

### 3.14 HVC energie en hergebruik (HVC)

HVC has contributed to several tasks in WP1 and WP2.

The specific work comprised:

Task1.1: Closing knowledge gaps on emissions’ prediction, control and monitoring


Together with TNO and Twence, HVC has assessed emissions in the WtE sector by defining the use cases, performing multiple emission measurement campaigns (in WP2) and process the data in a way that it could be used in the various models, techno-economical evaluations and the recommendations.

Task 2.1: Emission mitigation at HVC capture plant at the Alkmaar Waste-to-Energy plant

TNO has performed multiple campaigns at HVC with their emissions measurement equipment (FTIR, ELPI+ and various test columns). Support was provided by HVC in preparation, design of measurement/testing protocols, on site activities in interaction with HVC facilities, evaluating results and dissemination of outcomes.

One of the (unexpected) focal points in the HVC campaign was the assessment of the effect of the Wet Electrostatic Precipitator (WESP) on the formation of aerosols and the subsequent effect of them on the amine emissions from the absorber. The TNO measuring campaign noticed high amine emissions that regularly dropped every 6 hours, which appeared to coincide with the programmed rinsing of the WESPs. An improvised measuring campaign with one or two of the parallel WESPs switched off, proved their negative influence. Subsequently, HVC modified the intake of flue gas into the absorber of the carbon capture unit: from downstream to upstream of the WESPs. So, by chance the first practical spin-off of the Scope project was obtained: a permanent reduction of amine emissions of HVC's pilot plant for carbon capture. This positive effect was substantiated by later TNO measuring campaigns and reported on by TNO within this project.

Linde has provided its expertise in Work Packages 1-4 as a provider of capture plant technology for relevant industrial use cases, contributing to the technical, economic, and ecological evaluations.

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### 3.15 Linde Gmbh, Linde Engineering (Linde)

#### Work Package 1 (WP1):

Linde has contributed engineering expertise to support partners during discussions and evaluations of the developed emissions control tools and process models. Additionally, Linde has been involved in the analysis and development of the techno-economic analysis of emission control strategies.

#### Work Package 2 (WP2):

Linde has provided its know-how for planning and evaluating test campaigns at the Pilot Plant in Niederaussem, such as testing the dynamic behavior of an amine wash unit and its impact on emissions. Furthermore, Linde has collaborated with HWU, TNO, RWE, and ACC to ensure industrially realistic results through cost estimation and techno-economic analysis of plant costs. Linde has also reviewed deliverables from project partners (e.g., D2.5, D2.8, and D2.9) and other public articles.


#### Work Packages 3 and 4 (WP3 & WP4):

Linde has actively participated in workshops, technical meetings, and online meetings, sharing industrial knowledge and experiences from constructed and operated plants. Additionally, Linde has taken part in SPRINT events, such as SPRINT #6 in London, 2024.

### 3.16 OGT Simulation Software (OGT)

Optimized Gas Treating, Inc. participated in WP1 by updating and validating their ProTreat® process simulation software's CESAR1 model for use by other partners. This was done by performing a refit of physical properties, kinetics, and VLE of the CESAR1 system using recently published data. This included VLE data that was generated by NTNU as part of the SCOPE project. The updated CESAR1 model was validated using RWE pilot plant data in a collaboration with Hovyu. The model improvements and plant validation were presented at PCCC-7 and GHGT-17.

Additionally, OGT developed an excel interface with the ProTreat® model so that the thermodynamic parameters of the CESAR1 model could be overridden. This interface was provided to NETL, who used it along with an internal program to develop an uncertainty quantification framework for the CESAR1 system.

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### 3.17 Guru Gobind Singh Indraprastha University (GGS IPU)

GGS IPU has been the coordinator of the project with project national contact and contributed to some tasks in the project (Task 1.1, Task 2.5, Task 3.1, Task 3.3, Task 4.5, Task 4.3, Task 5.1, and Task 5.2). More specifically the following work has been conducted:


Task 1.1: Closing knowledge gaps on emissions’ prediction, control and monitoring: A conceptual CO2 capture process design was carried out for the attachment to the coal-fired power plant of NTPC, Vindychal, using benchmark CO2 capture technology.

Task 2.5: Evaluation of emission mitigation technologies for capture plants at coal power plants and fertilizer production units in India: A conceptual process design will be worked out, including equipment sizing and costs of a PCCC plant retrofitted for 2 cases - a coal fired power station and an industrial scale plant - with India specific boundary conditions.

Task 3.1, Task 3.2 and Task 3.3: Environmental quality standards, impacts and risk assessment: The major aim of this sub-task is to identify missing data for hazard assessment, risk of emission of hazardous compounds (amines and its by-products/degradation products), and impact on local ecosystem components. The task includes to address missing data and gaps, including conducting additional standard single compound ecotoxicity testing, as needed. A review data from previous environmental studies of amine solvents and degradation products to determine if any should be categorized as potential persistent, bioaccumulative and/or toxic compounds (PBTs) had been studied. The review study is described in D3.2 as a report entitled “Assessment of the Impact of Various Amines on Micro- and Macro-organisms and their Potential Biodegradability in the Ecosystem” was uploaded on the SCOPE website.

Task 4.3 Investigating civil society acceptance of amine-based CCUS in value chains in participating countries: Development of qualitative national survey questionnaire for India: A countrywide survey on public perceptions and awareness of CCUS technology in India has been conducted. The survey mainly addresses the public understanding of climate sciences, knowledge of low-emission technologies (particularly amine-based CCUS technology), public interests and concerns about the positive and negative impacts of CCUS technology, and public judgements towards government-supported amine-based CCUS policies.

Task 4.5: SPRINT: The 3rd SPRINT event was organised in GGS IPU (hybrid mode) in India on the topic “Mitigating Environmental Impacts of Post-Combustion Carbon Capture Plants”. The SPRINT (Stakeholder, Policy, Research, and Industry Network) event, hosted by GGS Indraprastha University (GGSIPU), had provided a valuable opportunity for key stakeholders to share knowledge among universities, technology institutes, research institutes, industry operators, regulators, and other stakeholders involved in the permitting process and development of environmental quality standards. The SPRINT event in India was immensely successful with lively discussions with stakeholders, policy makers, academicians, scientists, representatives from pollution control boards, thermal power industry and NGOs.

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Task 5.1: Project Management: GGSIPU has been active in all management activities related to e.g. planning and monitoring of progress, reporting to SCOPE coordinator, quality assurance, establishment of the Consortium Agreement and arrangement of meetings. Furthermore, GGS IPU is the national contact person for the Indian partners (3) and thus responsible for the technical and financial monitoring and reporting to the national funding agency. Together with the other WP-leaders, progress is reported in D5.1, D5.2, D5.3, D5.4 (final report) in addition to mid-term report and quarterly TLRs.

Task 5.2: Dissemination and exploitation: India has been part of the planning of all events organised during SCOPE project and contributed to the dissemination and exploitation activities wherever possible.


### 3.18 National Energy Technology Laboratory (NETL)

The NETL team worked in collaboration with HWU to develop an Aspen Plus process modelling framework for prediction of CO<sub>2</sub> capture and amine emissions for the CESAR1 solvent system. In developing the model, HWU regressed thermodynamic model parameters with new VLE data measured as part of the SCOPE program and NETL adjusted existing reaction kinetics models for consistency with the new thermodynamic model. Flowsheets with various process scales and flue gas sources were developed, and the modelling framework was validated with pilot plant process data from TCM and RWE. This work was documented in the WP1 deliverable D1.2 report titled “Model Validation and Emission Validation in WtE, Power Plant, and Refineries”.

The NETL team also worked in collaboration with OGT to develop an uncertainty quantification (UQ) framework for the CESAR1 solvent system. OGT developed an Excel interface that serves as an intermediate in connecting the ProTreat process models with the Framework for Optimization, Quantification of Uncertainty, and Surrogates (FOQUS) platform maintained by the Carbon Capture Simulation for Industry Impact (CCSI<sup>2</sup>), a research consortium led by NETL. This framework made accessible thermodynamic model parameters so that their probability distributions could be estimated through a Bayesian inference methodology that incorporates VLE data. Prior to the project ending, some preliminary work was completed for Bayesian estimation for thermodynamic model parameters and propagation of the distributions through the ProTreat process model.

### 3.19 Environment Agency (EA)

Environment Agency remit and expertise: The Environment Agency regulates large industrial plants in England and is preparing to regulate new industrial-scale Carbon capture plants. The Environment Agency has been a partner to the SCOPE project and has contributed advice, expertise, and experience towards its research on the sustainable and environmentally safe operation of capture plants. Our contribution has focussed on Work Package 3 (Environmental standards, impacts, and risk assessment) and has involved Environment Agency specialists from its:

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- 
- Chief Scientist’s Group
  - Air Quality Modelling and Assessment Unit (AQMAU)
  - Energy Industries Decarbonisation Team.

Environment Agency involvement: Over the 4 years of the project, specialists from the Environment Agency have attended most SCOPE meetings (usually remotely), including the final project meeting and dissemination event in London (in person). We have advised on work in progress with particular reference to:

- Atmospheric dispersion modelling and assessment of plume impacts from carbon capture plants.
- Atmospheric chemistry schemes for the formation and degradation of N-amines in airborne plumes.
- Significant topics for regulatory evidence, including the design of auditable air quality assessments, and the treatment of uncertainties.

Engagement with SCOPE partners: As well as participating in SCOPE meetings, the Environment Agency has set up and/or contributed to technical discussions with SCOPE partners, including discussions with:

- Cambridge Environmental Research Consultants on atmospheric modelling and chemistry
- Imperial College on environmental impact assessment and analysis of population exposures
- SINTEF on Chemical and Environmental Process Engineering.


Overall, the Environment Agency has contributed to SCOPE by using its experience of air quality science, environmental assessment and industry regulation to advise on a range of topics, and especially on atmospheric dispersion and on airborne impacts on receiving environments from carbon capture. The Environment Agency’s remit was not focussed on a specific deliverable, but instead its contributions have informed, guided, and enhanced the deliverables of other SCOPE partners over the past 4 years.

### 3.20 Indian Institute of Technology Kharagpur (IITKGP)

IIT KGP has been the partner of the project and contributed to the tasks in the project (Task 1.1, Task 2.5, Task 3.1 and Task 3.2). More specifically the following work has been conducted:

Task 1.1: Closing knowledge gaps on emissions’ prediction, control and monitoring: A conceptual CO<sub>2</sub> capture process design was carried out for the attachment to the coal-fired power plant of NTPC, Vindychal, using benchmark CO<sub>2</sub> capture technology.

Task 2.5: Evaluation of emission mitigation technologies for capture plants at coal power plants and fertilizer production units in India: Even after a project extension until December 2024 most likely the planned measurements on the composition of flue gas of a power plant and a chemical plant or any other industrial flue gas source cannot be finalised. A conceptual process design will be worked out, including

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equipment sizing and costs of a PCCC plant retrofitted for 2 cases - a coal fired power station and an industrial scale plant - with India specific boundary conditions.

Task 3.1, Task 3.2 and Task 3.3: Environmental quality standards, impacts and risk assessment: The major aim of this sub-task is to identify missing data for hazard assessment, risk of emission of hazardous compounds (amines and its by-products/degradation products), and impact on local ecosystem components. The task includes to address missing data and gaps, including conducting additional standard single compound ecotoxicity testing, as needed. A review data from previous environmental studies of amine solvents and degradation products to determine if any should be categorized as potential persistent, bio-accumulative and/or toxic compounds (PBTs) had been studied. The review study is described in D3.2 as a report entitled “Assessment of the Impact of Various Amines on Micro- and Macro-organisms and their Potential Biodegradability in the Ecosystem” was uploaded on the SCOPE website.

### 3.21 Microfilt India Pvt. Ltd. (MIPL)

MIPL has been the partner of the consortium of the project and contributed to some tasks in the project (Task 1.1 and Task 2.5). More specifically the following work has been conducted:

Task 1.1: Closing knowledge gaps on emissions’ prediction, control and monitoring: A conceptual CO<sub>2</sub> capture process design was carried out for the attachment to the coal-fired power plant of NTPC, Vindychal, using benchmark CO<sub>2</sub> capture technology.


Task 2.5: A conceptual process design will be worked out, including equipment sizing and costs of a PCCC plant retrofitted for 2 cases - a coal fired power station and an industrial scale plant - with India specific boundary conditions.

### 3.22 Cambridge Environmental Research Consultants Ltd. (CERC)

CERC contributed to WP3 Sub-task 3.1.3, Atmospheric dispersion and fate of emissions, as follows.

CERC updated the amine chemistry module within the ADMS Gaussian-type plume dispersion model. The aim of this work was to improve versatility in modelling and to account for additional effects within the chemistry scheme. The model has been developed so that, rather than only being able to model a single source and single amine, it is now possible to model multiple sources and multiple amines within the same setup. This reduces the number of model runs required.

CERC also incorporated additional effects into the amine chemistry module, including accounting for the uptake of amines into liquid water droplets present within the plume. This is important, as some amine species are highly soluble, and this absorption into water inhibits chemical reactions and thus production

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of nitramines and nitrosamines. These updates were incorporated into ADMS 6, which has been used for modelling carried out by Imperial College within the SCOPE project and by the wider ADMS user base.

CERC provided project licences for ADMS to project partner Imperial College for their work on this sub-task, as well as ADMS training and support in their use of the ADMS Amine module.”

### 3.23 Aker Carbon Capture (ACC), now SLB Capturi (SLBC)

The contributions from SLB Capturi to SCOPE have been in the direction of bringing an industrial perspective to the activities. This has manifested in a variety of ways. SLB Capturi has contributed to the project in the following work packages:

WP1 – SLB Capturi has joined discussions with all partners regarding planning of experiments and interpretation of results, especially in the first months of the project. SLB Capturi supported the technological evaluation by sharing insights obtained from industrial suppliers. We have shared information regarding our experience procuring Brownian Demister Units (BDUs) that was used in the final evaluation. We have also participated in the workshop held in Niederaussem where we openly shared SLB Capturi’s emission mitigation and emission monitoring philosophy.

WP3 – SLB Capturi participated in several workshops and actively engaged with the other partners, including the EA and CERC, sharing our concerns and experiences with acquiring atmospheric chemistry data for deriving proper amine reactivity (e.g., to nitrosamines), environmental permitting in different locations, and which monitoring and reporting mechanisms are necessary for ensuring proper supervision of industrial scale carbon capture plants.

## 4 Short description of activities and final results

### 4.1 Activities and final technical results

#### 4.1.1 WP1: Effective emission management tools for large scale deployment

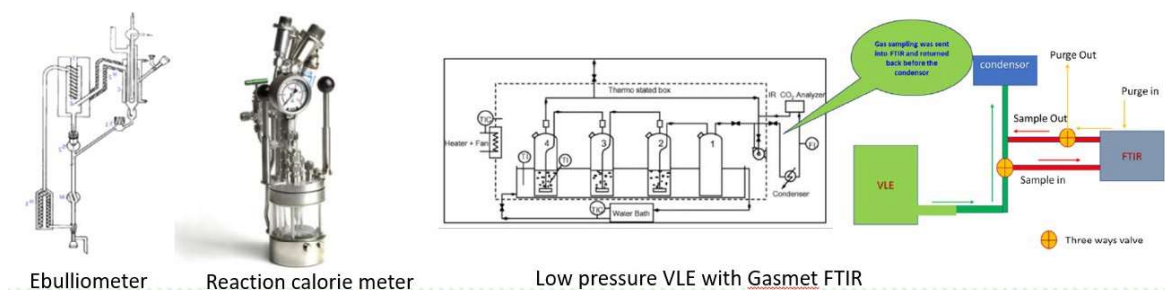
In WP1 important work has been done on the topics of:

- Generating datasets focussed on emissions to support the demonstrations and modelling activities.
- Developing and upgrading new and existing models to assess emission behaviour of CO<sub>2</sub> capture plants.
- Improve the possibilities of online monitoring of emissions
- Developing a new and advanced framework the Techno-Economical Analysis, that will be made available to the community and can set a new standard.
- In the last year of the project, a Techno-economical Assessment has been made of multiple emissions mitigation technologies in multiple sectors leading to cost estimates for the use of these mitigation technologies in full scale implementation.

These topics are described in more detail in the following paragraphs.


#### Generating datasets focussed on emissions to support the demonstrations and modelling activities.

Generation of new datasets based on vapour-liquid equilibrium experiments of loaded amines (MEA and CESAR1) and ammonia solutions at compositions relevant for water wash systems. The experiments were performed in three different apparatuses. Different data of different types of VLE are provided for different concentrations (MEA and blends of AMP/PZ), temperatures, and loadings.



**Figure 4-1: The measurement setups used in the VLE experiments.**

The ebulliometer was used to measure both unloaded and loaded amine solutions of MEA and blends of AMP/PZ at different temperatures. The reaction calorimeter, CPA202, equipped with a glass electrode

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was used to provide VLE and pH data at different concentrations and temperatures. The low-pressure Vapor-liquid equilibrium setup equipped with an FTIR was used to measure the volatilities of amines directly. Measurements PZ and AMP/PZ mixtures were less successful. All data has been made available to the project partners.

### Developing and upgrading new and existing models to assess emission behaviour of CO<sub>2</sub> capture plants.

The aerosol model was improved and validated with data from RWE. The model performed quite well with the data from WP2 which will help us to better understand aerosol emissions, how they behave and how they can be mitigated. The results were presented in Project Meeting 5 at Twence early 2024, and a manuscript has been submitted for publication.

Below some results are given of the emissions with and without a WESP in the process. In this figure, the experimental values are averaged over the period chosen and the outlet demister efficiency is adjusted to give close to experimental PPZ emissions. As can be seen, the model and experimental values of the (aerosol) emissions well in line with each other.


	Amine emissions, mg/Nm <sup>3</sup>			Amine emissions, mg/Nm <sup>3</sup>	
	AMP	PPZ		AMP	PPZ<
With WESP, mod. Gas phase	26.7	0.25	No WESP, mod. Gas phase	31.0	0.3
With WESP, mod. Aerosol	51.5	20.1	No WESP, mod. Aerosol	28.9	11.8
With WESP, mod. Total	78.2	20.4	No WESP, mod. Total	59.9	12.1
With WESP, exp.	61.9	18.9	No WESP, exp.	48.1	12.7

**Figure 4-2: Amine Emissions**

The CESAR1 VLE model in Protreat has been upgraded using data from the TCM and RWE campaigns. This will increase the accuracy and quality of the process simulations in the commercial ProTreat software package which will become available to all the users of ProTreat. Also, the ASPEN+ CESAR1 model was further validated using data from TCM and RWE.

### Improve the possibilities of online monitoring of emissions

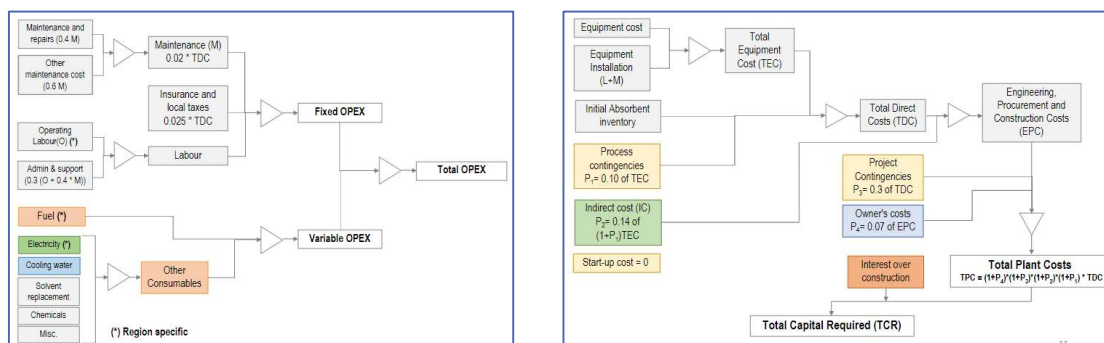
Online emission monitoring was also a topic in WP1. In SCOPE the ACEMS system for online monitoring of emissions was upgraded and modified. Improvements were made in the equipment considering reduction of sampling time, further automation of the process and sample taking and improvement of data processing. The ACEMS prototype has been equipped with automation capability for both gas and water-wash sampling. Improvement of the sampling frequency has been successfully demonstrated. The results obtained in this study for nitrosamine and the degradation product, even under dynamic conditions, indicated good potential to expand the ACEMS measurement components list. This will open

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coverage of a wider spectrum for the solvent components of concern in CESAR1. The improved ACEMS has been demonstrated in the Tiller plant and very recently at RWE (no results available yet).

**Developing a new and advanced framework for the Techno-Economical Analysis, that will be made available to the community and can set a new standard.**

As mentioned above the development of the framework to assess the different emission mitigation technologies was an extensive effort and an important result of the project. It's a well-documented method, including cost information, on how to perform a TEA and what boundary conditions and assumptions need to be defined. The case studies in the SCOPE project were all performed using the framework.



**Figure 4-3 OPEX and CAPEX analysis.**

The techno-economic analysis was performed with the focus on emission control strategies. Solvents considered were MEA and CESAR1 and we analysed use cases for Waste-to-Energy, supercritical coal power plant, refinery and NTCP coal power plant. Emission mitigation strategies studied in the analysis were: water wash, double water wash, dry bed, acid wash and BDU.

The main conclusion from all the case studies was:

- Addition of an emission reduction technique represents 3-7 euros/ton CO<sub>2</sub> additional costs
- To maintain the right to operate, emission mitigation should be an integral part of a capture plant.

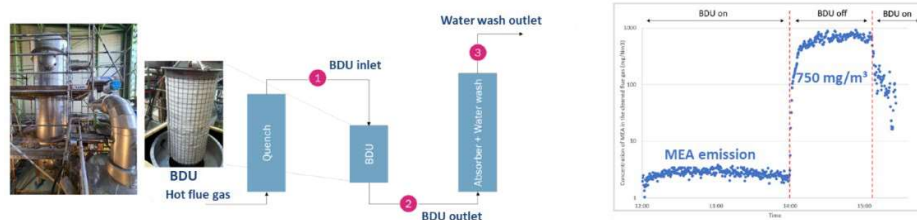
The key take-away from the SCOPE project is that currently available technologies allow for controlling and monitoring emissions from amine-based CO<sub>2</sub> capture plants within desired limits (set by permit authorities). Moreover, emissions control represents around 5% of the CO<sub>2</sub> capture costs. Therefore, emissions control and monitoring are not seen as a barrier for the large-scale implementation of amine-based CO<sub>2</sub> capture.

There is still work to do to further improve control and monitoring techniques, which can further contribute to lowering costs and improving accuracy of emissions measurements. These should be

understood as improvements to the technology that should take place alongside and to support large-scale implementation, and not as required developments that must happen prior to implementation.

#### 4.1.2 WP2: Demonstration of emission management technologies at capture pilot plants


**Task 2.1 Emission mitigation at Twence’s capture plant at the Hengelo Waste-to-Energy plant:** In total four testing campaigns using MEA and the emission mitigation technologies water wash, Brownian Demister Unit (BDU), acid wash and lean loading have been carried out. Especially the performance of the BDU ON (in-line) or OFF (by-passed) and effects of operating parameters (water wash flowrate, temperature) on particle concentrations in the flue gas and emissions was investigated (Figure 4-4).



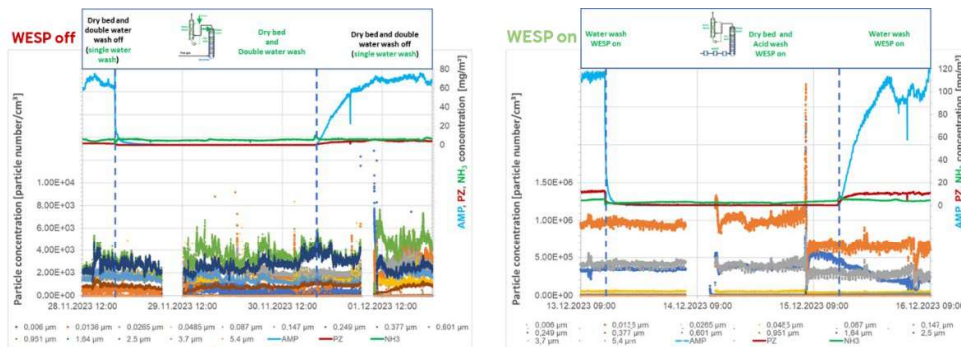
**Figure 4-4 Effect of the BDU on the emissions of MEA at TWENCE’s capture plant.**

In 3-years of assessment it has been demonstrated that the BDU can remove > 99% of the particles from the flue gas, independently from the temperature or flowrate in the water wash. Practical and economic aspects of aerosol-based emission mitigation have analysed. Besides the investment cost, the operation and maintenance cost of a BDU is ca. 7 €/tCO<sub>2</sub>. At Twence, no maintenance was required since the installation of the BDU. The pilot plant is only operated with the BDU, and no downtime occurred, associated to the BDU. However, a limitation of the technology is the increased pressure drop. An important result on the quality of captured and liquified CO<sub>2</sub> at TWENCE’s Waste-to-Energy plant is that the concentrations of all measured trace components are well below the limits defined by the EIGA standard (EIGA doc 70/17), available for the existing CO<sub>2</sub> industry in Europe. The quality of the liquified CO<sub>2</sub> was analysed using an Unisensor Carboscan 300 system. The only component that was measured at values approaching the stated limit was O<sub>2</sub>. However, it was demonstrated that the O<sub>2</sub> concentration could be controlled by altering standard operating parameters. Additionally, samples of liquified CO<sub>2</sub> from the capture plant at Niederaussem (using CESAR1) have been analysed by an external laboratory and in parallel TWENCE’s Carboscan system. The CO<sub>2</sub> from Niederaussem fulfils also the EIGA specification. Main deviations have been found in the comparative analyses regarding moisture content and O<sub>2</sub> content. The AMP and PZ concentration was below the detection limit of 0,002 ppm V/V.

**Task 2.2 Emission mitigation at RWE’s capture plant at the lignite-fired power plant Niederaussem:** At RWE’s capture pilot plant at Niederaussem (flue gas from a lignite fired power plant) 4 campaigns on volatile and aerosol-based emissions and the performance of more than 20 different emission mitigation technologies (water wash, double water wash, acid wash, dry bed (OASE aerozone®), wet electrostatic

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precipitator (WESP), two pretreatment technologies) and configurations have been carried out, based on 42,000 h testing with CESAR1. The tests comprised the analysis of the effects of aging of CESAR1 (very aged/fresh), elevated CO<sub>2</sub> capture rates (90-98%), elevated O<sub>2</sub> content in the flue gas (5-16 vol.-%), dynamics of emission mitigation (start/stop behaviour, load changes). Additionally, cause-and-effect relationships of formation mechanisms of aerosol-based and volatile emissions and effect mechanisms of mitigation technologies have been investigated, the composition of droplet samples between water wash and demister have been determined, and the waste stream formation of emission mitigation technologies has been analysed. By sampling and analysing macroscopic amounts of aerosol nuclei (ELPI+, SEM/EDX) upstream of the CO<sub>2</sub> absorber, it was confirmed that the WESP causes aerosol-based emissions, and that the nuclei consist mainly of Na<sub>x</sub>S<sub>y</sub>O<sub>x</sub>. Regarding the effect of solvent aging, it was demonstrated that a strong decrease of AMP emissions with aging of CESAR1 occurs, with and without WESP, and some decrease of PZ emissions. Activation of the WESP causes a strong increase of AMP and especially PZ emissions for fresh solvent. The AMP emissions of CESAR1 are far too high to be controlled just with a single water wash. It was demonstrated for the water wash that effects of the CO<sub>2</sub> capture rate between 90 and 98% on the emissions are small. Just the AMP emissions slightly increase with the CO<sub>2</sub> capture rate, but the emissions of PZ and NH<sub>3</sub> are independent from the capture rate. At capture rates around 95% and elevated O<sub>2</sub> content in the flue gas, the combination of a dry bed and an acid wash is an effective measure to control the emissions (Figure 4-5). It was demonstrated that effective emissions mitigation technologies are available, regardless of particle number and O<sub>2</sub> concentration in the flue gas, solvent aging, and CO<sub>2</sub> capture rate.



**Figure 4-5 Effect of the dry bed with double water wash (left, WESP off) and acid wash (right, WESP on) on AMP, PZ and NH<sub>3</sub> emissions of CESAR1.**

27 tests on “load following” and “shut down/warm start-up” scenarios have been realised and demonstrated that after any flow rate perturbation, the plant consistently returned to steady state quickly. Peaks in AMP and PZ emissions occurred during load following and shut-down/start-up tests, but the dry bed significantly reduces AMP and PZ emission peaks below 2 mg/Nm<sup>3</sup> and 1 mg/Nm<sup>3</sup>.

**Task 2.3 Analysis of emission mechanisms at SINTEF IND’s capture plant at the CO<sub>2</sub> Lab at Tiller and Niederaussem capture plant:** 930 kg of the long-time aged CESAR1 (34,000 operating hours) was

transported from Niederaussem to Tiller for the tests in Task 2.3. It could be demonstrated that the ACEMS was capable to follow dynamic trends in emissions. However, it was observed that with respect to most of the analysed components, the calculated concentrations from the ACEMS samples are somewhat underestimated compared to other measurement techniques (FTIR, manual impinger). Since it was also observed that that a major part of emitted compounds is water-soluble and collecting the condensate is sufficient to capture them, it is believed that the accuracy of the ACEMS is mostly related to the appropriate sampling rate, meeting the isokinetic condition. In addition, the effect of changes in process parameters on different classes of compounds has been assessed. The performance of ACEMS was also validated in a campaign at Niederaussem on volatile and aerosol-based emissions.

#### Task 2.4 Emission mitigation at HVC’s capture plant at the Alkmaar Biomass-to-Energy plant:

In three test campaigns at HVC’s capture plant at the Waste-to-Energy plant using MDEA/PZ as solvent, it was shown how the operation of two WESPs affects the formation of aerosol nuclei in the flue gas and causes high amine emissions. The emissions are highest when both WESPs are on, and lowest when both WESPs are off (Figure 4-6). The aerosols contain more MDEA than PZ. Additionally, a transportable water wash column was installed between absorber outlet and water wash and the emissions were measured for different L/G ratios, from 0 (dry bed configuration) to 4.0. The emission reduction increases with increased liquid flow in the wash (not significantly in the presence of aerosols). It can be concluded that the water wash and the dry bed technology are efficient emission mitigation strategies.

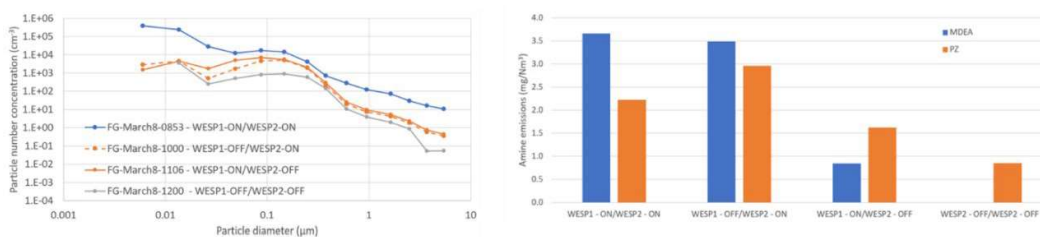


Figure 4-6 Aerosol formation for the MDEA/PZ-based solvent due to the operation of one or two WESPs.

**Task 2.5 Evaluation of emission mitigation technologies for capture plants at coal power plant and fertilizer production in India:** Despite a detailed test plan for field measurements at a CO<sub>2</sub> capture plant sites in India, which describes the prepared measurement methodology of the testing campaigns and regarding laboratory analysis of the impact of amine-rich waste streams on local ecosystems it was impossible to realise measurement campaigns regarding volatile emissions at the Tuticorin site (alkali chemicals and fertilizers production, solvent CDRmax) and at Vindychal (hard coal fired power plant). Instead, it was worked on the process design including equipment sizing and costs of a capture plant retrofitted for 2 cases (coal fired power station and an industrial-scale plant, with India specific boundary conditions).



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### 4.1.3 WP3: Environmental quality standards, impacts and risk assessment


#### Task 3.1 Methods and guidelines for environmental and health risk assessment Sub-task 3.1.1

**Environmental hazard method description and development:** The partners reviewed the principles and methodologies of environmental risk assessment (ERA). In the public **deliverable report D3.1**, the risk-based approach used in SCOPE was also introduced. Reliable data on degradation, bioaccumulation and ecotoxicity of amines, solvents, and degradation products relevant for carbon capture technologies were also summarised (Figure 4-7). Finally, the partners described the use of assessment factors and mixture models in ERA and presented Predicted No-Effect Environmental concentrations (PNECs) for several amines, solvents, and degradation products. Based on this, the risk of emissions of potential PBTs have been addressed providing a better understanding of potential environmental risks of discharges and to support future ERA processes related to carbon capture. A further public **deliverable D3.2** has been produced providing an assessment of the impact of various amines on micro- and macro-organisms and their potential biodegradability in the ecosystem. Specifically, the report outlined the ecotoxicological effects of amines, reporting on findings of acute and chronic toxicity, effects on marine organisms, freshwater fish, aquatic invertebrates, the toxic effects of aromatic amines on eukaryotic protists (Ciliates). In addition, effects of amines on terrestrial plants, algae and cyanobacteria, bacteria response as well as the potential impacts of amines on ecosystems have also been presented.

Substance	Abb.	CAS no.	Persistence (years)		Biodegradability		Bioaccumulation		Toxicity					
			Hydrolysis	Photohydrolysis	Primary	Ultimate	Ready/bioaccumulable	Octanol-water	Bioconcentration	Fish	Daphnia	PNEC	PNEC	
			months (days)	months (days)	Estimated time factor	Estimated time factor	Yes/No	Yes/No	log K <sub>ow</sub>	BCF (mg/L)	LC50 (mg/L)	LC50 (mg/L)	mg/L	mg/L
Acetic acid		64-19-7	No data	17.2	6,1467 (days)	6,1467 (days)	Yes	0.17	0.7484	4603	12270	25796	4000	4.403
Acetic acid		14849-7	No data	19.3	4,4891 (days)	3,7164 (days)	Yes	0.74	0.894	4603	12270	25796	4000	4.46
Acetic acid		15521-4	No data	0.1	9,9488 (days)	3,2488 (days)	Yes	0.27	0.893	34000	98056	91900	48956	58.96
Hydroxyphenyl ethylamine	HEPE	2098-11-4	No data	0.8	9,9979 (days)	2,9398 (days)	Yes	0.01	0.9172	No data*	No data*	No data*	No data*	No data*
Hydroxyphenyl ethylamine	HEPE	5879-28-9	No data	No data	No data	No data	No data	No data	No data	No data	No data	No data	No data	No data
Hexamine		7668-41-7	No data	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	100	260	545	100	0.1
Hexamethylene		50-09-0	No data	3.9	4,0621 (weeks)	3,1555 (weeks)	Yes	0.95	0.996	48	46	13	13	0.013
Hexylamine		73-07-0	No data	0.6	3,9908 (days)	3,1243 (days)	Yes	0.84	0.9365	152	183	34	34	0.084
Hexylamine		107-23-8	No data	3.8	4,0621 (weeks)	3,1555 (weeks)	Yes	0.96	0.994	8196	16264	38130	8196	3.819
Hexamine		8744-1	No data	32.6	3,7471 (days)	3,0743 (days)	Yes	0.24	0.929	4824	2451	711	711	0.711
Hexamine		76-64-8	No data	0.4	3,7123 (days)	3,0561 (days)	Yes	0.84	0.9644	106	127	203	106	0.106
Hexamine		7449-5	No data	0.5	3,8462 (days)	3,1556 (days)	Yes	0.57	0.9144	43	28	33	28	0.033
Hexylamine		124-63-8	No data	0.2	3,8309 (days)	3,1560 (days)	Yes	0.34	0.9366	39	21	33	21	0.032
Hexylamine		75-04-7	No data	0.4	3,8209 (days)	3,1246 (days)	Yes	0.13	0.9559	28	21	23	21	0.021
Hexylamine		104-69-7	No data	0.1	3,7859 (days)	3,0205 (days)	Yes	0.38	0.962	107	8	8	8	0.008
Hexylmethanamine		624-79-2	No data	0.1	3,8657 (days)	3,0990 (days)	Yes	0.35	1.025	17	14	15	14	0.014
Hexylamine		107-23-8	No data	0.3	3,8077 (days)	3,0390 (days)	Yes	0.48	1.067	37	34	33	34	0.034
Hexylamine		2164-80-9	No data	No data	No data	No data	No data	No data	No data	No data	No data	No data	No data	No data
Hexylmethanamine		75-02-5	No data	1.9	3,7397 (days)	3,0343 (days)	Yes	0.31	0.9181	145	102	330	145	0.145
Hexylmethanamine		76-24-9	No data	11.8	3,7296 (days)	3,0333 (days)	Yes	0.19	0.9514	106	742	2106	106	0.106
N,N-Diethylmethylethylenediamine (DEED)	DEED	131-41-9	No data	0.05	3,9039 (days)	3,1775 (days)	Yes	0.13	0.8914	1017	790	10380	790	0.790
Hexamine		76-12-7	No data	1.8	3,9882 (days)	3,0564 (days)	Yes	0.52	0.8916	19	29825	9160	74	0.074
Hexamine		60-35-5	No data	5.4	3,9679 (days)	3,0114 (days)	Yes	0.26	0.8941	11	15510	3230	11	0.011
Hexylamine		142-19-9	No data	1.7	4,0138 (days)	3,0790 (days)	Yes	0.47	0.9614	188	74637	19922	188	0.188
Hydroxyphenyl ethylamine	HEPEA	6434-39-5	No data	No data	No data	No data	No data	No data	No data	No data	No data	No data	No data	No data

Figure 4-7 Extract of the compiled database on degradation, bioaccumulation and ecotoxicity of amines, solvents and degradation products

**Sub-task 3.1.2 Health-related hazard assessment – data for dispersion models:** A comprehensive review of health-related scientific information on the status of occupational health and safety issues associated with potential exposure to amines and their by-products, together with concentrations and sources, has also been conducted and a public **deliverable D3.3** of the project was presented in November 2022. This deliverable was updated once more with the latest literature and made available in August 2025. The report focuses on airborne exposure to amines or exposure through drinking water for the purpose of undertaking a human health risk assessment, comparing concentrations with occupational limits and assessing and quantifying potential health risks following acute and chronic exposure to these chemicals. It aims to help to evaluate the persistence (biodegradability, toxicity and bio-accumulation) and environmental impacts of PCC emissions. **Sub-task 3.1.3 Atmospheric dispersion and fate of emissions:**


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The Gaussian type plume air dispersion model ADMS primarily used to model the air quality impact of existing and proposed industrial installations was updated to include a number of modifications to the ADMS amine module functionality, improving versatility in modelling, allowance for multiple sources and more than one amine in each source, as well as allowance for hygroscopic particulate emissions. These updates have been incorporated in the ADMS 6 software that has been made available for use in SCOPE. For the regional cluster and industry case studies reported Task 3.2.

**Task 3.2 Case studies around facilities - emissions modelling and risk assessment:** Atmospheric ground-level concentrations modelling results, varying as a function of distance from emitting PCC facilities, in the UK, Norway and Germany have been carried out for single facility source and multiple facility sources as appropriate. A scenario approach was chosen to define potential implementation of post-combustion capture options combining emission sources at one site. The **deliverables D3.5** (Teesside industrial cluster, UK), **D3.6** (TCM, Norway) and **D3.7** (Hurth, Germany) report on the integrated atmospheric emissions and degradation modelling and the methodology for human health risk assessment around amine based post-combustion carbon capture plants that has been developed in SCOPE. With the help of our Dutch colleagues and industry partners, have also set up a theoretical imaginary case study around the port of Rotterdam. The results are reported within this report (after the end of the SCOPE project). The main focus of the work was the integration of a detailed air dispersion modelling process to estimate ground level amine degradation product concentrations with a location specific human health risk assessment process, considering the human chronic residential exposure to the substances via the inhalation pathway. Since the quality of input data for the air dispersion modelling is of critical importance, a detailed data preparation process was developed, which was implemented for all case studies. In order to enable a contextualised human health risk assessment, a spatial receptor allocation process was also developed to enable the probabilistic estimation of the cancer risk in the region of interest for every individual.

Figure 4-8 illustrates the key results for one of the UK scenarios studied on the basis of planned PCCC developments in the Teesside region. The scenario accounts for three sources (NZE, TVERF, Redcar Energy Centre) with respective emissions  $1.41 \text{ g s}^{-1}\text{MEA}$ ,  $0.41 \text{ g s}^{-1}\text{DMA}$  and  $0.0017 \text{ g s}^{-1}\text{DMA-NS}$ , assessed for a five year period (2015 to 2019) considering two meteorological stations' data over the periods (Tess Valley Airport and Loftus), parameterised for the key degradation parameter c value at 0.0053 (high), 0.0039 (mid) & 0.00245 (low) level and considering the UK permit limit of  $0.2 \text{ ng m}^{-3}$  annual average. These results indicate that the planned PCCC developments do not pose a significant risk to public health.


For the Norwegian case study, the work conducted included two scenarios. The first scenario was that of the TCM Pilot Plant ( $16.67 \text{ sm}^3/\text{s}$ ) only. The second scenario included the TCM Pilot Plant with the same emission ( $16.67 \text{ sm}^3/\text{s}$ ) and an Imaginary Source (linearly scaled from Pilot Plant based on flue gas volume), aiming to decarbonise the 4 refinery stacks and a potential  $\text{H}_2$  production process ( $279.48 \text{ sm}^3/\text{s}$ ), but not the flare ( $6.24 \text{ sm}^3/\text{s}$ ). In this case the emissions are PZ Amine, AMP amine, PZ NS, PZ NA and AMP

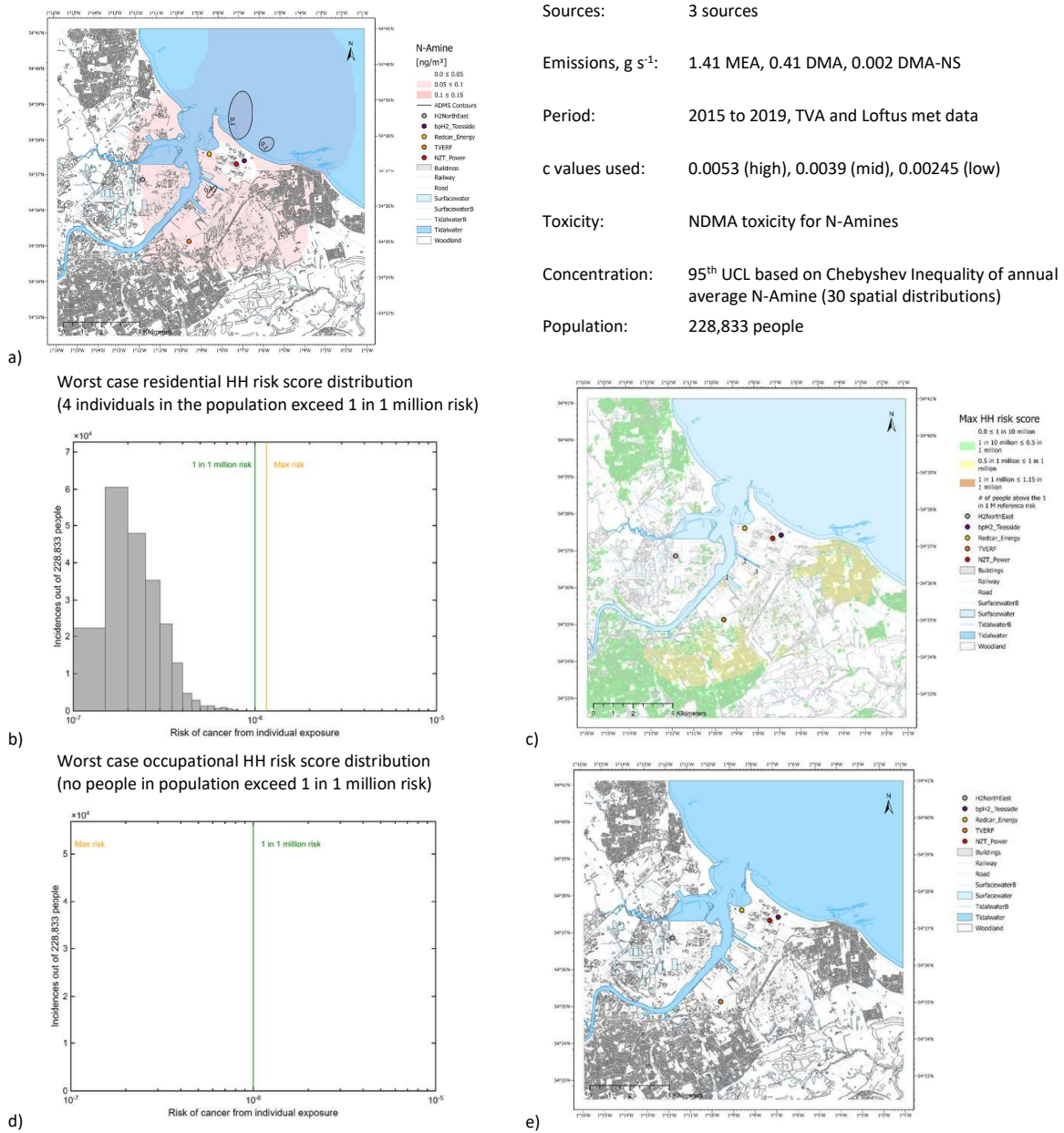
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NA. The first scenario produces very low emission levels and unremarkable potential risk for the 16 spatial distributions estimated (max risk estimated at 0.15 of the reference risk). The imaginary scenario results are shown in Figure 4-9, with emissions of  $0.221 \text{ g s}^{-1}\text{AMP}$ ,  $0.075 \text{ g s}^{-1}\text{PZ}$ , accounting for chemistry with  $\text{PZ } k_2$  ( $7.95 \times 10^{-10}$ ); AMP branching ratio (0.24) for the period 2015 to 2019 and for two c values, 0.00392 (high) and 0.0015 (low). The Norwegian Permit Limit used for the assessment is  $0.3 \text{ ng m}^{-3}$  annual average. These results indicate that the full refinery scale imaginary scenario assessed does not pose an occupational human health risk, while for the worst case human health lifetime risk the estimated maximum value is less than two in a million.


For the German case study, set up in the region of Hürth, the imaginary scenario set up has considered as source a sewage sludge waste to power generation with PCCC using PZ Amine, AMP amine. Two scenarios of source emissions were considered, the first with  $0.01 \text{ g s}^{-1}\text{AMP}$  and  $0.002 \text{ g s}^{-1}\text{PZ}$ , and a higher scenario of  $0.024 \text{ g s}^{-1}\text{AMP}$ ,  $0.004 \text{ g s}^{-1}\text{PZ}$ , accounting for chemistry with  $\text{PZ } k_2$  ( $4.63 \times 10^{-11}$ ); AMP branching ratio (0.52) for the period from 2015 to 2019 and for two c values, 0.00519 (high) and 0.0018 (low). The German Permit Limit used for the assessment is  $0.3 \text{ ng m}^{-3}$  annual average. Figure 4-10 illustrates the results which indicate that the imaginary scenario considered would not pose a significant risk to public health.

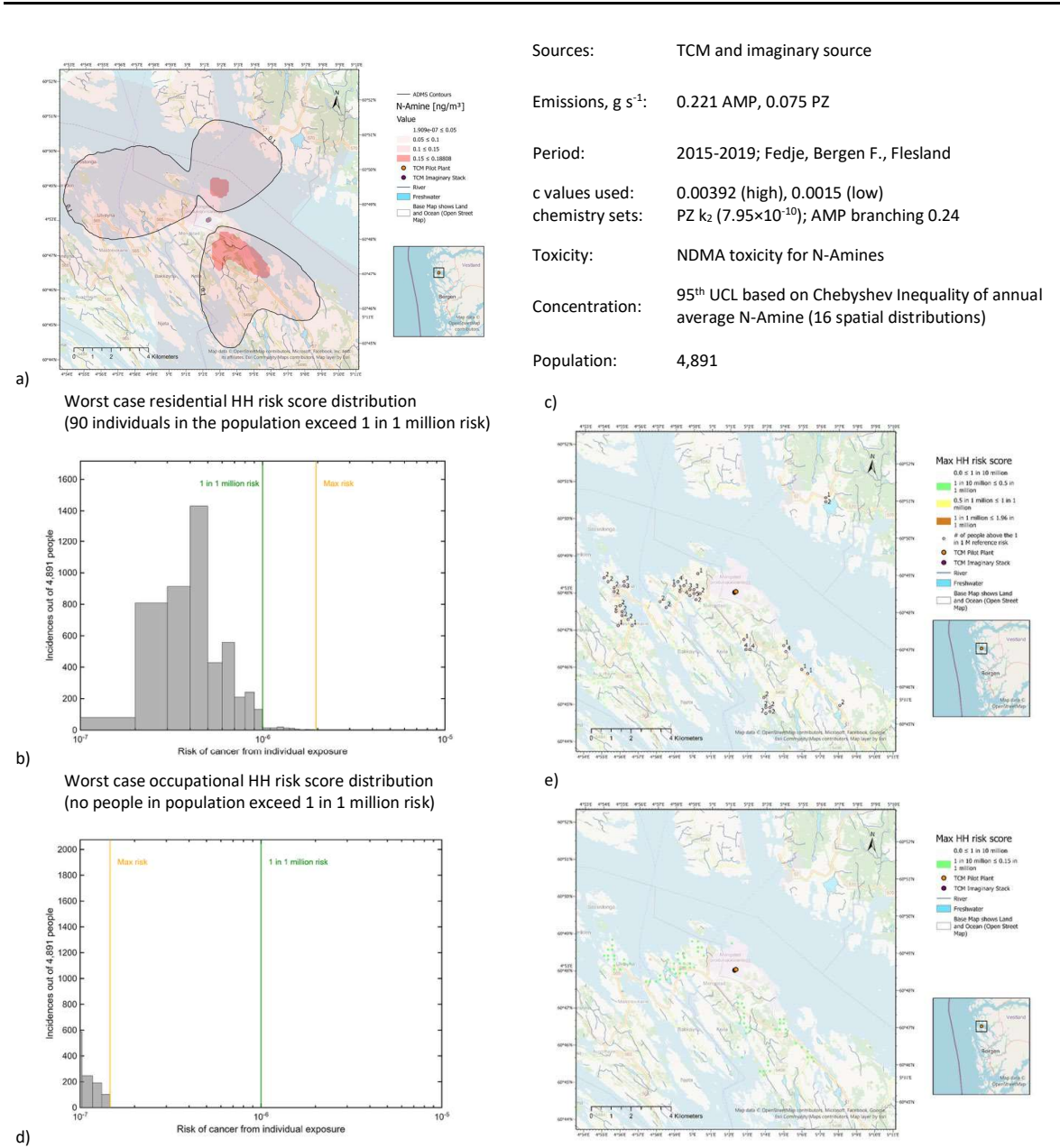
For the Netherlands case study, set up in the region of Rotterdam, the imaginary scenario set up has considered as source a waste to energy power generation with PCCC that would be releasing MEA NA, DMA NA and DMA NS as output pollutants. Two scenarios of source emissions were considered, the first with  $1.287 \text{ g s}^{-1}\text{AMP}$  and  $0.07 \text{ g s}^{-1}\text{PZ}$ , and a higher scenario of  $0.244 \text{ g s}^{-1}\text{AMP}$ ,  $0.013 \text{ g s}^{-1}\text{PZ}$  for the period from 2015 to 2019 and for two c values, 0.00503 (high) and 0.00185 (low). The Dutch Permit Limit used for the assessment is  $0.3 \text{ ng m}^{-3}$  annual average. Figure 4-11 illustrates the results which indicate that the imaginary scenario considered would not pose a significant risk to public health.

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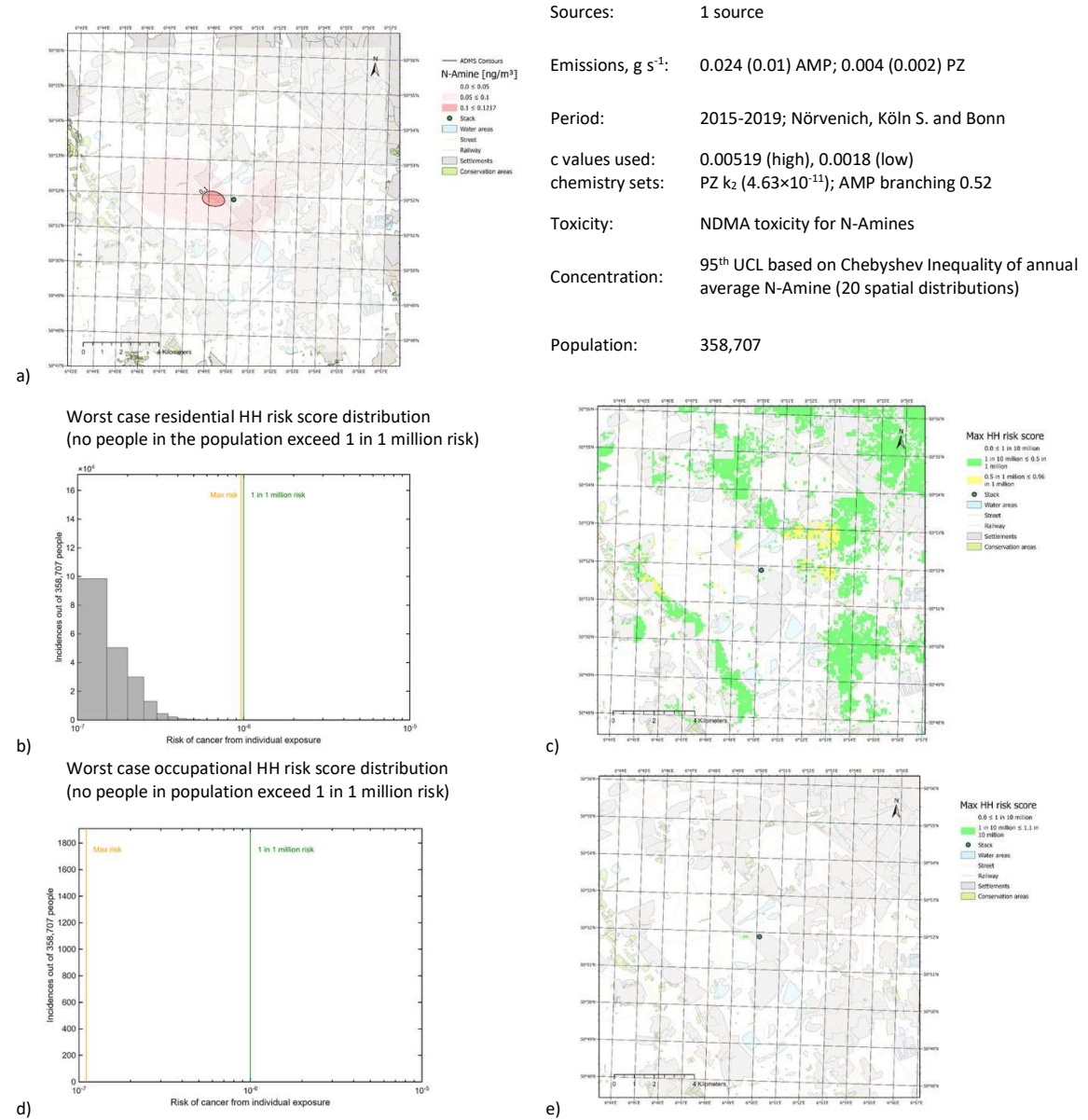
**Figure 4-8 Teesside industrial cluster scenario N-amine exposure and risk a) 95<sup>th</sup> Upper Confidence Limit calculated based on Chebyshev Inequality of Annual average N-Amine concentration (sum of MEA NA, DMA NA and DMA NS) 2015-2019, spatial max is 0.178  $ng\ m^{-3}$  (58.9% of EAL); b) and c) probabilistic result and map, respectively, of the worst case residential human health risk score, max risk 1.15 $\times$  reference risk, all sites located within the industrial complex; d) and e) probabilistic result and map, respectively, of the worst case occupational human health risk, no individuals exceed reference risk, max risk 0.08 $\times$  reference risk.**

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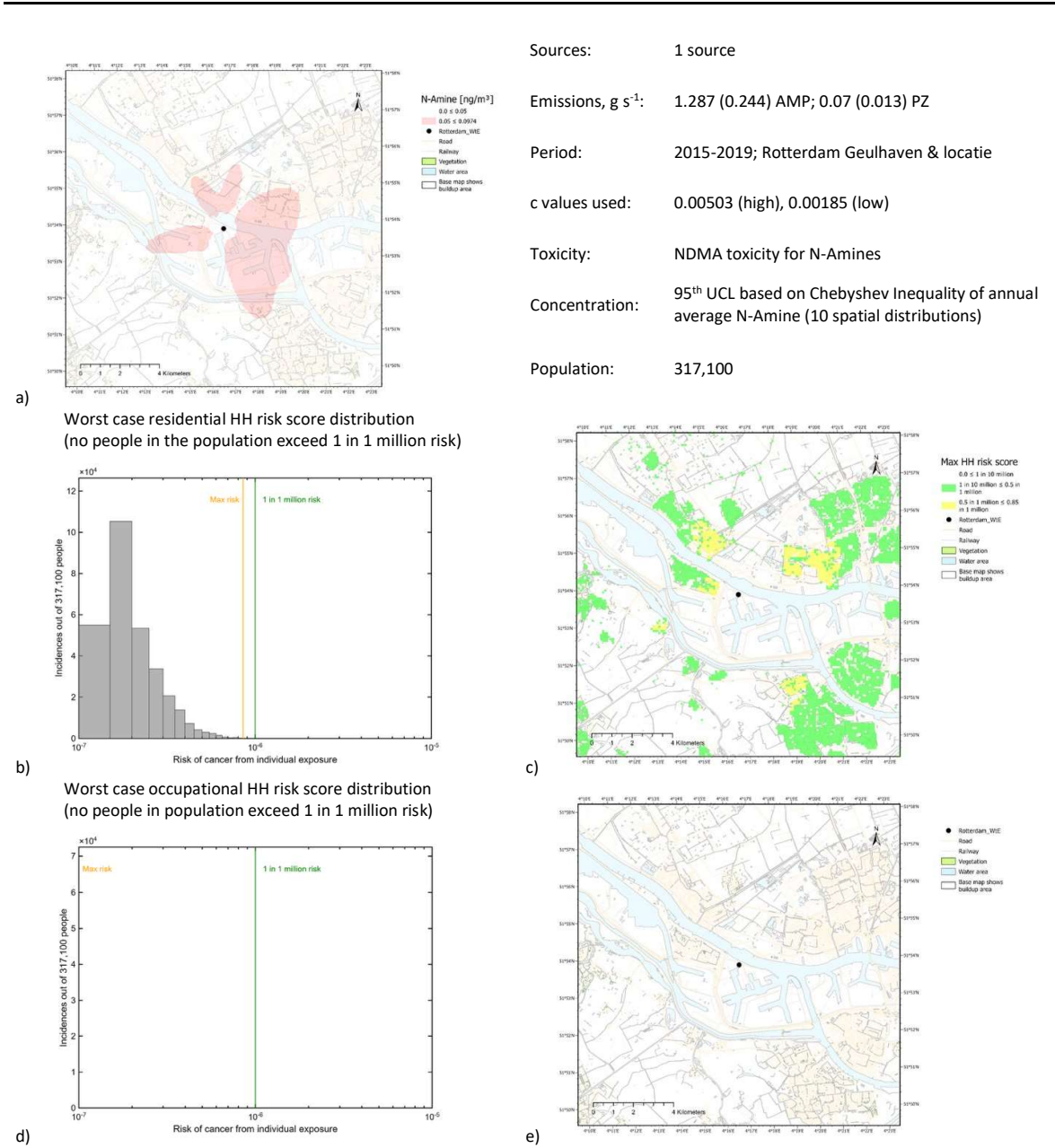
**Figure 4-9 Imaginary scenario of two sources (TCM pilot and refinery with potential H<sub>2</sub> production) N-amine exposure and risk a) 95<sup>th</sup> Upper Confidence Limit calculated based on Chebyshev Inequality of Annual average N-Amine concentration (sum of PZ Amine, AMP amine, PZ NS, PZ NA and AMP NA) 2015-2019, spatial max is 0.1881 ng m<sup>-3</sup> (62.7% of EAL); b) and c) probabilistic result and map, respectively, of the worst case residential human health risk score, 90 individual's risk in population is estimated between 1 in 1 Million and 1 in 100k risk, max risk 1.96× reference risk; d) and e) probabilistic result and map, respectively, of the worst case occupational human health risk, no individuals exceed reference risk, max risk 0.15× reference risk.**

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**Figure 4-10 Imaginary scenario of Sewage Sludge power generation in Hürth, Germany N-amine exposure and risk a) 95<sup>th</sup> Upper Confidence Limit calculated based on Chebyshev Inequality of Annual average N-Amine concentration (sum of PZ Amine, AMP amine, PZ NS, PZ NA and AMP NA) 2015-2019, spatial max is 0.122 ng m<sup>-3</sup> (40.6% of EAL); b) and c) probabilistic result and map, respectively, of the worst case residential human health risk score, no individuals exceed reference risk, max risk 0.96× reference risk; d) and e) probabilistic result and map, respectively, of the worst case occupational human health risk, no individuals exceed reference risk, max risk 0.11× reference risk.**

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**Figure 4-11 Imaginary scenario of Waste to Energy power generation in Rotterdam, the Netherlands N-amine exposure and risk a) 95<sup>th</sup> Upper Confidence Limit calculated based on Chebyshev Inequality of Annual average N-Amine concentration (sum of MEA NA, DMA NA and DMA NS) 2015-2019, spatial max is 0.097 ng m<sup>-3</sup> (32.5% of EAL); b) and c) probabilistic result and map, respectively, of the worst case residential human health risk score, no individuals exceed reference risk, max risk 0.85× reference risk; d) and e) probabilistic result and map, respectively, of the worst case occupational human health risk, no individuals exceed reference risk, max risk 0.02× reference risk.**

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#### 4.1.4 WP4: Mapping state support, market readiness and civil society concerns to promote the legitimacy of amine-based CCUS


##### Task 4.1 Investigating state promotion strategies for amine-based CCUS

All research tasks were finished but the Deliverable 4.1, “Mapping state support for CCUS: The politics, policies and strategies for bringing CCUS to markets in the UK, Netherlands, Germany, Norway and India,” was not submitted before the principal investigator left SPRU. Nevertheless, in August 2023 a presentation based on this work was delivered at the Royal Geographical Society-IBG Annual International Conference 2023 in London at Imperial College. The conclusions in this presentation were

- Nationally-specific support strategies reflect a variety of relational dynamics:
  - Historical capacities for industrial policy (e.g. which instruments to use; how much to consult; what kinds of oversight).
  - Societal expectations, including civil society advocacy for carbon emissions reductions and community backlash.
  - Industry reticence / readiness to reduce based on existing asset base and perception of financial risks.
- UK-Norway comparison underscores different approaches to consultation and competition in industrial policy. What are the implications?
- Societal acceptance in UK and Netherlands shows that local community responses reflect regional and local lived-experiences and perceptions of injustice, as well as how labour and environmental advocacy groups frame the impacts of CCS projects.

##### Task 4.2 Investigating of market readiness for amine-based CCUS value chains

In this task the market readiness was assessed for amine-based CCUS by examining the value chains poised to adopt CCS/CCU for hard-to-abate sectors including cement, power, steel, and chemicals. The work that was done by SPRU in this task was focused on cement and power. The research entailed analysis of industry trade association publications, academic and business reports, peer-reviewed scientific literatures, news media, and observation of various industry and think-tank conferences featuring key players in these sectors. The analysis underscores the importance of proper accounting of emissions and co-benefits, along with the role that regulation and industrial policy may play in establishing the downstream conditions needed to support CCUS value chains. Thus, whereas research in 4.1 developed recommendations for Task 4.4 regarding policies to “push” CCUS into the market, the recommendations emerging from for 4.2 focused on policies that help to “pull” amine-based CCUS technologies into the market, such as downstream market-based policy instruments and institutions including the ETS, CBAM, development of improved carbon accounting tools and more.

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### Task 4.3 Investigating civil society acceptance of amine-based CCUS in value chains in participating countries

This work was only partly completed for UK in which various focus groups were interviewed about the public opinion. In Figure 4-12 an example of categorizing the feedback from the various groups is shown. In Figure 4-13 an extract of the UK survey is shown.

Media	Codes													Totals								
	Local Histories: Industrial heritage	Pride in industrial heritage	Past industrial governance	Past social cohesion & quality of life	Past industrial relations	Past career & workforce trends	Lived experiences: Quality of life,	Environmental (in)justice	Social inequalities, deprivation,	Blight & municipal divestment	Becoming 'green'	Social cohesion and quality of life	Concerns about Industrial		Decarbonization, but not at the	CCS risks & concerns	Hydrogen risks & concerns	Future Visions & Expectations	Leading the next "green" industrial	Unlocking local carbon lock-in	Social cohesion for future	Becoming a desirable place
UK FGs Wales Group 2 new.pdf		2	10	2	3	5		8	6	2	3	6		11	7	2			12		4	83
UK FGs Wales Group 1 new.pdf		1	15	2	1	5		7	6	4	4	5		3	2	2		2	15			74
UK FGs Merseyside Group 2		1	13	3	1	7		12	8	5	4			7	4	3		1	18	1		88
UK FGs Merseyside Group 1		3	14	3	2	7			6	1	1	5		3	4	5		4	8	2	3	71
UK FGs Grangemouth_Scotland		2	19	7	2	8		8	2	2	6	5		1	5	4		3	14	1	2	91
UK FGs Grangemouth_Scotland		3	9	1	2			11	14	4	2	8		4	7	5		2	12			84
Totals		12	80	18	11	32		46	42	18	20	29		29	29	21		12	79	4	9	

Figure 4-12: UK Focus groups: Frequency and code applications

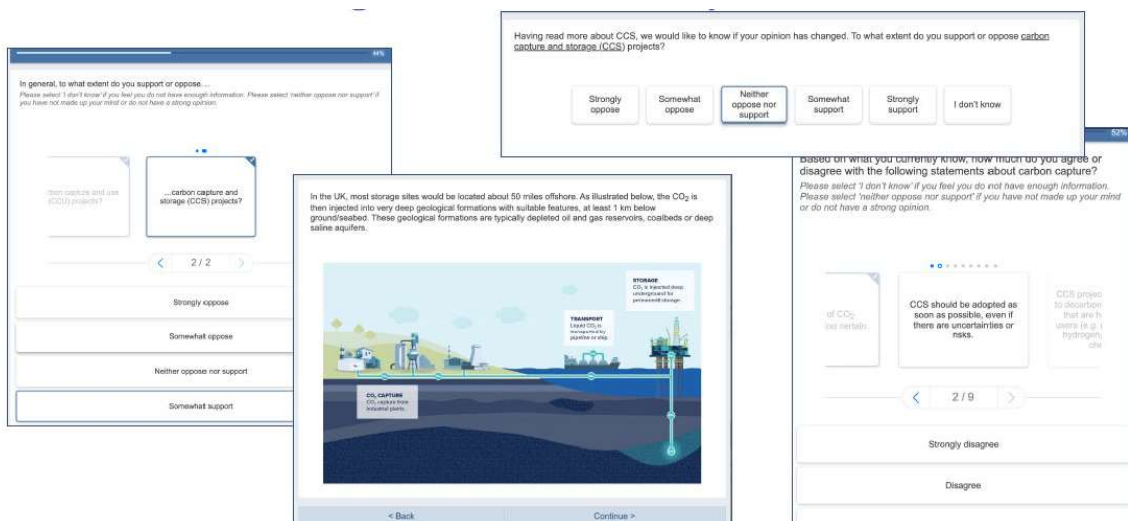



Figure 4-13: Example from the UK survey

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#### **Task 4.4 Governance strategies and practices that can ensure decision-makers from government and industry are accountable to diverse publics**

In this task the idea was to bring together insights developed from the three previous tasks to highlight governance gaps and areas of weak accountability that undermine the legitimacy and social acceptance of CCUS, with recommendations for how to address those deficiencies. Unfortunately, this work was never completed as it was planned after the principal investigator left SPRU.

#### **Task 4.5 Knowledge transfer through the Stakeholder, Policy, Research and Industry NetWork (SPRINT)**

The main activities in this task have been to share knowledge between universities, research institutes and industry operators, relevant governmental and non-governmental organizations including regulators, and any other stakeholders involved in or having expertise on permitting processes, and industry and regulatory developments. All 6 SPRINT events have been successfully completed. A public report has been written with a summary of the events.

After organizing all events we can conclude that:


- Emission mitigation is essential to get and maintain a license to operate.
- There are rules in all countries regarding emission monitoring (what components, how, where and when to measure them).
- The above-mentioned rules differ per country and even within the country.
- SPRINT has given information on monitoring technologies and emissions mitigation technologies there were applied in the various countries.
- There are funding mechanisms in place in most countries to support the implementation of CCUS but again, these mechanisms are very different from each other between countries.
- Harmonizing rules among the countries might be too ambitious and difficult. Full scale plants are (being) built in most countries that participated in SCOPE, so the need to have uniform rules is maybe also less necessary than anticipated when we have put SCOPE together.

#### **4.1.5 WP5: Project management, dissemination, and exploitation**

##### *4.1.5.1 Task 5.1 Project management*

Sub-task 5.1.1: Project planning, monitoring, and execution

The project management and dissemination activities require special attention in a large project like SCOPE. With 24 partners and over 45 deliverables and around 32 milestones, the project management requires close follow up of deviations and follow up of any issues deviating from the plan. On the other hand, delays can occur, which might not be a problem when the delay is not affecting any other tasks or if those involved in affected tasks are aware of the consequences and accept the mitigation plan as defined. The main target for the project is to deliver results with as high quality as possible within the boundary conditions set by the project (planning in time and budget).

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Though SCOPE covers a rather limited area, it covers the whole chain of amine emission from the source in the absorber through the water-wash section and other emission mitigation measures, through the atmosphere and finally the effect it might have on the environment. SCOPE is the first project in which this approach is attempted in order to obtain more holistically solutions to how this side-effect of amine-based CO<sub>2</sub> capture can be handled in the best possible way. However, it is a bit challenging as it requires collaboration across the usual boundaries and disciplines.

#### Sub-Task 5.1.2: Legal support

Most of the work related to this sub-task was in the beginning of the project to establish the consortium agreement. The process of getting consensus on this agreement was very challenging and time-consuming for the Coordinator. Nevertheless, after rounds with 5 various versions and additionally several bilateral meetings we were able to sign the consortium agreement three months after start-up.


Legal support was asked for towards the end of the project when the partner SPRU decided to pull out without being able to complete their commitment. However, we decided to not pursue this issue any further.

#### Sub-Task 5.1.3: Financial support

The financial activities for SCOPE are handled at national level in Norway (SINTEF), The Netherlands (TNO), Germany (RWE), UK (IMPERIAL), USA (NETL), India (GGS IPU).

#### Sub-Task 5.1.4: Organize and participate in meetings

Since the consortium agreement was not signed before the kick-off meeting, there was no official general assembly (GA) meeting during that event. However, some voting was conducted by e-mail later and the first general assembly meeting was arranged in connection with the project meeting in Germany in November 2022. The second and last GA was arranged together with the project meeting in Norway, October 2023. There have been several monthly/bi-monthly meetings in the project management team (PMT) and seven technical project meetings (kick-off in Trondheim, Norway in late October 2021, one in Bergen/TCM, Norway in early May 2022, and one in Cologne/Niederaussem, Germany in November 2022, Trondheim, Norway in June 2023 adjacent to the TCCS-12 conference, one in Porsgrunn, Norway in October 2023, one in Hengelo, The Netherlands in April 2024, and finally one in London in December 2024 in connection with the final dissemination event, which was a SPRINT event) in addition to 6 SPRINT events in the total project period. Except for the SPRINT event #3 which was organised in India and the SPRINT event #5, which was organised as a webinar, all the other events have been organised together with the project meetings (Bergen/TCM, Cologne/Niederaussem, Trondheim, London). The PMT meetings have been organised using the TEAMS online platform, while the kick-off and project meetings were organised as hybrid (both in-person and online participation). Quite many of the project participants

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prefer the online version, which is not so good for the collaboration. However, of course this reduces the travel costs while also more people are allowed to join. More challenging especially for the whole day meetings is the spread in time-zones from -6.5 to +6 while the meetings are organised in Europe (-1/0).

The Coordinator of SCOPE, Hanne Kvamsdal (SINTEF IND), has given the presentation of SCOPE and some major results at the yearly ACT Knowledge sharing conference (Rotterdam, The Netherlands, June 2022, Paris, France, October 2023, Oslo, Norway, 2024). She was also invited to the Climit Summit conference in Larvik, Norway, in February 2023.

There has been some collaboration with the ACT2 project LAUNCH as many of the partners were involved in that project as well, but since the focus in SCOPE is a bit special compared to other ACT projects, there is not so much to gain from technical collaboration. However, other aspects of the project (like the challenge with the Consortium Agreement and the work related to Social Acceptance) were discussed in the Rotterdam conference with Coordinators of other ACT projects but this did not lead to any further collaboration

#### *4.1.5.2 Task 5.2 Dissemination and exploitation*

##### Sub-task 5.2.1 Kick-off event and project briefing


As already mentioned, the project kick-off meeting was arranged as a hybrid meeting in Trondheim, Norway October 27th - 28th 2021. A summary of the project is presented at the SCOPE web-page (<https://www.scope-act.org/>)

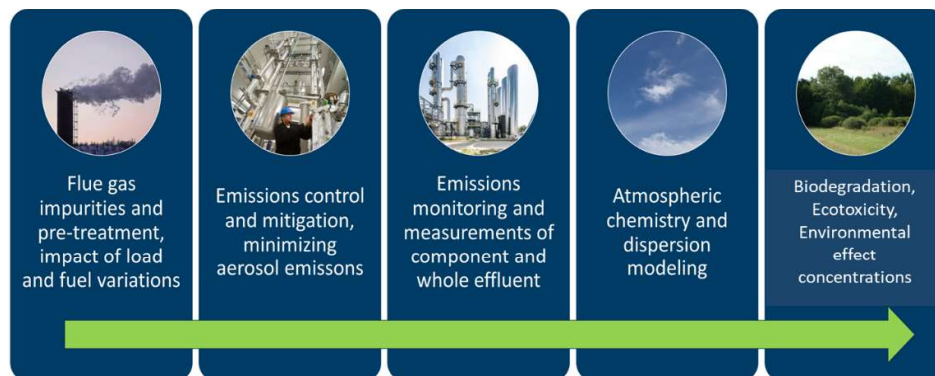
##### Sub-task 5.2.2 Develop a Communications and Dissemination Strategy

A communication and dissemination strategy was established and reported in deliverable D5.6 (issued 11<sup>th</sup> November 2021).

##### Sub-task 5.2.3 Commissioning of project visual identity and website

The logo can be seen in the heading of this report while the project overview picture is shown in Figure 4-14. The Logo was established as part of the project, while the overview picture was established during the proposal phase. Both have been actively used to present the project.

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**Figure 4-14: SCOPE project overview picture**

Templates for project deliverable reports, MoM, and presentations (including poster) were established for the partners. Seven major updates about SCOPE events and other dissemination activities were posted at our established web-site (<https://www.scope-act.org/>). Also accounts on Twitter and LinkedIn were established (@SCOPE\_ACT).

#### Sub-task 5.2.4: Targeted communications and engagement throughout the project

Dissemination is an important part of SCOPE and dissemination of project results were actively pursued, taken into account the interest of the project partners. IMPERIAL together with SINTEF IND was proactive in branding SCOPE and making the project known by the public and scientific community. Project “news” (e.g., SPRINT events) and important posts at our website were announced on Twitter and LinkedIn.

All public materials (public deliverables, presentations at conferences and public meetings, conference and journal publications are made available either directly at the website or as a link to conference proceedings or journals. See Chapter 8 for further details.

It should be noted that the SPRINT#4 event was a side-event of the TCCS-12 conference and it was fully open to public. A link to the project website from the TCCC-12 website was established to inform about the event and also so that participants outside the consortium could register for the event. This information was also published at the LinkedIn page for the CO<sub>2</sub> capture group at SINTEF. Though it was planned to have one webinar per technical WP (1-4) it turned out to be too ambitious and only one webinar was arranged in June 2024, but this webinar titled “Emission control technologies: Insights from SCOPE campaigns” covered aspects from both WP1 and 2 as these WPs were very integrated. It was planned a webinar from WP4 (Task 4.1 to 4.4) in October, but since the WP-leader, representing the partner SPRU, pulled out from the project in May and no one else were actually involved in these tasks, it was decided to abandon it. WP3 topics were addressed specifically in the final dissemination event in December 2024 instead of a separate webinar.

## 4.2 Overview of financial results

The financial results are shown in Table 4-1 (one partner from UK, both US partners and one Indian partner are missing). As can be seen some partners have used more while others have used less.

**Table 4-1: Financial progress for the period 01.10.2021-31.12.2024. All numbers in EURO.**


Partner	WP1	WP2	WP3	WP4	WP5	Total M39	Actual% of total budget
SINTEF AS	88155	108200	11389	24829	210933	443506	110.9 %
SINTEF Ocean AS			130276			130276	98,2 %
NTNU	143907					143907	100,3 %
TNO	153709	153.283	2.425	49939	25347	384709	100,7%
Imperial College			712279	37080	139819	889178	103.6%
RWE Power AG *	22705	1951455	3763	969	38377	2017268	135.0%
TOTAL E&P NORGE AS	5855	3903	13662	9758		33178	132.9%
University of Sussex				124472		124472	59.7%
Herriott-Watt University	335268	84061				419329	99.7%
NILU			60825			60825	100.6%
Technology Centre Mongstad	11548	3434	13736	5606		20822	72.1%
Herøya Industripark AS	3674	2450	8574	6124		20822	83,4 %
Hovyu B.V.	145200				10000	155200	100%



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Twence B.V.	31260	382135				413395	79.6%
HVC		32555			3971	36526	133,8 %
Linde GmbH, Linde Engineering Division	27000	58000	9115	5000		99115	55%
OGT							
GG5 IP University		8010	29368	5340	10679	53397	55%
NETL							
Environment Agency			6840			6840	100%
IIT, Kharagpur	13500	15000	14000	4000	10000	56500	59%
Microfilt India Pvt. Ltd.							
Cambridge Environmental Research Consultants Ltd			46174			46174	92.3 %
Aker Carbon Capture	10083		5882	4201		20166	55.9 %
<b>Total</b>	<b>847957</b>	<b>2565295</b>	<b>1056238</b>	<b>147676</b>	<b>295336</b>	<b>5575605</b> <b>6004881</b>	<b>93%</b> <b>Applied for</b>

\* 14591 Euros of RWE's stated costs for WP2 are still outstanding invoices.

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## 5 Project impact

### 5.1 Contribution to the facilitation of the emergence of CCUS

The SCOPE project has covered many aspects along the continuous path of the treated gas from source to recipient, which are important for a sustainable and environmentally safe operation of CO<sub>2</sub> capture plants. Important questions addressed in the project is how we shall determine the effect of emissions and what is actually acceptable capture plant emission of amines and its degradation compounds. We know it is possible to reduce capture plant emissions to meet regulatory requirements, but are these requirements adequate and based upon health/environmental effects, and what are the associated costs ? Though the answers are case specific, SCOPE has contributed with insights into many important aspects like effect of various emission mitigation technologies, modelling of emission, atmospheric dispersion modelling, fate of chemicals in the environment and determination of acceptable concentrations in the environment. These insights are valuable for emission guidelines established by the environmental authorities. More details concerning the specific key results are covered in the next section.

Though the SCOPE project has closed important knowledge gaps, there are still a need for further studies within the topics covered in SCOPE. These are already started or planned for. For example, the ongoing project AURORA (<https://aurora-heu.eu/>), in which the aim is to qualify the CESAR1 solvent for commercialisation, utilises the knowledge gained from SCOPE related to emission mitigation technologies and the economic framework for cost-estimation of such technologies, emission modelling and online emission monitoring to further improve emission control.

The economic framework developed in SCOPE will also be used in the CETP DRIVE project, that is coordinated by TNO.

### 5.2 Key expected results and impact

An overview of the key expected results and their impact is shown in Table 5-1.

**Table 5-1: SCOPE key results and impact**

WP	Key expected results	Impact	Status
1	Improve online monitoring systems.	This will increase the speed and accuracy of plant control leading to better process quality and it opens the door to further control	The ACEMS is modified and commissioned in WP1. Deployment in WP2, first at Tiller, at the very end of the project at RWE.



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	<p>Improve prediction of amine emissions by further develop and validate models</p> <p>Develop a Framework to assess the implications of emission mitigation in various sectors</p>	<p>automation, leading to lower emissions and OPEX.</p> <p>Better models lead to better predictability in both volatile and aerosol emission which is important for understanding plant operation and designing new plants.</p> <p>The Framework will be published and could be a new standard. The use cases will inform end users about the possibility on the implementation of emission mitigation measures</p>	<p>Models have been developed and validated with data from WP2 to better predict emissions (aerosol model) and to support the design of pilot plants with emission mitigation technologies (ProTreat and ASPEN).</p> <p>The Framework is being made public. Uses cases have been defined and reported.</p>
<p><b>2</b></p>	<p>Provide reliable process data, operational data, sample analysis and operational experiences from tests at industrial sites for the assessment of the performance of emission mitigation technologies for capture plants.</p>	<p>High quality data from real test are available for model evaluation and TEA and LCA.</p> <p>Confirmation of the very high purity of captured and liquefied CO<sub>2</sub> from amine-based CO<sub>2</sub> capture.</p> <p>Demonstration that effective emission mitigation technologies are available, regardless of particle number and O<sub>2</sub> concentration in the flue gas,</p>	<p>Comprehensive data files are available from five campaigns at industrial sites. Analyses data of the purity of captured and liquefied CO<sub>2</sub> from two industrial sites using two solvents (MEA, CESAR1) has been presented to the public.</p> <p>Real-world data on the effectiveness of several options for industry to mitigate aerosol-based and volatile emissions for a wide range of boundary</p>

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		solvent aging, and CO <sub>2</sub> capture rate.	conditions have been published.
<b>3</b>	Integrated results from the testing and modelling work in WP1 and WP2 in the scenarios development work carried out in Task 3.2 for single emission sources and also for the regional decarbonisation studies carried out. Followed up to human health risk assessment for each of these case studies and considered ecological impacts in experimental settings.	Achieved integration between project elements and illustrated that the differences between sites, industrial systems configurations, geographies, weather conditions and background pollution levels need to be considered concurrently and specifically to ensure the selected PCCC designs offer acceptable and confident protection of the local environment and human health.	The integrated modelling tools developed have been implemented for regional case studies in the UK, Norway, Germany and the Netherlands.
<b>3</b>	Development of Environmental and Health Quality Standards for critical emissions	Considered the project results, advice and input from regulators and industry stakeholders to provide advice for planned and future PCC facilities.	

### 5.3 Policy development

The SCOPE impacts on policy development have come primarily from WP4 through the SPRINT forums (Task 4.5). The workshops and discussions in the workshops have brought SCOPE partners and researchers into conversation with a small number of regulatory and other policy decision-makers. A central aim of all other WP4 research tasks (i.e., 4.1, 4.2, 4.3) was to identify additional needs for policy support. Unfortunately, this work was not completed as the principal investigator left SPRU and they could not provide a suitable replacement.

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## 5.4 Public acceptance and gender issues

There is no gender issues related to technology development of technology for CO<sub>2</sub> capture, but it might be an issue how amine-based absorption and the effect of emission of the environment is seen by men and women. It was the plan to check out this particularly in SCOPE as part of WP4, but as the principal investigator left the project, it has not been possible to further pursue this within the project.

## 6 Implementation


SCOPE is important for many of the Research and Innovation (R&I) Activities proposed in the SET-Plan TWG9 CCS and CCU Implementation Plan. Especially, results of SCOPE are highly relevant for the Delivery of regional CCS and CCU clusters.

## 7 Collaboration and coordination within the Consortium

The work-package leaders have checked the progress for each partner on WP-level by arranging regular meetings.

Since the start of the project, monthly joint meetings with WP1 and WP2 were organised because they are very linked together. Within WP1 the modellers also met on a monthly basis to discuss more in depth the technical challenges in modelling and validation. Additionally, a team from RWE, NTNU, HWU and TNO used the data of the first test campaign at Niederaussem in WP2 to evaluate and optimise models on vapour-based and aerosol-based emissions and the effect of emission mitigation measures (water wash, dry bed, wet ESP). In this campaign measurement equipment from TNO could be continuously used by RWE staff, after training by TNO. Data packages from Niederaussem have been also used for the further development of the modelling tools ProTreat (OGT, HOVYU) and Aspen plus (NETL). Special samples (droplets between water wash and demister, composition of water wash liquid) have been taken at Niederaussem by RWE to validate an advanced aerosol model from NTNU. The transport of aged CESAR1 solvent from RWE to SINTEF was carried out and used in a test campaign at Tiller. Furthermore, the interaction between all work packages were more intensified towards the end since a lot of data became available for use among the work packages, especially the cost estimations for different emission mitigation measures in WP1, the analysis of their environmental impact in WP3, and consequences for civil society acceptance in WP4.

Furthermore, at least every second month the Project Management Team has met online to discuss progress and issues in that respect. All WP-leaders, one person from USA and two persons from India are members of the PMT to ensure updates from each of the three continents. Every 6<sup>th</sup> months, a project meeting often combined with a SPRINT event were arranged to ensure involvement of all partners. The

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project meetings are arranged as hybrid meetings, but a challenge is the time difference between the three continents when arranging full day meetings. Unfortunately, the partner SPRU left the project in 2024, without providing their deliverables for the project. This was disappointing.

Since the Climate change and the mitigation option from deployment of CCSU have a world-wide focus, it is important to work together to identify differences and similarities faced by the various partners in different countries and continents. The SCOPE project covers a very narrow focus area, but it is an important area for a type of technology that may be deployed in many different countries and continents of the world. The SCOPE consortium was built to ensure a broad impact in that respect and thus a clear added value is seen from trans-national collaboration.

## 8 Dissemination activities (including list of publications)

### 8.1 Participation in Conferences


The most important conference attended in the reporting period was the 16th International Conference on Greenhouse Gas Control Technologies, GHGT-16, which were arranged in Lyon, France from 23-27<sup>th</sup> October 2022. However, several contributions have been submitted to conferences that are arranged in 2023. Papers and presentations for the GHGT-16 conference are available at the project web-site (<https://www.scope-act.org/ghgt16>), while the abstracts submitted for the others will be uploaded when accepted.

#### 8.1.1 16<sup>th</sup> International Conference on Greenhouse Gas Control Technologies, GHGT-16

Four abstracts submitted for the GHGT-16 conference in Lyon, France in October 2022 were accepted and four papers for the conference proceedings were submitted 30<sup>th</sup> August. These four are listed in the following table.

**Table 8-1: Papers and presentations from the partners at the GHGT-16 conference**

WP	Type of publication	Authors	Partners	Title	Date/year
1	PoPa	H. M. Kvamsdal, P. van Os, P. Moser, A. Korre, A. Martin, M. S. Matuszewski, N.C. Gupta, P. Khakharia, C. McNally	SINTEF IND, TNO, RWE, IMPERIAL, SPRU. NETL, GGS IPU, MIPL, IMPERIAL	SCOPE: an ERA-NET ACT project on sustainable operation of post-combustion capture plant	23-27.10/2022

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1	PoPa	Charithea Charalambous, Laura Herraiz, Ardi Hartono, Hanna Knuutila, Susana Garcia	HWU, HWU, NTNU, NTNU, HWU	Advancing the large-scale development of PCC processes by providing essential VLE data for aqueous solutions of amines	23-27.10/2022
2	OPa	Juliana Monteiro, Eirini Skylogianni, Arjen Huizinga, Joost Kiewik, Mathijs Vos	TNO, TNO, TNO, Twence, Twence	Aerosol and volatile emissions control in an amine-based CO <sub>2</sub> capture plant	23-27.10/2022
5	PoPa	Diego D. D. Pinto, Juliana G. M.-S. Monteiro, Eirini Skylogiani, Peter Moser, Georg Wiechers	Hovvy, TNO, TNO, RWE, RWE	Validation of process simulator with new plant data for MEA and CESAR1	23-27.10/2022

### 8.1.2 16th International Conference on CHEMICAL AND PROCESS ENGINEERING, ICHEAP16


One abstract was submitted for presentation at the ICHEAP16 conference, 21-24 May 2023, in Naples, Italy (<https://www.aidic.it/icheap16/>). The title and authors are:

"Thermodynamic Validation of CESAR1 Model and Effect of Water Wash Configurations" by Diego Pinto (Hovvy) and Jeffrey A. Weinfeld (OGT).

### 8.1.3 12<sup>th</sup> Trondheim Conference on CO<sub>2</sub> Capture, Transport and Storage, TCCS-12

Five abstracts have been submitted for presentation at the TCCS-12 conference, 19-21 June 2023, in Trondheim, Norway (<https://www.sintef.no/projectweb/tccs-12/>). The titles and authors are:

1. Title: SCOPE - Volatile and aerosol-based emissions of aged CESAR1 and their mitigation - measurement and simulation  
Authors: Peter Moser, Georg Wiechers, Marcel Busch, Knut Stahl, Susana Garcia, Laura Herraiz-Palomino, Charithea Charalambous, Mijndert van der Spek, Hallvard F. Svendsen, Maxime Francois, Hanna K. Knuutila, Peter van Os, Juliana Garcia Moretz-Sohn Monteiro, Roberta

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Veronezi Figueiredo, Eirini Skylogianni

Presentation type: Oral


2. Title: Vapor-liquid equilibria and pH of aqueous amines for better understanding of amine emissions  
Authors: Ardi Hartono, Hallvard F. Svendsen and Hanna K. Knuutila  
Presentation type: Poster
3. Title: DEMONSTRATION OF EMISSION MITIGATION STRATEGIES IN THE HVC AND TWENCE WASTE-TO-ENERGY PLANTS Authors: Eirini Skylogianni, Roberta Veronezi Figueiredo, Juliana Monteiro, Paul Gravesteijn, Melvin J.L. Kruijne, Arjen Huizinga, Peter van Os, Jan-Peter Born, Mathijs Vos  
Presentation type: Oral
4. Title: Parametric tests to study the potential for performance improvement of the absorber emissions monitoring system (ACEMS) prototype instrument developed at SINTEF Authors: Actor Chikukwa, Karol Michalski, Lars Hovdahl, Kai Hjarbo, Andreas Grimstvedt, Merete Wiig, Kai Vernstad, Aslak Einbu  
Presentation type: Oral
5. Title: Perspectives on CCUS deployment on large scale in India: Insights for low carbon pathways Authors: N. C. Gupta, Ruchika Tanwar, Dipesh, Anubha Kaushik, Rita Singh, A.K.Patrab, Pinaki Sar, Purvil Khakharia  
Presentation type: Oral

#### 8.1.4 POST COMBUSTION CAPTURE CONFERENCE PCCC7

Four abstracts were submitted in M19 for presentations at the PCCC7 conference in Pittsburgh, USA, 25<sup>th</sup>-27<sup>th</sup> September, 2023 (<https://ieaghg.org/conferences/2-uncategorised/1060-pccc-7>).

The titles and authors are (all oral presentations):

1. Title: Solvent aging-effect on emissions of CESAR1 and performance of emission mitigation technologies after 500 h and 32,000 h operation  
Authors: Peter Moser, Georg Wiechers, Susana Garcia, Laura Herraiz-Palomino, Hallvard F. Svendsen, Hanna K. Knuutila, Juliana Garcia Moretz-Sohn Monteiro, Eirini Skylogianni
2. Title: Emission measurement tests to study the potential for performance improvement of the absorber emissions monitoring system (ACEMS) prototype.  
Authors: Actor Chikukwa, Karol Michalski, Lars Hovdahl, Kai Hjarbo, Thor Mejdell, Andreas Grimstvedt, Merete Wiig, Kai Vernstad, Aslak Einbu
3. Title: Validation of a CESAR1 Solvent Model with a Focus on Water Wash Conditions  
Authors: Jeff Weinfeld and Diego Pinto
4. Title: Regulatory framework for sustainable and cost-efficient amine emission control  
Authors: Hanne Kvamsdal, Eirik F. da Silva, Karl Anders Hoff, Peter van Os. Peter Moser, Anna Korre

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### 8.1.5 GPA Europe Annual Conference

One abstract was submitted and presented at the GPA Europe Annual conference in Ludwigshafen, Germany, 9-11 October 2023 (<https://www.gpaeurope.com/event/gpa-europe-annual-conference>).

The title and authors are:

Title: Using CESAR1 solvent for post-combustion CO<sub>2</sub> capture

Authors: Diego Pinto (Hovyu) and Jeffrey A. Weinfeld (OGT).

### 8.1.6 UTCCS-7

Results from Task 2.2 were presented online by RWE at the University of Texas 7th Conference on Carbon Capture and Storage, Austin, Texas on January 24, 2024:

Title: Testing emission mitigation measures with differently degraded CESAR1 solvent at the capture plant at Niederaussem.

Authors: Peter Moser, Georg Wiechers, Maxime Francois, Hanna K. Knuutila, Susana Garcia, Laura Herraiz-Palomino, Juliana Garcia Moretz-Sohn Monteiro, Eirini Skylogianni

### 8.1.7 SETAC conference 2024

One abstract was submitted and presented at the SETAC Europe 34th Annual Meeting, Seville, Spain. May 5th-9th 2024. The title and authors are:

Title: Marine ecotoxicity of amines used as solvents in carbon capture processes: Species sensitivity distributions and additive toxicity aspects.

Authors: Hansen, B.H.; Wielogorska, E.; Altin, D.; Korre, A.; Farkas, J.; Da Silva, E.F.; Hoff, K.A.; Kvamsdal, H.M.; Sørensen, L.; Brakstad, O.G. 2024.


### 8.1.8 17th International Conference on Greenhouse Gas Control Technologies, GHGT-17

6 abstracts were submitted for the GHGT-17 conference in Calgary, Canada in October 2024 were accepted for oral presentation and 6 papers for the conference proceedings were submitted after the conference. These six are listed in the following table.

**Table 8-2: Papers and presentations from the partners at the GHGT-17 conference**

WP	Type of publication	Authors	Partners	Title	Date/year
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1	OPa	Jeffrey A. Weinfeld, Diego D. D. Pinto, Peter Moser, Georg Wiechers	OGT, Hovyu, RWE, RWE	Development and plant validation of a CESAR1 solvent model with an emphasis on water wash conditions	20-24.10/ 2024
1	OPa	Laura Herraiz, Eirini Skylogianni, Diego Di Domenico Pinto, Peter Moser, Georg Wiechers, Mijndert van der Spek, Peter van Os, Susana García	HWU, TNO, Hovyu, RWE, RWE, HWU, TNO, HWU	Techno-economic assessment of emissions mitigation technologies for post-combustion CO <sub>2</sub> capture using AMP/PZ	20-24.10/ 2024
2	OPa	Eirini Skylogianni, Joost Kiewik, Mathijs Vos, Juliana Monteiro	TNO, Twence, Twence, TNO	Experience from 3-year BDU operation in Twence's CO <sub>2</sub> capture pilot plant	20-24.10/ 2024
2	OPa	Peter Moser, Georg Wiechers, Sandra Schmidt, Hallvard F. Svendsen, Maxime Francois, Hanna K. Knuutila, Susana Garcia, Laura Herraiz-Palomino, Juliana Garcia Moretz-Sohn Monteiro, Eirini Skylogianni	RWE, RWE, RWE, NTNU, NTNU, NTNU, HWU, HWU, TNO, TNO	Demonstrating the mitigation of emissions of an AMP/PZ-based solvent at CO <sub>2</sub> capture rates from 90 to 98%	20-24.10/ 2024
2	OPa	Karol Michalski, Actor Chikukwa, Kai Hjarbo, Thor Mejdell, Andreas Grimstvedt, Kai Vernstad, Aslak Einbu	SINTEF	Demonstration of the ACEMS prototype instrument for continuous monitoring of absorber emissions from a long-time aged CESAR1 solvent	20-24.10/ 2024

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3	OPa	Quentin T. Wolf, Maria Lathouri, Anna Korre, Sevket Durucan	IMPERIAL	Methodology for human health risk assessment around amine based post-combustion carbon capture plants	20-24.10/ 2024
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## 8.2 Presentation and participation at smaller conferences, seminars and workshops

### 8.2.1 NCCS – Consortium days 2021

SINTEF IND was invited to give a presentation at the consortium days event for the national funded Centre for Environment-Friendly Energy Research NCCS (The Norwegian CCS Research Centre) (<https://www.sintef.no/projectweb/nccs/>), November 2021 in Trondheim, Norway . Karl Anders Hoff gave the presentation where he focused on the background of SCOPE and a short overview of the project.

### 8.2.2 ACT Knowledgesharing conference, 2022

The coordinator of SCOPE, Hanne Kvamsdal (SINTEF IND), gave the presentation of SCOPE and showed some preliminary results at the ACT Knowledgesharing conference 09.06.2022 in Rotterdam, The Netherlands.

### 8.2.3 Climit-summit 2023


The coordinator of SCOPE, Hanne Kvamsdal (SINTEF IND) was invited to give a presentation at the Climit Summit workshop 7th-9th February 2023 in Larvik in South-East Norway. This workshop is arranged by The Research Council of Norway every second year within the Climit program. The presentation is available at the project web-site (<https://www.scope-act.org/conference-papers>).

### 8.2.4 ACT Knowledgesharing conference, 2023

The coordinator of SCOPE, Hanne Kvamsdal (SINTEF IND), gave the presentation of SCOPE and showed some results at the ACT Knowledgesharing conference 4.-5 October 2023, Paris, France. A poster was also presented.

### 8.2.5 US-Norway bilateral meeting on CCUS

The annual bilateral meeting between US DoE and the Norwegian Ministry of Energy was hosted by US DoE in Washington DC in November 2023. The SCOPE project was invited for presentation in the project updates session from the Norwegian side. The presentation was given by Karl Anders Hoff from SINTEF.

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### 8.2.6 ACT Knowledgesharing conference, 2024

The coordinator of SCOPE, Hanne Kvamsdal (SINTEF IND), gave the presentation of SCOPE and showed some results at the ACT Knowledgesharing conference 11.-12 September 2024, Oslo, Norway.

## 8.3 Project arrangements

As part of the project and specifically as part of Task 4.5, 6 Stakeholder, Policy, Research, and Industry NeTwork (SPRINT) events were organised as indicated in Section 4.1.4. The aim of these events was to facilitate information exchange between stakeholders across the whole carbon capture chain on topics relevant to CCUS science, technology, and policy.

**Event #1:** Local workshop, “Regulations, Permitting and a Review of the Guidelines for Emissions Control”. This event was combined with a project meeting in Bergen and site visit to TCM, Norway. The workshop and meeting were hosted by TCM.

**Event #2:** Local workshop, “Developing best practices for emissions control”. This event was combined with a project meeting in Cologne, Germany, and a site visit to the Niederaussem pilot owned by RWE. The workshop and meeting were hosted by RWE.

**Event #3:** Local workshop, “Mitigating environmental impacts”. This workshop was conducted for the SCOPE project as a whole, and for the Indian context specifically. The workshop was organised by the Indian partners in New Dehli, India.

**Event #4:** Global symposium, “How to address, interact and act on the main knowledge gaps related to emissions”. This event was combined with a project meeting and in parallel with the international conference TCCS-12 in Trondheim, Norway. The workshop and meeting were hosted by SINTEF.

**Event #5:** Local workshop, “Developing best practices for emissions control,” This event was organised as a webinar.

**Event #6:** Global symposium, “SCOPE: Project results and recommendations for future research and policy initiatives.” This event was organized together with the final dissemination event (Task 5.2) to bring together all of the project teams together with non-SCOPE members of SPRINT to share findings. The final workshop was organised in London with IMPERIAL as the host.

## 8.4 Journal publications

All journal publications are summarised in Table 8-3.

**Table 8-3: Journal publications from the SCOPE project**

WP	Authors	Partners	Title	Journal	Link/status
1	Charitea Charalambous, Laura Herraiz, Ardi Hartono, Hanna Knuutila, Susana Garcia	HWU, HWU, NTNU, NTNU, HWU	Experimental VLE data for the AMP/PZ/H <sub>2</sub> O system under relevant water wash conditions for carbon capture applications	Chemical Engineering Science, 304, 1 February, 2025	<a href="https://doi.org/10.1016/j.ces.2024.120992">https://doi.org/10.1016/j.ces.2024.120992</a>
2	Peter Moser, Georg Wiechers, Hallvard F. Svendsen, Maxime Francois, Hanna K. Knuutila, Susana Garcia, Laura Herraiz, Juliana Monteiro, Eirini Skylogianni	RWE, RWE, NTNU, NTNU, NTNU, HWU, HWU, TNO, TNO	Demonstrating the effect of solvent aging on the volatile and aerosol-based emissions of the AMP/PZ-based solvent CESAR1 after 1,000 h and 30,000 h operation	Separation and Purification Technology, 258, Part A, 7 June 2025	<a href="https://doi.org/10.1016/j.seppur.2024.130320">https://doi.org/10.1016/j.seppur.2024.130320</a>
3	Svendsen H.F., Knuutila H.K., Hartono A., Morlando D., Francois M., Moser P., Wiechers,	NTNU, NTNU, NTNU, NTNU, RWE, RWE	Understanding aerosol growth and emissions: CO <sub>2</sub> capture in the RWE Niederaussem pilot plant using CESAR1		Under review
4	N.C. Gupta, Ruchika Tanwar, Dipesh, Anubha Kaushik, Rita Singh, A.K. Patra, Pinaki Sar, Purvil Khakharia	GGs IPU, GGS IPU, GGS IPU, GGS IPU, IITKGP, IITKGP, MIPL	Perspectives on CCUS deployment on large scale in India: Insights for low carbon pathways	Carbon Capture Science & Technology, 12, 2024	<a href="https://doi.org/10.1016/j.ccs.2024.100195">https://doi.org/10.1016/j.ccs.2024.100195</a>
5	Peter Moser, Georg Wiechers, Sandra Schmidt, Ferdinand Steffen, Peter Lindemann	RWE	From research to application - 15 years of operation of the CO <sub>2</sub> capture pilot plant at RWE's Innovation Center in Niederaussem and use of the results	vgbe energy journal, 9, 2024	ISSN 1435-3199 K43600, no doi



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6	Peter Moser, Georg Wiechers, Knut Stahl, Sandra Schmidt	RWE	Stressing the AMP/PZ-Based Solvent CESAR1–Pilot Plant Testing on the Effect of O <sub>2</sub> , NO <sub>2</sub> , and Regeneration Temperature on Solvent Degradation	Industrial & Engineering Chemistry Research, 06.02.2025	<a href="https://doi.org/10.1021/acs.iecr.4c04285">https://doi.org/10.1021/acs.iecr.4c04285</a>
7	Ningtong Yi, Laura Herraiz, Mengxiang Fang, Susana García, Mijndert van der Spek	HWU (+ Chinese student and supervisor at Zhejiang University)	Open access, thermodynamically consistent, electrolyte NRTL model for piperazine, AMP, water, CO <sub>2</sub> systems on Aspen Plus	Separation and Purification Technology, 350	<a href="https://doi.org/10.1016/j.seppur.2024.127924">https://doi.org/10.1016/j.seppur.2024.127924</a>