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SCOPE: an ERA-NET ACT project on sustainable operation of post-combustion capture plant

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Abstract

SCOPE (**S**ustainable **OPE**ration of post-combustion **C**apture plants) is a three-year project from the third ERA-NET Co-fund ACT program (http://www.act-ccs.eu/). The participants of SCOPE represent the ERA-NET ACT countries of Norway, The Netherlands, Germany, United Kingdom, USA, and India. The SCOPE consortium involves 24 partners from industry, authorities, research, and academia and has considerable involvement of industrial companies. The industrial partners are not only supporting the research but have also committed to directly invest and participate in the R&D and demonstration activities in the project, boosting the credibility of the project's potential for accelerated decarbonisation of the industry. In this paper, a high-level overview is given of the research being conducted in the project and its immediate impact on the CCUS community.

Keywords: CO_2-capture; chemical absorption; amine emission; environmental risk mitigation; societal awereness

Introduction

Amine-based chemical absorption is the leading technology for capturing and removing CO_2 from certain industrial processes, such as those used in cement, metallurgical and steel industries as well as waste incineration and power plants. Although amine-based technology is not new, early adopters have struggled to secure emission permits due to the lack of data on amine emissions and lack of well-defined regulatory procedures for documenting and modelling amine emissions. As a result, a better understanding of the overall environmental impacts of using amine-based chemical absorption to mitigate industrial emissions

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over time would accelerate the implementation of amine-based technologies for climate protection.

SCOPE (https://www.scope-act.org/) takes a holistic approach to ensure that emission reductions for amine based CCUS are technically feasible, cost-efficient, and robust enough to mitigate environmental risks and gain public acceptance. By following the continuous path of the treated gas from source to recipient (see illustration in Figure 1), SCOPE research is designed to address existing knowledge gaps and information-exchanges that are critical for realizing sustainable, environmentally safe CO_2 capture plants.

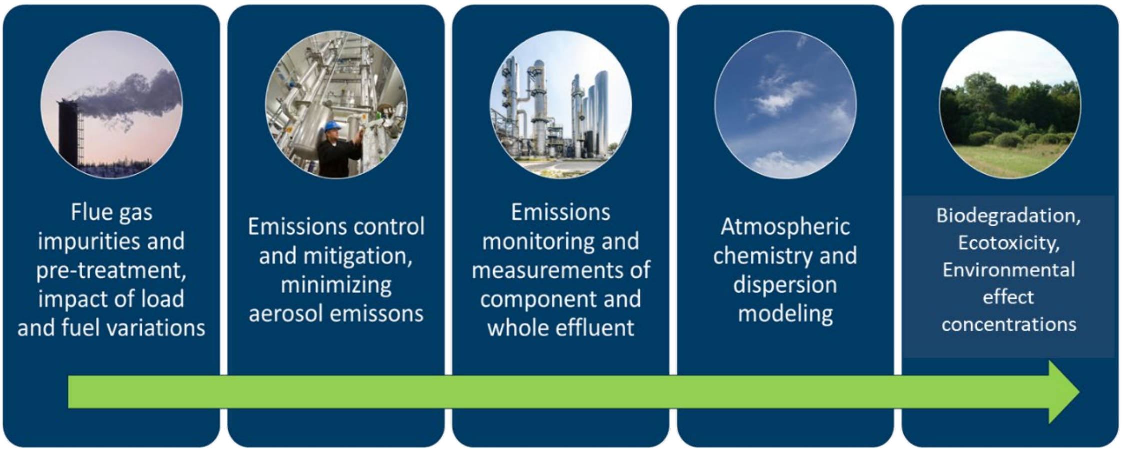

Figure 1: SCOPE governing approach

The SCOPE project, which started in October 2021 will entail 36 months with activities on development of knowledge for predicting volatile and aerosol-based emission and development of tools for online emission measurements, on demonstration of emission mitigation technologies and online emission measurement equipment, on establishing methods and rules for risk assessment of emissions from flue gas of CO_2-capture facilities, and mapping the concerns of publics in diverse countries and regions with regard to the social, environmental, economic and political impacts of amine-based CCUS developments. The emission mitigation technologies addressed in SCOPE will be assessed based on the results from the demonstration and modelling for large scale applications. Furthermore, the technological, economic, political, and regulatory challenges of commercializing amine-based CCUS projects will be clarified. The SCOPE partners (24 as listed in the Table 1) all being important stakeholders will conduct all these activities and they will ensure that remaining knowledge gaps are closed leading to accelerated deployment of large-scale amine-based capture technology and increased societal readiness level as illustrated in Figure 2. In the subsequent section the aims and objectives of the SCOPE project and the expected outcomes and the impact are given, followed by an overview of each topical focus area in SCOPE. Particularly, since the work in SCOPE is a continuation of several previous and other ongoing projects a summary of the most relevant findings and how they will be advanced in SCOPE is addressed for each focus area together with the innovations of the SCOPE project.

Table 1: SCOPE partners and country

	Participant organisation name	**Short name**	**Country**

1	SINTEF AS by its institute SINTEF Industry, The Coordinator of SCOPE	SINTEF IND	Norway
2	SINTEF Ocean AS	SINTEF OC	Norway
3	Norwegian University of Science and Technology	NTNU	Norway
4	NEDERLANDSE ORGANISATIE VOOR TOEGEPAST NATUURWETENSCHAPPELIJK ONDERZOEK	TNO	The Netherlands
5	Imperial College	IMPERIAL	United Kingdom
6	RWE Power Aktiengesellschaft	RWE	Germany
7	TotalEnergies EP Norge AS	TEPN	Norway
8	University of Sussex	SPRU	United Kingdom
9	Heriot-Watt University	HWU	United Kingdom
10	NILU	NILU	Norway
11	Technology Centre Mongstad	TCM	Norway
12	Herøya Industripark	HIP	Norway
13	Hovyu	Hovyu	The Netherlands
14	Twence B.V.	Twence	The Netherlands
15	N.V. HVC	HVC	The Netherlands
16	Linde GMbH, Linde Engineering	Linde	Germany
17	Optimized Gas Treating, Inc., OGT	OGT	USA
18	Guru Gobind Singh Indraprastha University	GGS IPU	India
19	National Energy Technology Laboratory	NETL	USA
20	Environment Agency	EA	United Kingdom
21	Indian Institute of Technology Kharagpur	IITKGP	India
22	Microfilt India Pvt. Ltd.	MIPL	India
23	Cambridge Environmental Research Consultants Ltd.	CERC	UK
24	Aker Carbon Capture AS	ACC	Norway

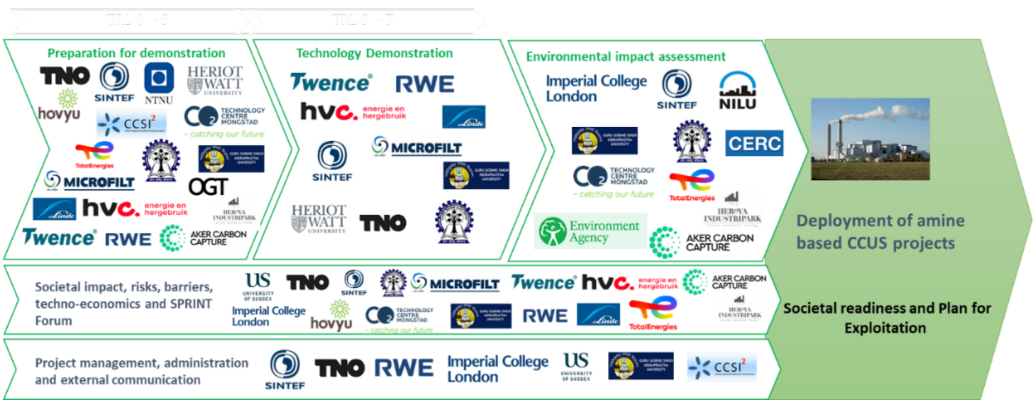

Figure 2: Work-flow for the SCOPE partners to reach the goal of accelerated deployment of amine based CCUS projects and increased societal readiness.

Overall goal and expected impact of SCOPE

The overall goal of SCOPE is to support the development of technology for emission control and enable the harmonization of regulations for amine-based CO_2 capture facilities. It will do this through the:

1. Development of effective **online monitoring systems and emission control guidelines**;

2. Validation of predicted amine emissions from solvents against data generated in the project through test campaigns at **5 different pilot plants**;

3. Effective utilization of knowledge about **environmental hazards** in **risk assessment** of amine-based CO_2 capture plants; and

4. Identification of societal concerns, **policies and practices** that may affect the **credibility of industrial decarbonisation using** amine-based CO_2 capture in different countries.

At the end of the SCOPE project, plant operators will have access to new tools and data; authorities will have new regulatory guidelines for setting environmental quality and health standards; and decision-makers seeking to support CCUS commercialisation will have clarity on the governance requirements needed to secure a social license to operate in diverse national settings.

Main focus areas and advancement in SCOPE

The main focus areas are:

1. I**mprovement of the predictions of amine emissions** from CO_2 capture plants by further development of existing models and validating them against **high quality pilot plant data.**
2. D**evelopment of efficient online monitoring systems** and effective management guidelines for emissions control.
3. Integration of science on environmental impact to **support risk assessment** of amine-based CO_2 capture plants
4. Determining policies and practices that strengthen public trust in the governance of amine-based CCUS and establish a **Stakeholder, Policy, Research and Industry NeTwork** (SPRINT) forum to facilitate discussions aimed at closing important knowledge gaps for advancing large-scale deployment of CCUS solutions.

In the following sub-sections, each focus area is further elaborated, particularly related to previous work and how this is advanced further in the SCOPE project.

1. Prediction of amine emissions

Amine emissions can be either vapour or liquid. Liquid emissions may occur in the form of entrained droplets (diameter larger than 5 µm) or aerosols droplets (diameter lower than 5 µm). Entrained droplets can be easily removed using conventional mist eliminators, and this phenomenon is well understood. Volatile- and aerosol-based emissions are of relevance towards understanding and controlling emissions. Besides amines, ammonia and other volatile degradation products may be emitted from post-combustion CO_2 capture plants.

Though the topic on emission and degradation has been extensively covered by previous projects, there are still knowledge gaps and particularly the ALIGN-CCUS project (ACT1: https://www.alignccus.eu/)[1,2] pointed out several which will be addressed within the SCOPE project. One issue of crucial importance is the difficulty of differentiating between volatile and aerosol-based emissions. The technologies available to mitigate volatile-based emissions are not effective towards aerosols. Therefore, proper understanding of the emissions nature is crucial for designing effective control strategies. Volatile emission and the use of a

water-wash in the top of the absorber as an effective means of controlling volatile emission is much better understood[e.g., 3] than the formation mechanism of aerosol-based emission . However, aerosols may lead to unacceptable high amounts of emission, and their mitigation needs innovative technologies and approaches which must be evaluated in pilot plant-scale.
To predict the formation and the impact on emission, models have been developed and in SCOPE these will be further improved and validated in various pilot plants (listed in Table 2) and made available in simulation tools.

2. *Online monitoring and management guidelines*

Continuous chemical monitoring of large-scale CO_2 capture plants is necessary for process optimization, process control, solvent degradation and for emission control and documentation. Analytes of sub-ppm concentrations in the emissions are important for monitoring, as ppm per volume flue gas emitted converts to tons per year emitted to air from the plant considering the large volume of gas treated. Emission monitoring is thus mandatory for amine-based carbon capture plants. However, high water content in gas and aerosols represent a challenge for traditional methods for ambient air analysis.

Though there are available industrial gas sensors, such as FTIR, they cannot be used for monitoring of critical trace gas compounds like nitrosamines and nitramines. Thus, manual isokinetic gas sampling followed by chemical analysis in laboratory is the currently available approach to monitor harmful trace gas emissions from amine-based carbon capture processes. Nevertheless, SINTEF has for some years been developing an online emission monitoring system named ACEMS (Absorber Continuous Emission Monitoring System) with the aim of monitoring the whole range of emitted components (solvent and solvent degradation products). The established prototype was successfully tested for monitoring of trace gas emission from a CO_2 capture pilot plant, demonstrating measurements of nitrosamines at levels not detectable by today's industrial online analysers[4]. The prototype will be further developed and improved in SCOPE.

The technologies available for controlling amine emissions were also reviewed in the ALIGN-CCUS project[1]. A total of 9 technologies were evaluated regarding TRL, emissions removal efficiency, OPEX and bare equipment costs (BEC). However, the removal efficiency, arguably the most relevant of these factors, could not be evaluated on a quantitative basis due to lack of available data. This is an obvious knowledge gap, that hinders the selection of the best mitigation technology for a given situation, and which will be closed in SCOPE through extensive testing within the different pilots as listed in Table 2.

Table 2: Test facilities and corresponding activities used during SCOPE

The test facilities in SCOPE Flue gas/Capture capacity/Solvent	Available emission mitigation tools and configurations/ measurement techniques
Hengelo (Twence), The Netherlands  Waste-to-energy plant 500 kg CO_2/h Solvent: 30% MEA, Flue gas: CO_2 9.5 vol.-%, O_2 8.3 vol.-%,	• Brownian demister downstream the flue gas quench • The water wash downstream the absorber will be used to evaluate operational parameters • A small mobile column will be used as acid wash downstream the water wash (ca. 3 Nm^3/h) to evaluate the impact of operational parameters on ammonia emission reduction • FTIR, particle size distribution (ELPI and SMPS+C) 6 measuring campaigns in 3 years

The test facilities in SCOPE Flue gas/Capture capacity/Solvent	Available emission mitigation tools and configurations/ measurement techniques
24/7 operation.	• CO_2 quality monitoring using UniSensor CARBOSCAN 300
Niederaussem (RWE), Germany  Lignite-fired power plant: 300 kg CO_2/h Solvent: CESAR1 (blend of AMP and PZ)) Flue gas: CO_2 15.2 vol.-%, O_2 5.0 vol.-% and mimicked flue gas from gas turbine/sewage sludge combustion: CO_2 4 vol.-%, O_2 15.0 vol.-% 24/7 operation	• The performance of the emission mitigation tools acid wash, double water wash, dry bed and two flue gas pre-treatment technologies will be evaluated (in total 20 different configurations); aerosol particles will be generated using a wet electric precipitator (WESP) • Test of emission mitigation tools at CO_2 capture rates: 90, 95 and 98% • Test with mimicked flue gas from sewage sludge combustion by adding air to lignite-based raw gas • FTIR, particle size distribution (ELPI and optical particle counter), and ACEMS • 4 measuring campaigns after 500, 5000 and >10000h solvent operation and change of the flue gas composition
Tiller CO_2 Lab (SINTEF), Norway  Biomass or propane incineration: 30-40 kg CO_2/h Solvent: CESAR1 Flue gas: CO_2 11vol.-%, O_2 4vol.-%, Campaign operation	• Plant operation with selected water wash section options. • Aerosol and emission measurements for investigations at stationary and transient operating conditions • Particulate dosing for aerosol generation. • Comparative test of mimicked flue gas from Niederaussem capture plant with increased oxygen content at steady state. • Use of aged CESAR1 from Niederaussem (RWE) • Test of dynamic behaviour of emissions • FTIR, ACEMS campaign operation
Alkmaar (HVC), The Netherlands	• A mobile Brownian demister unit will be used downstream the flue gas quench to study the impact on emissions; • The water wash downstream the absorber will be used to evaluate operational parameters; • A small mobile column will be used as acid wash downstream the water wash (ca. 3 Nm³/h) to evaluate the impact of operational parameters on ammonia emission reduction; • FTIR, particle size distribution (ELPI and optical particle counter); 6 measuring campaigns in 3 years.

The test facilities in SCOPE Flue gas/Capture capacity/Solvent	Available emission mitigation tools and configurations/ measurement techniques
 Waste-to-energy plant 540 kg CO_2/h Solvent: MDEA/Piperazine blend Flue gas: CO_2 15,3 vol.-%, O_2 5.6 vol.-%, 24/7 operation.	
Tuticorin site, India  Alkali Chemicals and Fertilizers: 60 kt CO_2/a Solvent: CDRmax (Proprietary solvent of Carbon Clean Ltd) Flue gas: CO_2 ~ 12 vol.-%, O_2 8 vol.-%, 24/7 operation	• The CO_2 capture plant at Tuticorin is in operation and based on proprietary technology (absorption-desorption based) using CDRmax , a proprietary solvent of Carbon Clean Ltd. The capture plant is equipped with a DCC with pre-scrubber and a single stage water wash downstream the absorber for controlling emissions. • Measurement of VOCs and NH_3, total particle number and mass concentration (by CPC and Anderson Impactorrom), sulphuric acid measurements of flue gas before and after CO_2 capture plant

3. *Environmental risk assessment*

Environmental risk assessments combine science on health and environmental effects with estimates of environmental concentrations of substances of concern in order to evaluate the environmental impacts of a technology or facility. The determination of environmental concentrations is the result of a combination of the release concentration monitored by dispersion and degradation/ transformation processes, differing between various environmental compartments (Figure 3).

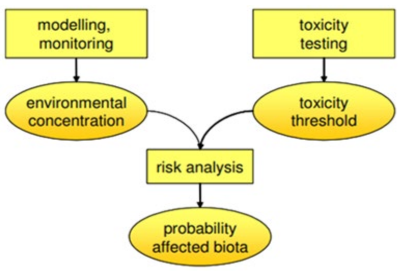

Figure 3: Overview of the environmental risk assessment

For emissions to air, degradation processes such as hydrolysis, photo-oxidation, transport by particles/aerosols, and precipitation to soil and aquatic environments are important, while environmental concentrations in soil, aquatic and sediment systems depend on distributions between particulate and soluble phases, transport processes and various degradation processes including biodegradation, photodegradation in water, and hydrolysis. Knowledge of environmental concentrations combined with data on potential hazards for humans and the environment provided from a variety of bioassays, often in combination with assessment factors, can be used to determine toxicity thresholds, which are critical for risk regulations that ensure public and environmental health as well as for designing effective emission mitigation technologies.

Although the adverse effects of most of the emitted trace compounds present in amine-based carbon capture plants are known, assessment of the impact on the environment surrounding planned post combustion capture (PCC) facilities, including dispersion and fate, deposition and effects on the surface environment and water resources, etc. have not been assessed thoroughly. Understanding such potential impacts and risks imposed by these emissions is imperative for design, planning and mitigating any possible short-/long-term effects for facility based as well as larger-scale assessment of impacts to the environment and economy.

Generic risk assessment methodologies have not been developed for PCC emissions, and currently permits are given by national environmental authorities on a case-by-case basis. More mature risk assessment-based approaches have been developed for other industries. For example, the European offshore industry is required to control discharges of chemicals, based on their environmental properties (ecotoxicity, biodegradation and bioaccumulation), with tests performed according to internationally accepted guidelines and strict acceptance thresholds for each test[5]. In recent years, determination and management in the European offshore industry have changed more to the concern of complete emissions, instead of the single constituents/compounds of the emission, and a system for Whole Effluent Toxicity (WET) has been developed, as recommended by OSPAR[6]. For mixed emissions, additive toxicity may also be tested and compared to the toxicity of the complete emission[7]. These considerations will be investigated for the first time in SCOPE in relation to PCC facilities. A basic principle in this risk assessment-based approach is to screen 1) if an emission is persistent, bio-accumulative and/or toxic (PBT), 2) if predicted environmental concentrations are higher than the toxicity thresholds, and 3) establish Best Available Technique(s) (BAT) and Best Environmental Practice (BEP) of emissions.

During several previous projects, the SCOPE partners have provided health, safety and environmental data from experimental studies and literature reviews of amine solvents and degradation products and used dynamic dispersion models to determine environmental concentrations of emissions from PCC facilities. In addition, the partners have generated fate and health data from experimental studies with nitrosamines and nitramines[*e.g.*, 8]. It is not yet known if these amines compounds are degraded to less hazardous products, or just to other nitrosamines and nitramines[9]. The SCOPE partners have also been engaged in environmental studies of amine solvents and their degradation products, as well as reviewed the associated environmental concerns of CO_2 emissions[10].

Risk assessment of emissions from PCC facilities will be performed by combining hazard data (e.g. NOEC) of the most sensitive test species with environmental concentrations, e.g. as the ratios between predicted environmental concentrations and predicted no-effect concentrations (PEC/PNEC), and by inclusion of assessment factors to determined PNEC values from ecotoxicity data. In SCOPE, the risk assessment of emissions from PCC will be advanced by including health, risk, and environmental data into physical dispersion models, which has not been conducted previously, in a comparable way as previously implemented in ocean risk models.

4. *Public trust and establishment of SPRINT*

Societal acceptance is vital for the commercial-scale deployment of CCUS projects. Opposition to emerging technologies like CCUS can mount quickly, threatening policy agendas and industry investments and potentially slowing the implementation of projects[12]. Much is already known from environmental psychology about the various factors influencing public support and acceptance for CCUS. However, more attention is needed on the relationship between citizen support/opposition for CCUS and other nationally-specific factors relating to public trust. Like other large-scale industrial transitions involving new technologies, CCUS projects are often fraught with concerns regarding justice and accountability, which can lead to 'legitimacy crises' whereby government support for industry (e.g., industrial policy or regulation) is seen as lacking democratic legitimacy and potentially the lack of a 'social license to operate (SLO)' or industry[13].

Yet, there is no 'magic formula' to gaining public trust, legitimacy or SLO. Whether and how legitimacy is conferred depends on nationally-specific concerns, institutions, and market developments – not only related to CCUS but also to past experiences with other technologies. For example, a recent study shows public scepticism towards CCUS in the UK is coloured by the recent experience in England over fracking. Government and industry efforts to develop the UK's shale gas grew increasingly controversial over time at both local and national levels. Controversy emerged around streamlined permitting processes and the lack of regulatory engagement on certain risks of great concern to local communities (e.g. waste water disposal), sowing doubts among broad swaths of the UK public that regulators and policymakers are either unable or unwilling to develop new technologies safely and responsibly.

SCOPE will utilize existing models of how specific technologies and industries gain widespread societal acceptance and community-level SLO to develop a new framework for understanding CCUS legitimacy. This framework is premised on the notion of legitimacy being the product of the specific concerns of civil society that form in response state support being afforded to the new technology and the broader market readiness of the technology. As presented in Figure 4, the legitimacy of amine-based CCUS technology and pilot projects will be investigated as the product nationally-specific configurations of civil society concerns, which emerge in response to state support and market readiness towards CCUS.

In addition to development of the new approach to understand societal acceptance using a new framework for investigating CCUS legitimacy, the other conceptual innovation of SCOPE is the establishment of the SPRINT forum. By creating SPRINT, a communication platform for cross-fertilization between researchers and diverse stakeholders will be developed. SPRINT events will facilitate discussions on topics relevant to SCOPE to close important knowledge gaps for advancing large-scale deployment of CCUS solutions. The knowledge exchange in SPRINT is focussed on getting to know the needs of both industry and non-industry stakeholders' questions relating to best practices for managing emissions, reducing risk, and streamlining permitting processes.

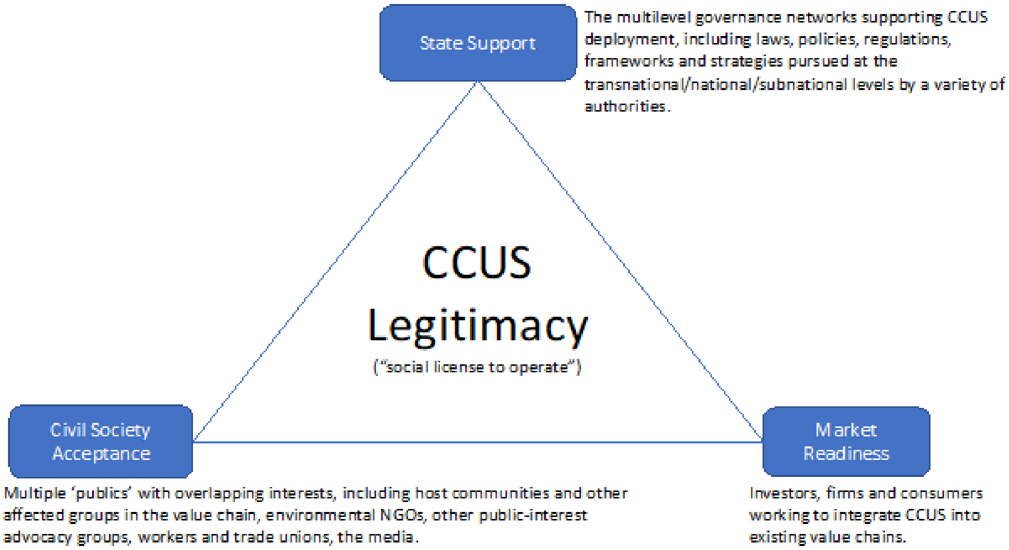

Figure 4: SCOPE framework for understanding CCUS legitimacy (adapted from[14])

Methodologies utilised to obtain goals

In SCOPE two sets of case studies will be developed:

(1) **regional industrial use-case studies** evaluating CO_2 capture at industries that focus on emissions control as well as national case studies on societal acceptance of CCUS
  a) **Norway:** West Coast cluster at Mongstad and Grenland Cluster (Southeast of Norway)
  b) **UK:** Net Zero Teeside (Northweast of UK), South Wales industry cluster (SWIC), and Grangemouth (Scotland)
  c) **The Netherlands:** Single source (Twence waste-to-energy plant) and multiple source (Rotterdam cluster)
  d) **Germany:** industrial cluster (Biomass or waste combustion with CCU)
  e) **India:** single source (Tuticorin Alkali Chemicals and Fertilizers plant)

(2) **4 national cases of CCUS legitimacy**
  a) Norway, UK, The Netherlands, and India

For the regional case studies, a new multi-level approach to evaluating case studies for CO_2 capture at industries that focus on emissions control will be followed in SCOPE. As represented in Figure 5, if the techno-economic and environmental of a proposed CO_2 capture plant can be overcome, the resulting plant design will be more robust than those proposed in previous studies, such as ALIGN-CCUS, which did not factor the plant's environmental impact and national CO_2 price policies into the design. Plant operations and business models that align with industrial, governmental, and societal requirements enjoy a stronger license to operate and capture plants are more likely to be realized. A close collaboration between the focus areas as described previously will deliver such robust results.

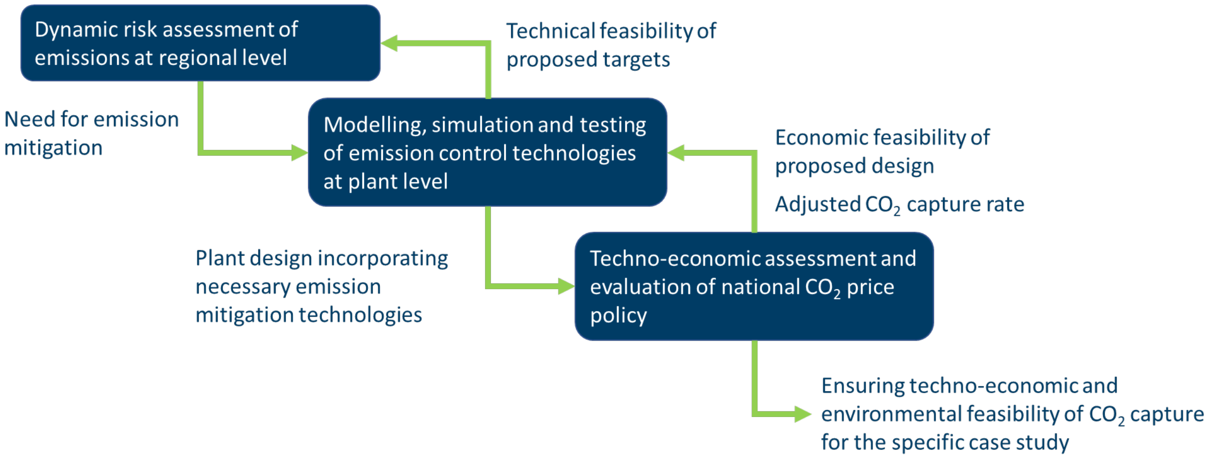

Figure 5: SCOPE integrated activities for techno-economics and environmental feasibility of CO_2 capture for industrial use cases

The goals of the project will be realized through experimental work in lab and pilots, through modelling and simulation and other theoretical studies as well as through communication with key stakeholders and the public. Effective and prompt knowledge exchange and sharing of results achieved in the project will be ensured via the establishment of the Stakeholder, Policy, Research and Industry NeTwork (SPRINT) forum and the arrangement of various knowledge exchange activities. Six various SPRINT events over the course of the project are planned, as listed in Table 3, of which the first one has already been conducted. These events encompass workshops, symposium/courses, and site visits to pilot projects. Specific stakeholders will be invited for the local symposia while there be an open invitation for the two global symposia. More information will be posted on the web-site (www.scope-act.org).

Table 3: Sprint events

Event #	Type of workshop	Title	Venue	When
1	Local	Regulations, Permitting and a Review of the Guidelines for Emissions Control	Bergen, Norway	3rd May 2022
2	Local	Developing best practices for emissions control	Niederaussem, Germany	8th November 2022
3	Local	Mitigating environmental impacts	India, Delhi	March 2023
4	Global	Review of SCOPE progress and preliminary findings	Trondheim, Norway	22nd June, 2023
5	Local	Emission mitigation technologies for post-combustion capture plants	Delft/Hengelo, Netherlands	April 2024
6	Global	SCOPE: Project results and recommendations for future research and policy initiatives	London, UK	September 2024

Conclusions

Being an ACT funded project, SCOPE aims to **accelerate large scale CO_2 capture projects** by providing critical data, methodologies and tools that are essential for plant owners and regulators engaged in managing emissions and permitting processes, and builds connections between diverse stakeholders to facilitate much-needed knowledge exchange on technical and regulatory developments by:

1. Validating the predictions of amine emissions from CO_2 capture solvents against **new pilot plant data;**
2. Developing efficient **online monitoring systems and effective management guidelines** for emissions control;
3. Integrating science on **environmental hazard identification for risk assessment** of amine-based CO_2 capture plants;
4. Determining what **policies and practices strengthen public trust** in the governance of amine-based CCUS in multiple political jurisdictions.

The SCOPE project is undertaken by an international consortium of science, technology and policy experts and stakeholders in Norway, the UK, the Netherlands, Germany, India, and USA. This transnational cooperation prioritizes closing critical knowledge gaps and ensuring information exchange between stakeholders, through original, multi-disciplinary research and collaboration, including the creation of the SCOPE Stakeholder, Policy, Research and Industry NeTwork (SPRINT). The overarching aim of SCOPE is to support the development of emission control technologies and the harmonisation of regulatory frameworks for amine-based CCUS.

More details about the project and project results can be found at the project web-site (www.scope-act.org). Important news and events will also be launched in social media (@SCOPE_ACT) and summarized together with important results in biannual newsletters.

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