Large Bench-scale Development of a Non-Aqueous Solvent CO_2 Capture Process for Coal-fired Power Plants

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DE-FE0026466
DOE Program Manager: Steve Mascaro
Budget Period 1 Project Review Meeting with DOE/NETL

April 27, 2017

Accelerated Technology Pathway

DOE ARPA-E Project	DOE NETL Project	DOE NETL Project (Current)	Future Development	Commercial
2010 – 2013	2014 – 2016	2015 – 2018	2018 – 2021	2021+
1 – 3 TRLs	4 TRL	5 – 6 TRLs	7 – 8 TRLs	9 TRL

Lab-Scale Development / Evaluation

Funding: ~$2,700,000

- Solvent screening to identify promising solvent formulations
- Lab-scale evaluation of NAS Process
- Preliminary technical and economic assessments

Large Bench-scale System / Relevant Environment Testing

Funding: ~$3,000,000

- Finalize NAS formulation
  - *Address evaporative losses and solvent costs*
- Develop critical process components
  - *NAS wash / recovery section*
  - *NAS regenerator*
- Bench-scale testing within a process unit with major process components
- Demonstrate ≤ 2.0 GJ/T-CO_2 using bench-scale system
- Detailed solvent degradation and preliminary emissions studies
- Detailed techno-economic and EH&S assessments
  - *Demonstrate T&EA competitiveness and environmental permitability*

Combined SINTEF (Tiller)

Funding: ~2,700,000

- Tiller Plant (~60 kWe)
  - *Demonstrate all process components for NAS process in adiabatic system*
  - *Accurately quantify solvent losses and emissions*
  - *Test campaign on coal derived flue gas*
  - *Determine materials (metals, polymers, gaskets) compatibility*
  - *Collect critical process data to support scale up, develop engineering package for TCM*

TCM Pathway Large Scale Demonstration

- TCM (~10 MWe)
  - *Complete process unit with all components at minimum size required for confident scale-up*
  - *Collect critical process information to support detailed T&E assessments, emissions monitoring, long-term testing to develop reliability, availability and maintainability (RAM) metrics*

Presentation Overview

- Project Overview and Objectives
- Project Summary and Budget
- Budget Period 1 Update
  - Milestones and Accomplishments
  - NAS Solvent
  - Process Engineering and Design
  - Bench-Scale Testing
- Budget Period 2 Overview
  - Overview, Tasks, and Objectives
  - BP2 Progress
- Next Steps / Technology Development Pathway

Project Overview and Objectives

Project Overview

Objective: Continue the advancement of the NAS CO_2 Capture Process

- Increase solvent performance
- Design and build unique process modifications for Tiller
- Perform pilot testing of NAS on coal-derived flue gas
- Techno-economic and EHS evaluation

***Timeframe*:**

BP	Timeframe	Months
1	10/01/15 – 12/31/2016	15 months
2	01/01/17 – 06/30/2018	18 months

BP1 Milestones

Milestone	Description	Completion	Status
A	Kick-off Meeting	12/31/15	***Milestone Achieved.*** Kick-off meeting held at DOE/NETL site on 12/17/2015.
B	Updated project management plan	5/5/16	***Milestone Achieved.*** Revision 1 of PMP was approved by DOE/NETL on 6/27/2016.
C	Completion of 250 hours baseline testing at SINTEF Tiller plant	3/20/17	***Milestone Achieved.*** Performed MEA baseline testing at SINTEF and verified 3.6 GJ/Ton-CO_2 reboiler heat duty consistent with values reported in literature. Completed 400 hours of NAS baseline testing,
D	Engineering design package for Regenerator delivered to SINTEF.	10/31/16	***Milestone Achieved.*** A final design and engineering package has been delivered and included updated P&IDs, stream tables, and bill of materials for modification recommendations to SINTEF for their CO_2 capture unit at the Tiller plant.
E	Experimental data from formulation improvement confirming that the NAS solvents absorb less than 5wt% water..	12/31/16	***Milestone Achieved.*** Some NAS formulations are able to achieve the < 5 wt% target, however, the optimal formulations have a preferred water absorption target between 5 to 10 wt%.

BP1 Success Criteria

Success Criteria Description	Status / BP1 Achievement
Completion of 250 hours baseline testing at Tiller plant on coal-derived flue gas	***Completed.*** NAS testing in the Tiller plant facility followed SINTEF's testing of the NAS in their lab pilot system. NAS testing was conducted on propane-fired flue gas, and coal-fired boiler. A total of 405 hours of testing was completed.
Regenerator design package completed and agreed upon by project team.	***Success Criteria Achieved.*** See "Milestone D" description. RTI and SINTEF have agreed on Tiller plant design modifications. These recommended design changes will be implemented in BP2.

Project Summary and Budget

Project Summary

Objective:

Continue the advancement of the RTI's novel NAS CO_2 Capture Technology

- Demonstrate process on coal-derived flue gas
- Design and build unique process modifications for Tiller
- Increase solvent hydrophobicity
- Techno-economic and EHS evaluation

Specific Challenges:

- Implementation of NAS-specific regenerator
- Minimize rise in absorber temperature
- Obtain sufficient heat exchange for optimal performance
- Improve hydrophobicity of solvent

Timeframe:

10/1/15 to 12/31/16 (15 months)
10/1/15 to 06/30/18 (18 months)

R&D Strategic Approach

Breakdown of the Thermal Regeneration

$$q_R = \left[\frac{C_P(T_R - T_F)}{\Delta\alpha} \cdot \frac{M_{sol}}{M_{CO_2}} \cdot \frac{1}{x_{sol}}\right] + \left[\Delta H_{V,H_2O} \cdot \frac{p_{H_2O}}{p_{CO_2}} \cdot \frac{1}{M_{CO_2}}\right] + \left[\frac{\Delta H_{abs,CO_2}}{M_{CO_2}}\right]$$

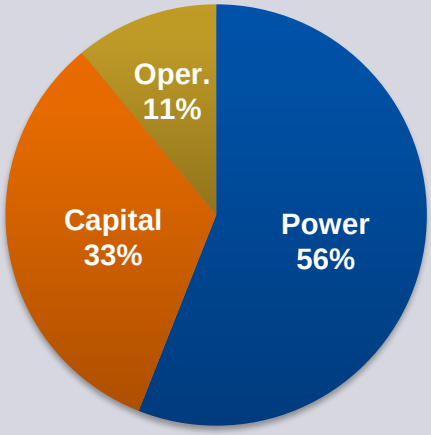
Reboiler Heat Duty — Sensible Heat — Heat of Vaporization — Heat of Absorption

Solvent	C_p [J/g K]	Δh_{abs} [kJ/mol]	Δh_{vap} [kJ/mol]	X_{solv} [mol solv./ mol sol'n]	$\Delta\alpha$ [mol CO_2/ mol solv.]	Reboiler Duty [GJ/tonne CO_2]
MEA (30%)	3.8	85	40	0.11	0.34	3.22
Lower Energy Solvent System	⬇	⬇	⬇	⬆	⬆	⬇
NAS	1.3	65	1	0.3	0.3	1.71

For NAS, heat of vaporization of water becomes a negligible term to the heat duty Process capable of achieving these criteria will have a lower energy penalty than SOTA processes

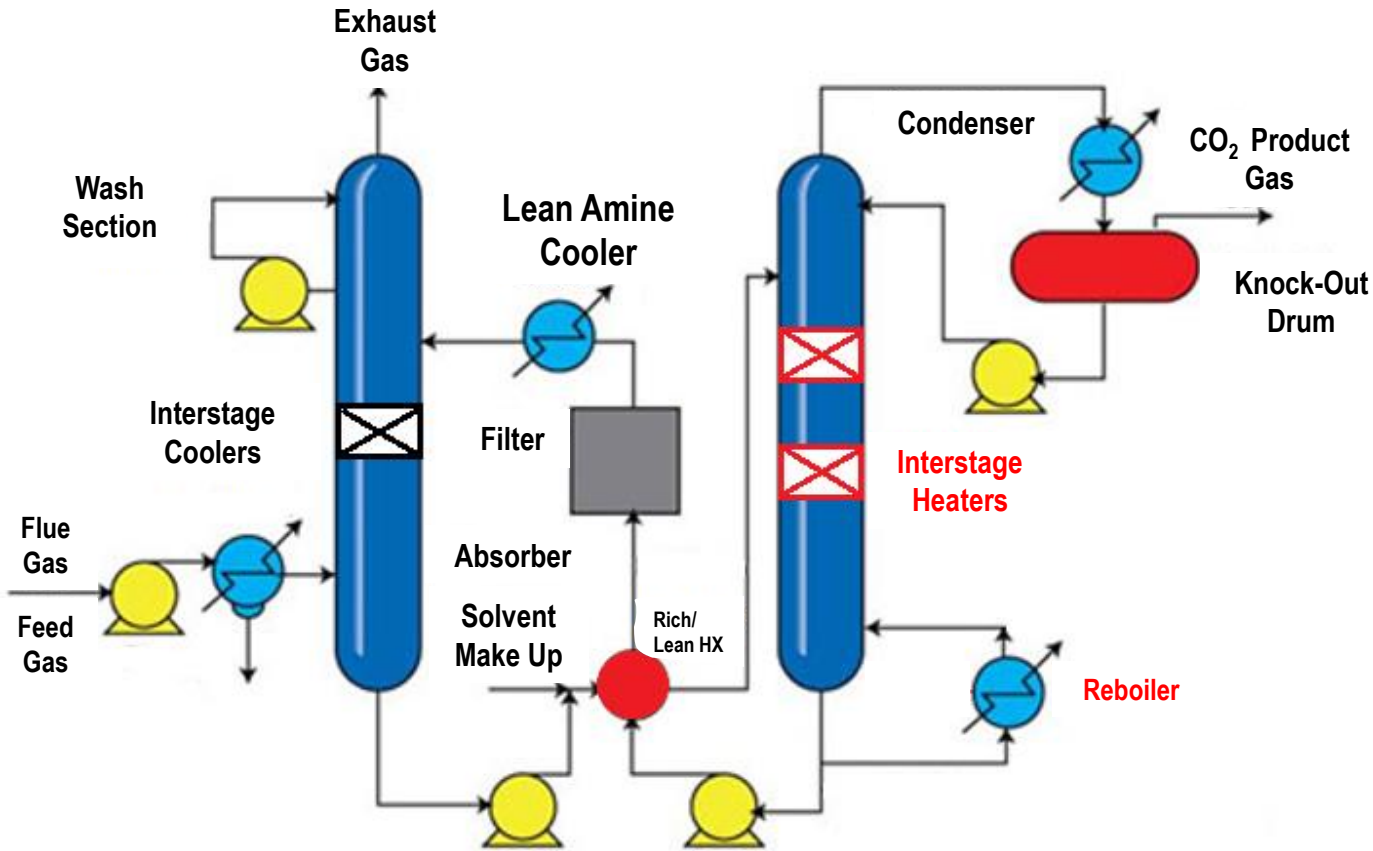
Path to Reducing ICOE and Cost of CO_2 Avoided

- Primarily focus on reducing energy consumption – reboiler duty
- Reduce capital expenditure
  - Simplify process arrangement
  - Materials of construction
- Limit operating cost increase

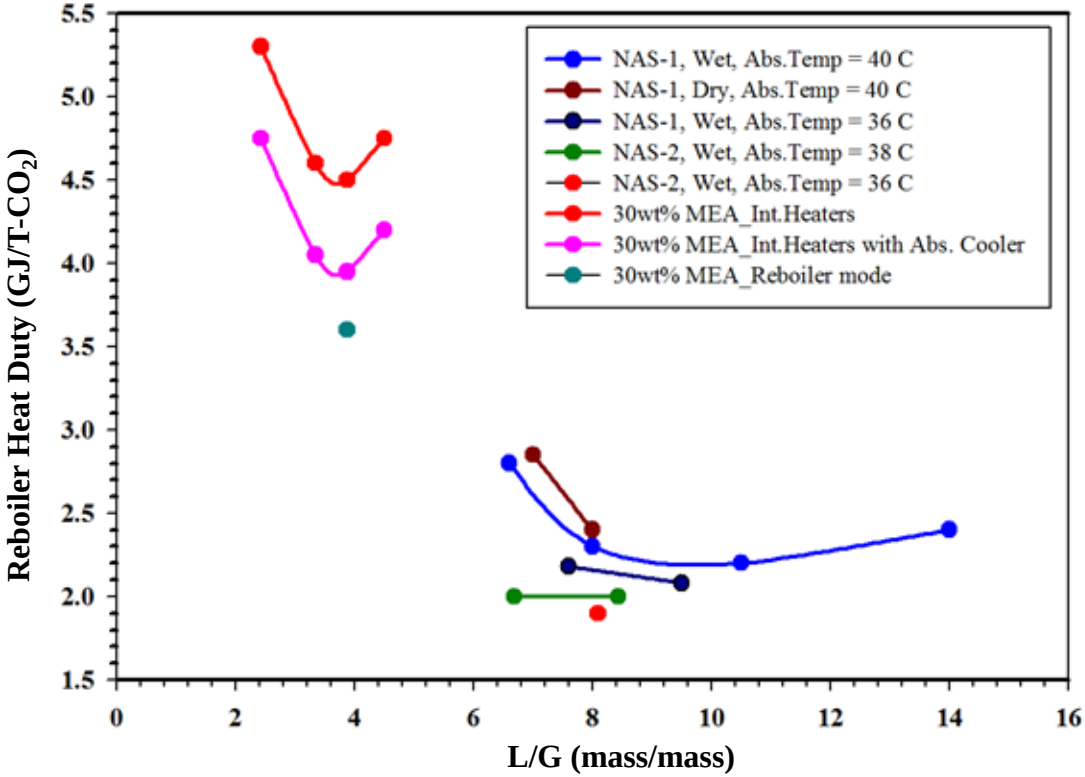


[1] Rochelle, G. T. Amine Scrubbing for CO_2 Capture. *Science* **2009,** 325, 1652-1654.

NAS Process

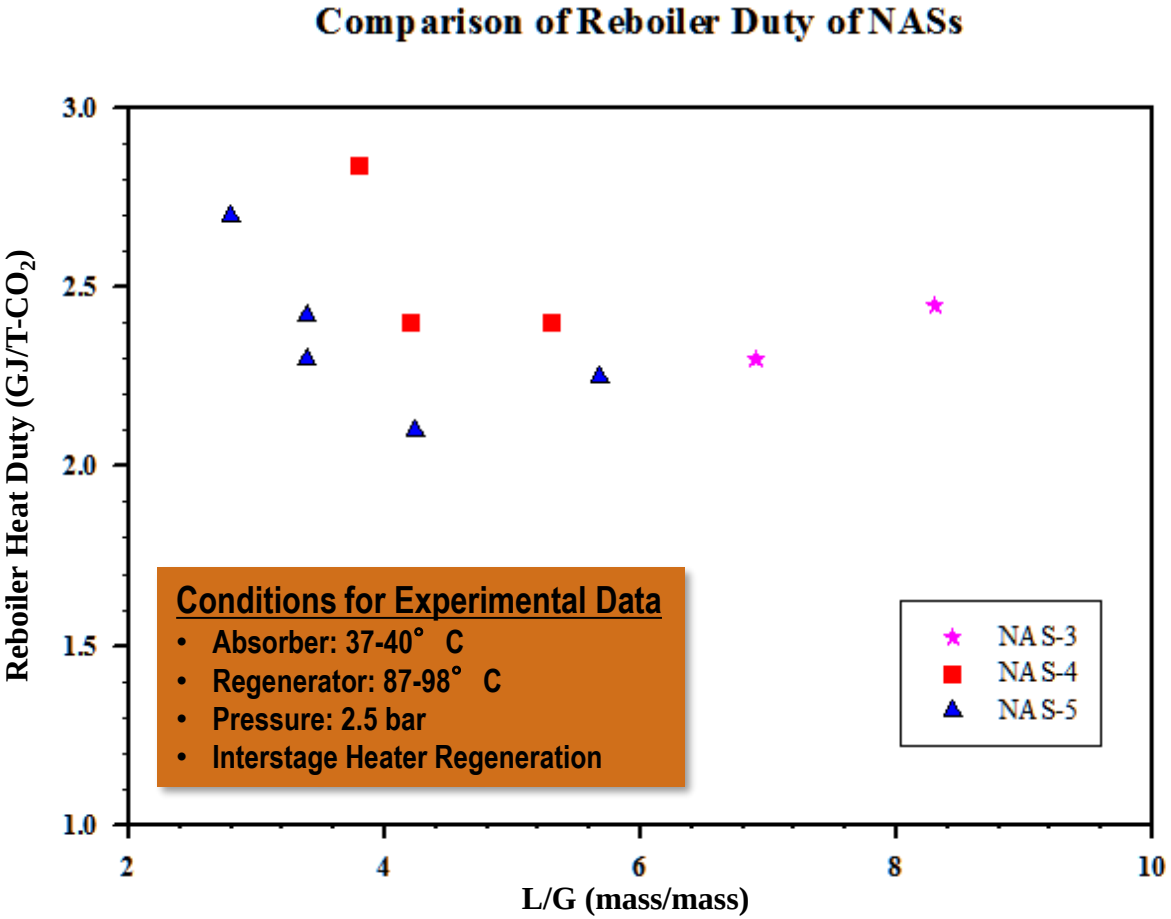

Exhaust Gas
Wash Section
Lean Amine Cooler
Condenser
CO_2 Product Gas
Knock-Out Drum
Interstage Coolers
Filter
Interstage Heaters
Flue Gas
Feed Gas
Absorber
Solvent Make Up
Rich/ Lean HX
Reboiler

Bench Scale Test Unit Results

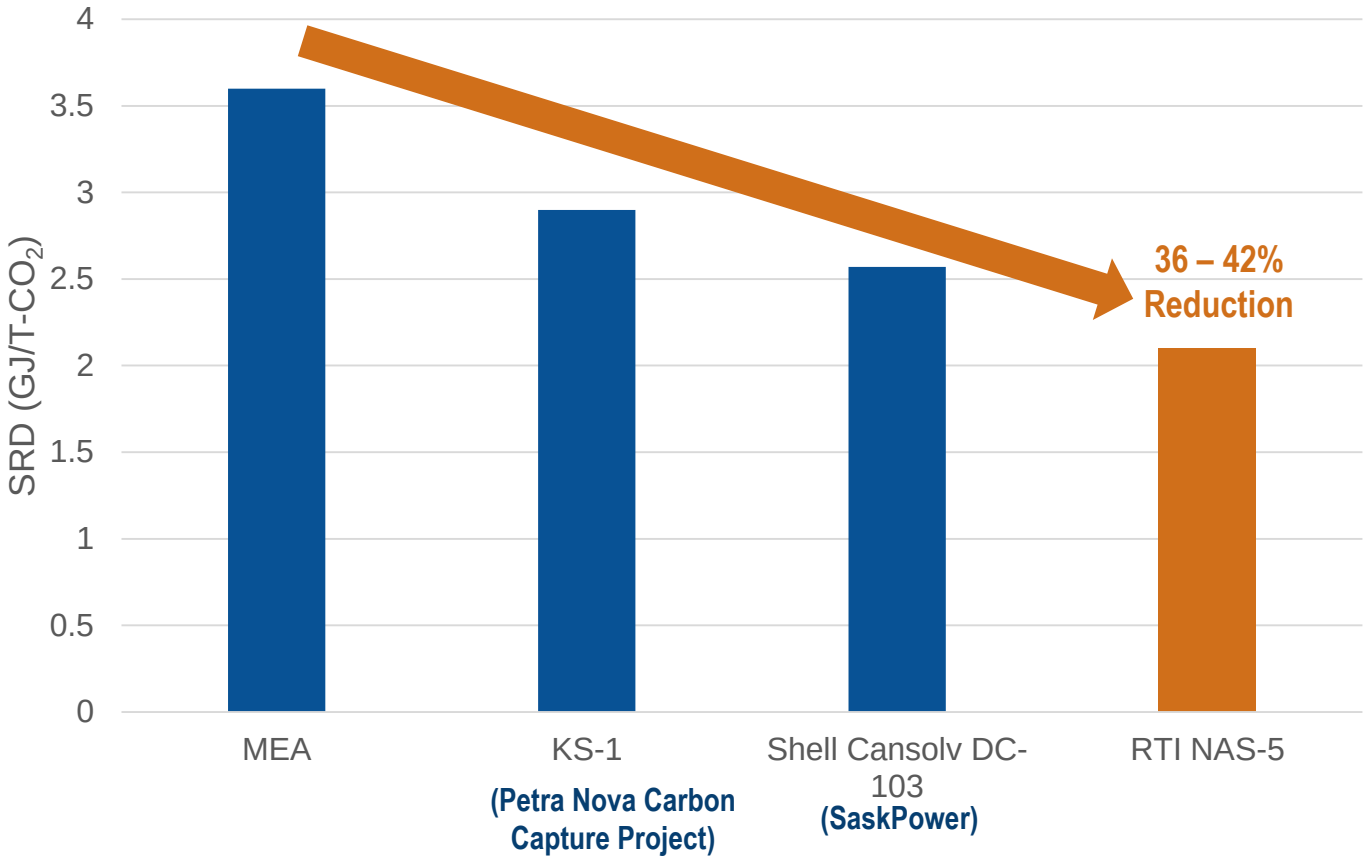


RTI non-aqueous solvents showing substantially reduced reboiler heat duties

Experimental Reboiler Duty Data



Specific Reboiler Duty Comparison



Small-Pilot Testing with Coal-fired Flue Gas at SINTEF

SINTEF

Objective:

- Design and build unique process modifications for SINTEF's Tiller plant
- Demonstrate RTI NAS process on coal-derived flue gas
- Finalize NAS solvent formulations
- Techno-economic and EHS evaluation

Current Work: Baseline Testing of NAS in Tiller Pilot Plant

- Compare MEA and NAS in conventional system
- Water balance
- Confirm reboiler heat duty
- Emission measurement

- **MEA baseline testing completed at Tiller plant**
- **NAS baseline testing completed**
  - **400 hours of testing with propane+coal flue gas**
  - **Confirmed the reduction in reboiler duty**

Coal Burner Installation at Tiller

Challenges with Coal Burner Testing of NAS in Tiller Pilot Plant

- **Particulates clogging filter**
- **Total run time 2 days with NAS**
- **Particulates clogging FTIR line**
- **Need new bag filter installation**

- **Coal flue gas test data same as those from propane flue gas data**
- **Confirmed the reduction in reboiler duty**

BP1 Accomplishments

BP1 Scope and Objectives

- **NAS Process testing at Tiller using propane+coal-derived flue gas**
- **Reduce the parasitic energy penalty to < 2.0 GJ_t/Tonne-CO_2 captured**

Other goals and objectives:

- Conduct baseline testing of MEA and
- Conduct NAS solvent degradation and material compatibility
- Design Regenerator and Absorber wash section,
- Improve the physical properties of NAS
- Improved NAS formulations and plan for scaled-up

NAS Prequalification in SINTEF's Lab Pilot System

Highlights and lessons learned:

- 9 total experimental runs of the NAS solvent were carried in SINTEF's lab pilot system
- CO_2-lean amine inlet temperature was identified as an important parameter to be controlled as it can affect solvent performance
- Capture efficiency was below 90% (initial theory being that absorber height is not sufficient and lean amine inlet temperature too low). These will not be an issue in larger Tiller test unit as that absorber column has an inter-stage cooler
- Some operational challenges experienced attributed to solids deposition within the CO_2 recycle from the Regenerator. This issue resolved at Tiller plant during NAS runs by controlling the regenerator column condenser temperatures.
- Test campaign enabled SINTEF first-hand experience with the NAS solvent and how it performs in a conventional CO2 capture unit.

Baseline Testing of NAS in Tiller Pilot Plant (Task 2)

Subtask 2.1 *– Procurement of required solvents and materials*
Subtask 2.2 *– MEA baseline testing in the Tiller plant*
Subtask 2.3 *– Procurement of NAS solvents*
Subtask 2.4 *– Prequalification NAS in SINTEF lab pilot*
Subtask 2.5 *– Materials degradation testing*
Subtask 2.6 *– NAS Baseline testing in the Tiller Plant*

Coal combustion furnace approved through CLIMIT Program – procured, constructed, installed at SINTEF

Research Objectives:

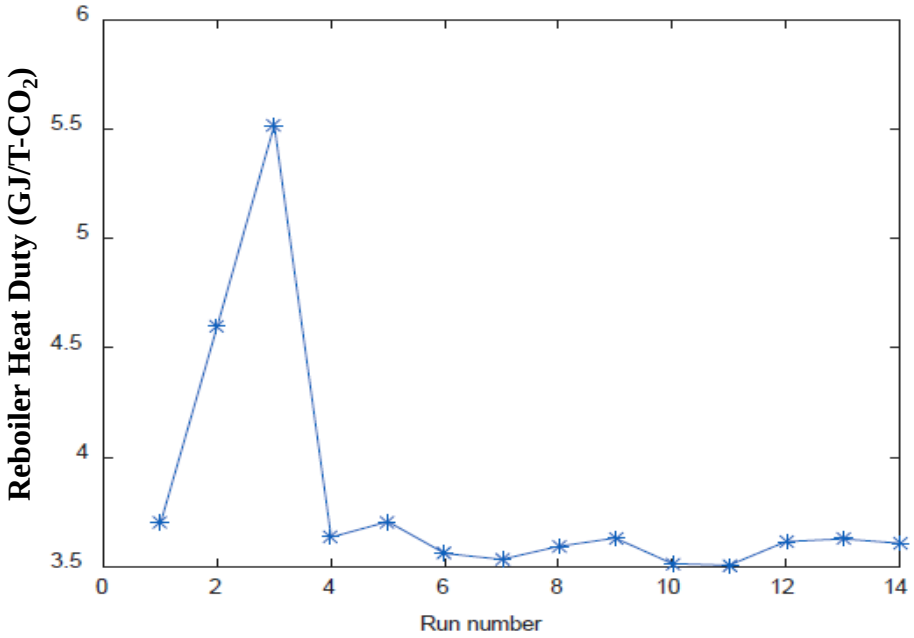
- Can the conventional system be operated without issue having a two-phase liquid condition?
- How much excess water must be added to the NAS solvent to enable the NAS process to reach the CO_2 capture efficiency target using a conventional stripper?
- What is the resulting impact on the reboiler heat duty?
- Any energy improvements for NAS over aqueous solvents when using a conventional stripper regenerator?

MEA/H_2O Baseline Testing at Tiller (Reboiler heat duty)

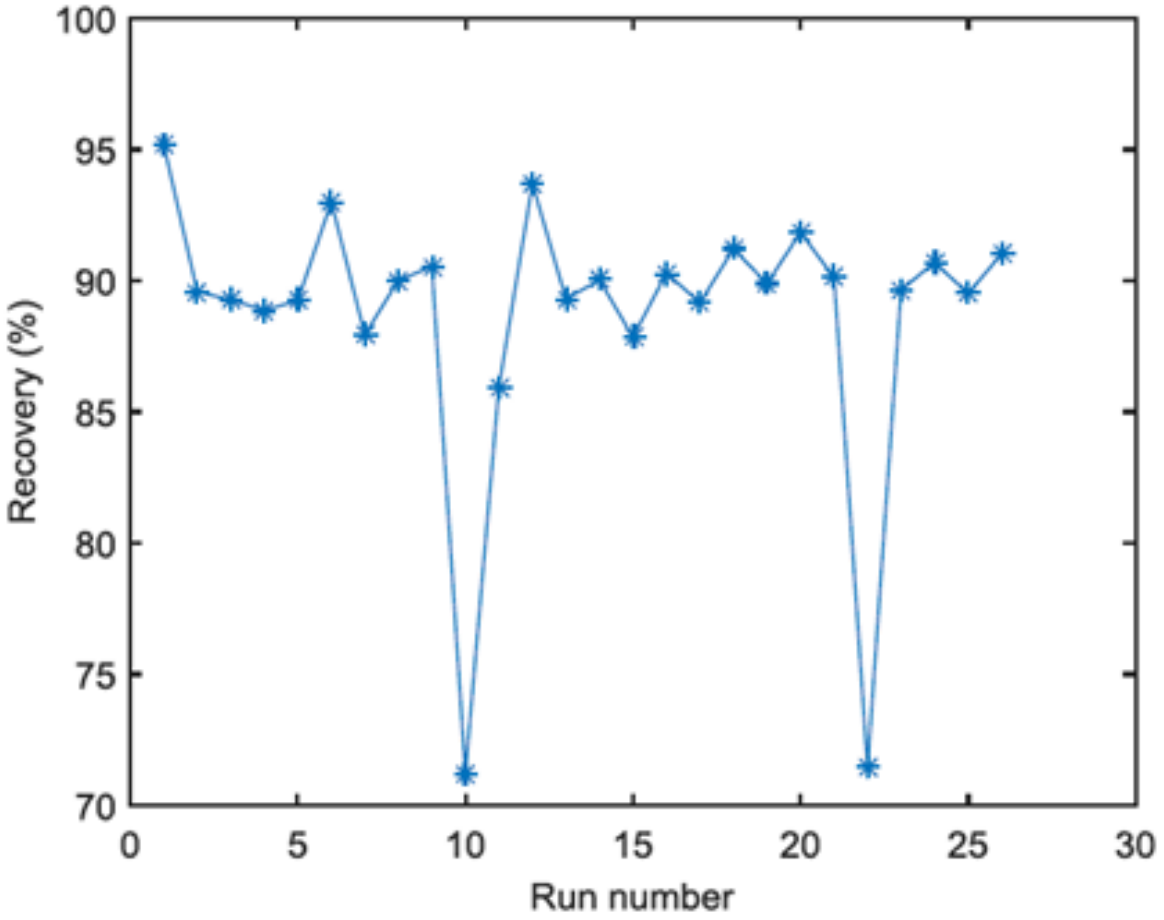
30 wt% MEA baseline testing at Tiller. 14 steady-state runs with varied parameters:

- Liquid circulation rate
- Heat rate (MJ/kg CO_2)
- Inlet gas humidity
- Intercooling
- Absorber packing height
- CO_2 capture efficiency
- Flue gas velocity

Specific reboiler duty:

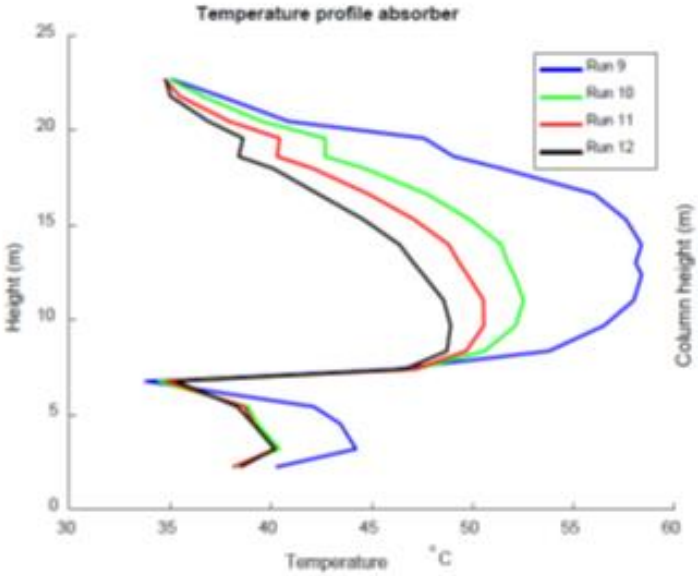


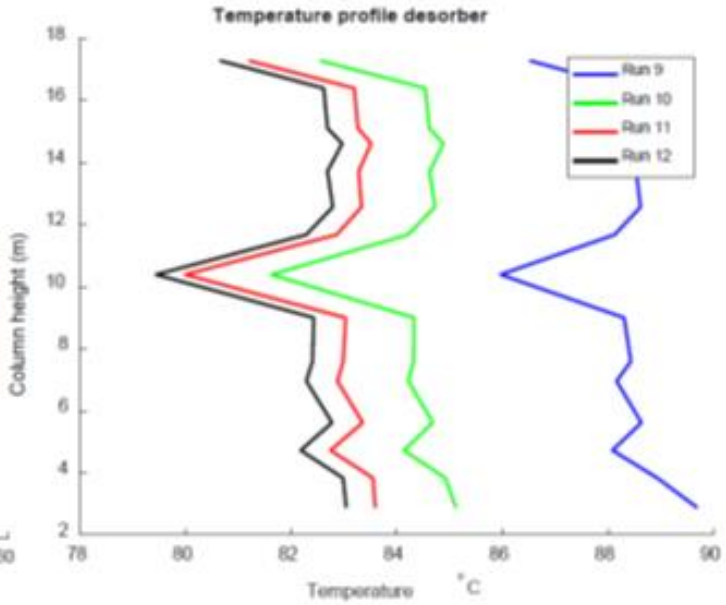
MEA/H_2O Baseline Testing at Tiller (CO_2 capture rate)



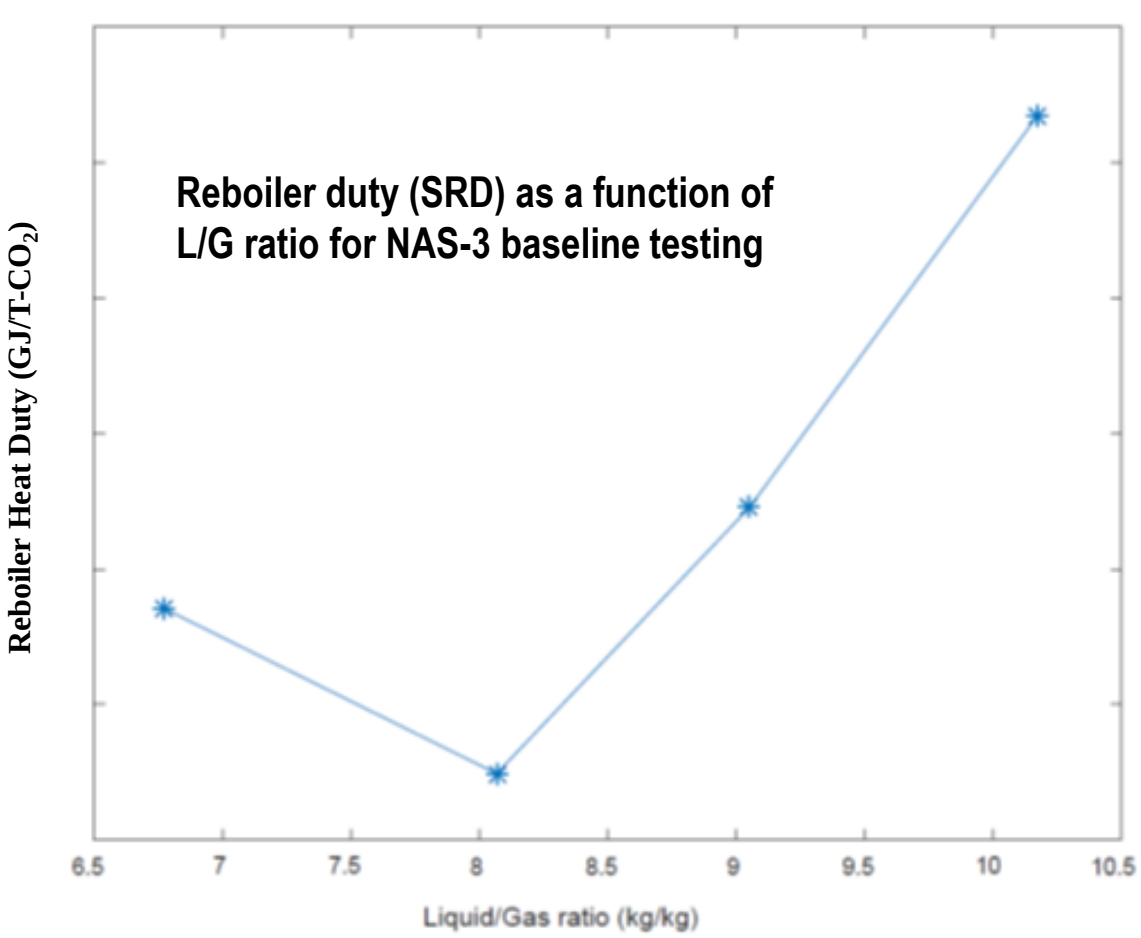
NAS Baseline Testing in SINTEF's Tiller Plant

Temperature profiles for NAS-3 baseline testing at SINTEF's Tiller Plant



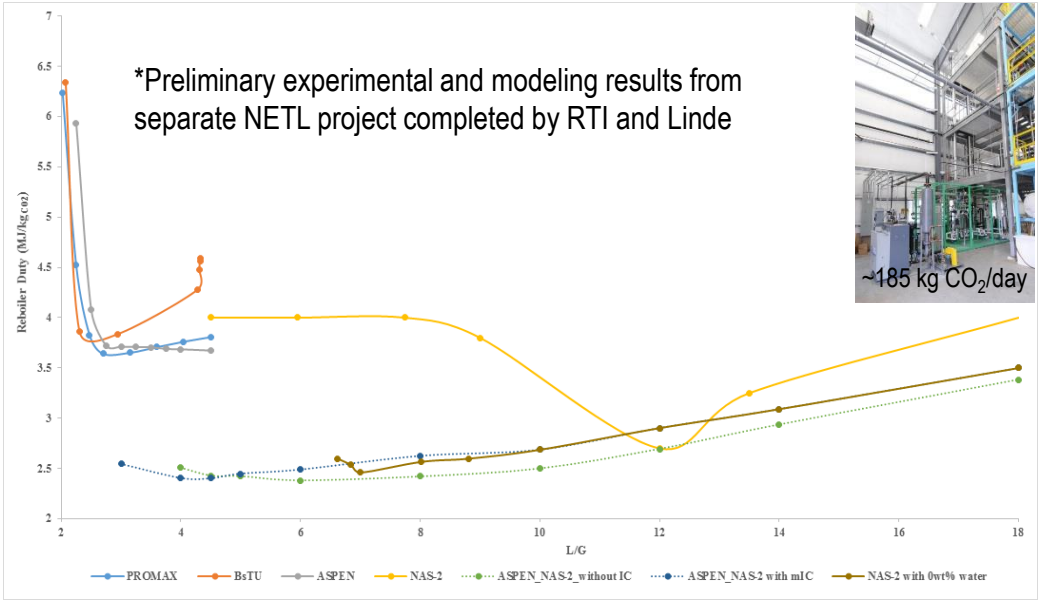


NAS Baseline Testing in SINTEF's Tiller Plant



Design of NAS-specific Components for Tiller (Task 3)

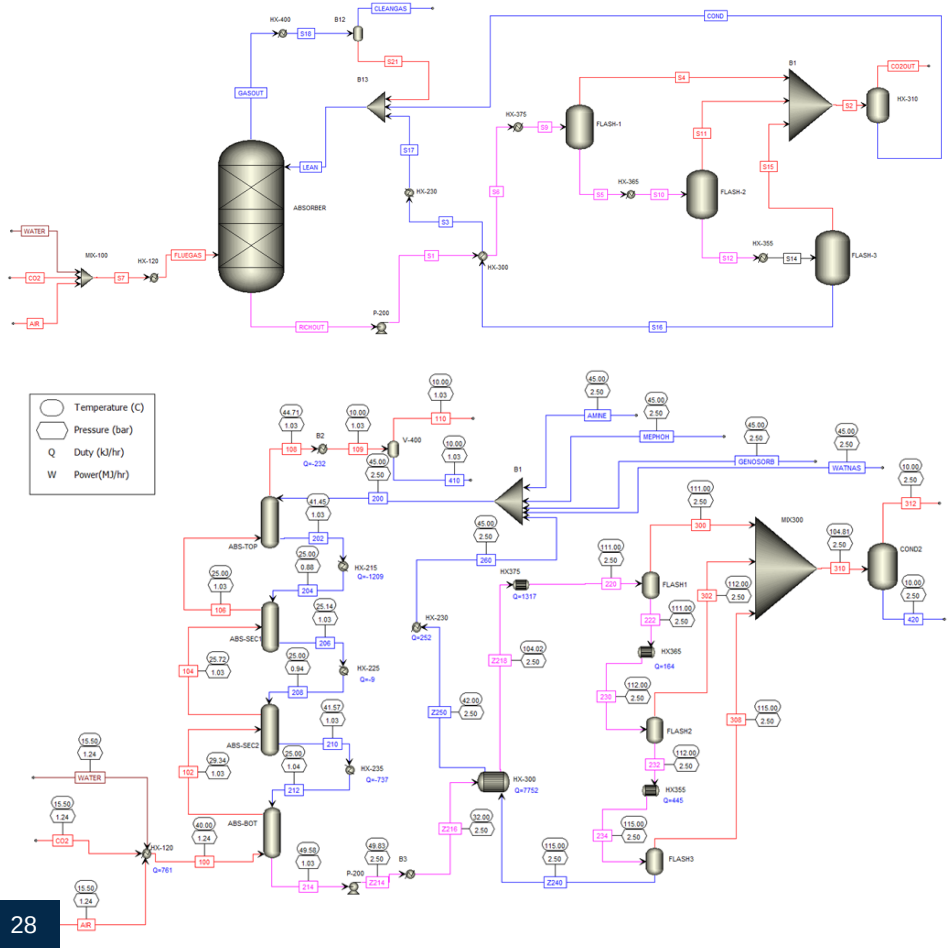
- Overall objective is to develop optimal designs for a NAS-based Regenerator unit and Absorber Wash section
- Regenerator design has been researched at a smaller scale on a separate NETL project
- Learnings from existing NETL project to be incorporated into the design of the larger regenerator unit for SINTEF's Tiller plant.



Subtask 3.1 *– Design and engineering of modular regenerator and absorber wash section*

Subtask 3.2 *– Tiller Plant integration design and planning*

Process Modeling



Developed rate-based process model Aspen ENRTL-SR

Thermodynamic and physical properties acquired experimentally:

- Henry's constant for CO_2
- Liquid heat capacity
- Vapor pressures
- Reference state properties
- Heat of vaporization
- Dissociation constants
- VLE
- Density
- Δh_{abs}
- Viscosity
- Surface tension
- Thermal conductivity
- Dielectric constant
- Diffusivity of CO_2

Used process model to direct bench-scale testing after initial runs

Budget Period 2 Overview

BP2 Scope and Objectives

BP2 objectives:

- Procurement, construction, integration, and shakedown of NAS-specific components in SINTEF's Tiller plant,
- Execution of systematic NAS solvent testing using coal-derived flue gas at SINTEF's Tiller plant which incorporates the NAS-specific process modifications,
- Completion of 400 hours cumulative testing on coal-derived flue gas at the Tiller plant, achieving 90% CO_2 capture and proper water balancing,
- Completion of a detailed Techno-Economic Analysis (TEA) to confirm that RTI's NAS-based technology can reduce the cost associated with CO_2 capture from coal-fired power plants.

Task 5.0 - Baseline Testing of NAS Using Coal-Fired Flue Gas

Subtask 5.1 – Materials degradation testing - Completed

Impact of the NAS on the materials of construction used in the Tiller plant

Subtask 5.2 – NAS Baseline testing in the Tiller Plant

- Baseline testing of the NAS solvent using coal-fired flue gas
- Need to study water balance, emissions, amine loss for longer duration

Task 6.0 –Solvent Formulation Improvement

- NAS-5 formulation testing remaining from Task 4.0 in BP1 will be completed.
- Parametric testing of NAS-5
- Water balance testing
- Wash section/emissions testing
- NAS reaction kinetics improvement
- NAS oxidative/thermal degradation improvement

Task 7 - Construction, Integration, and Shakedown of NAS-Specific Components in Tiller Plant

- SINTEF will lead this task in BP2
- Process components for optimized operation of the NAS solvents will be procured, fabricated and integrated into the Tiller plant
- Engineering design package provided by RTI as the basis for sizing
- Detailed engineering done by key members of the SINTEF team
- SINTEF to work with construction providers to construct NAS-specific adds
- SINTEF to perform shakedown tests with the new modules
    - **Subtask 7.1 – Design of NAS–specific components and solvents for Tiller Plant**
    - **Subtask 7.2 – Procurement of NAS–specific components and solvents for Tiller Plant**
        - Current NAS formulation components available at hundreds of liter scale
        - Modified regenerator materials
    - **Subtask 7.3 – Construction and integration of NAS-specific components within Tiller Plant**
        - Interstage coolers
        - Interstage heaters
        - Lean/rich heat exchanger expansion
    - **Subtask 7.4 – Shakedown testing of NAS-specific components at Tiller Plant**

Drums of current NAS formulation components

Task 8 - Bench-scale Testing of the NAS CO_2 Process in Coal-Fired Flue Gas

- Led by SINTEF in BP2 and completed at the Tiller plant.
- Testing using coal-derived flue gas
- Configuration incorporates the NAS-specific process modifications built in Task 7
- Completion of 400 hours cumulative bench-scale testing on coal-derived flue gas at 90% CO_2 capture and water balanced

Subtask 8.1 – Parametric testing campaign at Tiller Plant

- Will determine optimal operating parameters for the NAS solvents
- Process parameters such as absorber temperature, regenerator temperature, L/G ratio, and humidity of the flue gas will be varied
- Optimal parameters will be chosen for the long-term evaluation
- Anticipated to be completed in three months

Subtask 8.2 - Long-term performance testing campaign at Tiller Plant

- SINTEF will lead this sub-task
- Duration of the testing is planned for forty-one days.

Task 9 - Detailed Techno-Economic and EHS Analysis

- Will conduct a technical and economic feasibility study as described in Attachment 2 of DE-FOA0001235.
- Shall follow the analysis documented in the NETL report *"Cost and Performance Baseline for Fossil Energy Plants Volume 1: Bituminous Coal and Natural Gas to Electricity (Rev 2a, September 2013),"* aka Bituminous Baseline Study (BBS). The assessment shall follow Case 12, super-critical pulverized coal (PC) with CO_2 capture.
- RTI will also conduct an EH&S risk assessment as described in Attachment 3 of the FOA
- Evaluation of air, water, and solid wastes, toxicological impact, flammability, and corrosivity.

Subtask 9.1 – Updated process modeling

- Led by RTI
- Rate-based process model will be updated with data from coal-derived flue gas testing
- Model will be used to predict energy penalty for Case 12 using NAS solvents

Subtask 9.2 – Technoeconomic analysis

- Led by RTI
- Energy penalty from 7.1 to be used in the techno-economic analysis to compare the cost of a non-aqueous CO_2 capture to aqueous CO_2 capture

Subtask 9.3 – EH&S evaluation

- Led by RTI
- Conduct EHS assessment of emissions to air, contamination of water, and hazards of solid wastes as well as any toxicological effects that are known regarding NAS formulation components, fire danger, or concerns about the potential of the NAS solvents to corrode materials of construction.

BP2 Milestones

Task	Milestone Description	Planned Completion	Verification
7.3	**F.** NAS-specific components installed and commissioned at SINTEF Tiller plant.	8/31/17	Quarterly Report #8
8.2	**G.** Completion of 400 hours cumulative testing at SINTEF Tiller plant	2/21/18	Quarterly Report #9
9	**H.** Detailed techno-economic analysis report delivered to DOE.	6/30/18	Quarterly Report #11

Next Steps: NAS-Specific Components for SINTEF Plant

- Scale-up an optimal regenerator unit for NAS
- Regenerator process design
- How to incorporate new design at Tiller plant
- Testing next year with:
  - Optimal components at larger scale (60 kW)
  - Optimized NAS formulation; initial tests show reduced L/G with similar heat duty

Technology Development Pathway

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Next Steps: NAS Process Testing at NCCC and Cost/Benefit Analysis

Coal flue gas scope completion:

- further reduce the deployment risk
- accelerate NAS technology development at lower

1. Test NAS at NCCC using the SSTU
    - Test advanced NAS-5 formulation at NCCC to determine operating windows, solvent performance, water balance, emissions, amine loss, and other operational issues,
    - Continuous run of NAS-5 using coal-derived flue gas for at least two months

2. Cost/Benefit relative to the aqueous MEA based process
    - Estimate performance advantages and benefits of the NAS process

3. Solvent formulation adjustments to fit existing aqueous MEA based equipment
    - Amount of water in NAS
    - Water wash and emissions
    - Reboiler duty

Next Steps: Large Pilot Testing

- Large pilot testing for non-aqueous solvent technology targeted for 2018+
  - ~ 1 - 10 MW equivalent
  - Range of flue gas compositions (including coal, NGCC, etc)
  - Extended operation with finalized NAS formulation and process design
- Technology Center Mongstad and U.S. National Carbon Capture Center are potentially suitable sites

CO_2 Technology Centre Mongstad (TCM), Mongstad, Norway

National Carbon Capture Center (NCCC), Alabama, USA

Leveraging the U.S. – Norway Collaboration Framework

Partnering with Purpose. U.S. – Norway Cooperation

43 SINTEF Tiller Plant

Non-aqueous solvents for CO_2 capture with low regeneration heat requirement

- Cooperation between RTI and SINTEF
- Program is substantially supported by DOE NETL and Norway's CLIMIT program
  - Solvent degradation studies
  - Scale-up at SINTEF pilot facility
- Following cooperation framework between the U.S. Department of Energy and the Norwegian Ministry of Petroleum and Energy
- The cooperation enables a lower cost, lower risk, but accelerated pathway for CO_2 capture technology deployment

NATIONAL ENERGY TECHNOLOGY LABORATORY

GASSNOVA

RTI INTERNATIONAL

SINTEF

THE LINDE GROUP

RTI Novel CO_2 Solvents

Lab Development & Evaluation (2010-2013)

Solvent screening

Lab-scale evaluation of process

Large, Bench-Scale System (RTI Facility, 2014-2016)

Demonstration of key process features ($\leq$ 2.0 GJ/T-CO_2)

- Optimize NAS formulation
- Develop critical process components
- Detailed solvent degradation and preliminary emissions studies (SINTEF NASCHAR project)
- Detailed TEA and EH&S assessments

Pilot Testing at SINTEF Tiller Plant (Norway, 2015-2018)

Demonstration of all process components at in adiabatic system pilot scale (~60 kWe)

- Quantify solvent losses and emissions
- Test campaign on coal derived flue gas
- Collect critical process data to support scale up, develop engineering package

Future Demonstration (2017+)

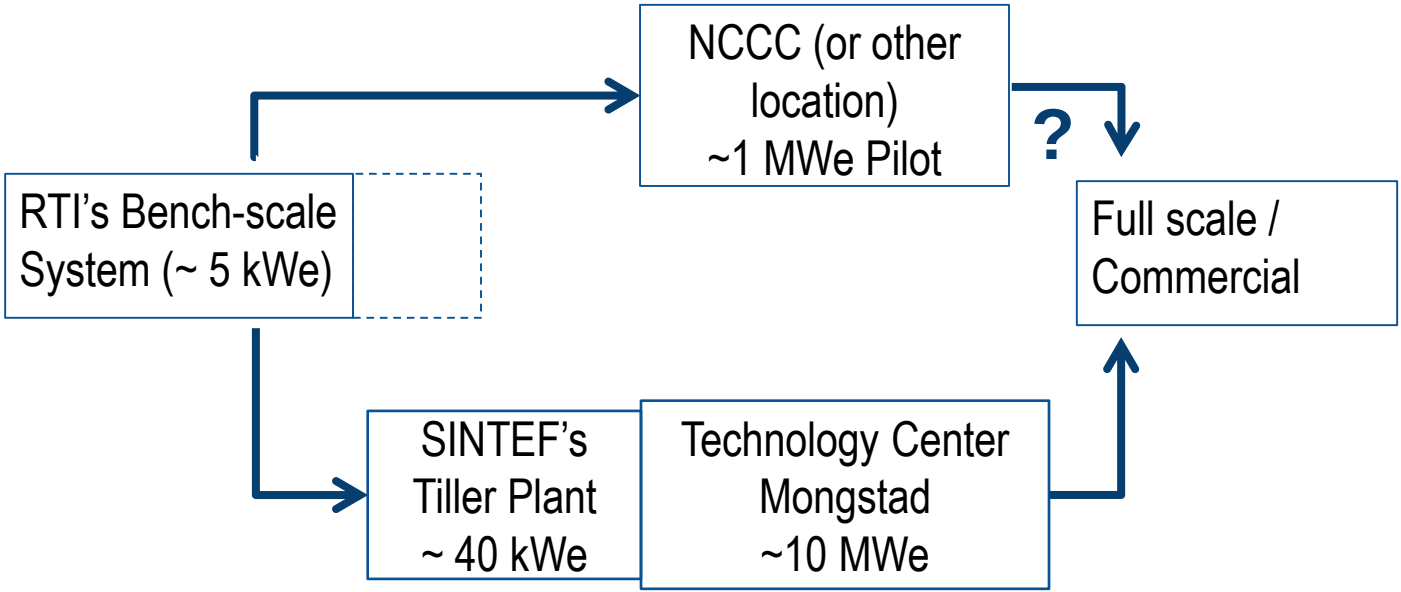
Pre-commercial Demonstration e.g. at Technology Centre Mongstad, Norway (~10 MWe)

Planning ongoing

- Complete process unit with all components at minimum size required for confident scale-up
- Collect critical process information to support detailed T&E assessments, emissions monitoring, long-term testing to develop reliability, availability and maintainability (RAM) metrics

Accelerated Technology Pathway, lower risk and cost

	DOE NETL Project (Current)	DOE NETL Project (Current)	Future Development	Commercial
Yr	2014-16	2015-18	2017 - 2020	2020+



Acknowledgments

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- DOE Project Manager: Steve Mascaro

- RTI cost share and project partner SINTEF