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Fluor Solvent Evaluation and Testing New Scope: Techno-economic Assessment of EEMPA Solvent for CO_2 Separations from Natural Gas Combined Cycle Power Plant

Final Report, FY24

Yuan Jiang (PM/PI)
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Charles J. Freeman
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U.S. DEPARTMENT OF ENERGY

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I Executive Summary

In this project, a techno-economic analysis (TEA) and accompanying sensitivity studies were conducted to assess the Pacific Northwest National Laboratory's (PNNL) leading water-lean carbon dioxide (CO_2) capture solvent, N-(2-ethoxyethyl)-3-morpholinopropan-1-amine (EEMPA), for capturing CO_2 from a natural gas combined cycle (NGCC) power plant at different levels of capture rate. Process models for the NGCC power plant, integrated with the EEMPA carbon capture processes, were developed in Aspen Plus V14 using the most up-to-date property package for the EEMPA-H_2O-CO_2 system. The TEA evaluated the EEMPA carbon capture process at standard capture rates (90%, 95%, and 97%) against Case B32B (Cansolv) described in the NETL Rev4a baseline report, and at higher capture rates aimed at achieving zero or negative emissions from the power plant (400 ppmv, 200 ppmv, and 100 ppmv CO_2 in exhaust gas) compared to typical direct air capture (DAC) technologies. The results suggested that the carbon capture cost reaches a minimum of $53.7/tonne CO_2 at 90% capture rate. Compared to Cansolv, one of the industrial benchmarks, EEMPA demonstrates 2-4% cost savings at capture rates up to 95%, but minimal savings at higher capture rates. The water lean-solvent system proves economically attractive for achieving moderate negative emissions (about 200 ppmv CO_2 in exhaust gas, and equivalent to 50% CO_2 removal from air) for NGCC flue gas, with marginal capture costs comparable to direct air capture (DAC) technologies. Sensitivity analyses reveal that the impact of EEMPA price on the above economic advantage could be minimal due to low solvent loss and degradation rate, The estimated marginal cost is 37% lower than DAC in the best-case scenario (lowest solvent price and solvent loss) and 8% lower in the worst-case scenario (highest solvent price and solvent loss). However, the marginal carbon capture cost exceeds $1,000/tonne CO_2 when transitioning from moderate to extreme negative emissions (100 ppmv CO_2 in exhaust gas), suggesting that water-lean solvents may not be economically competitive with other DAC technologies for removing more than 75% CO_2 from air. In addition, an initial connection was established with Technology Center Mongstad (TCM) for a potential pilot testing proposal.

II Solvent Overview

PNNL has spent over a decade researching point source carbon capture, including solvent molecular design, property prediction, synthesis, property measures, performance testing, process design optimization, and techno-economic analysis (TEA). These efforts ultimately led to the development of CO_2-binding organic liquids (CO_2BOLs), a class of single-component water-lean solvents designed to be more cost- and energy-effective than traditional aqueous amines. CO_2BOLs come in various formulations and have been thoroughly studied for their ability to capture CO_2. EEMPA, as illustrated in Figure 1 (a), is a particularly promising CO_2BOL requiring less energy for heating and cooling due to lower sensible heat. Additionally, EEMPA has faster CO_2 uptake kinetics, reducing the size and complexity of equipment needed. The viscosity of EEMPA is comparable to traditional solvents, making it a drop-in solvent for existing systems. Perhaps most importantly, EEMPA operates with minimal water content (less than 5%), which minimizes energy wasted on water evaporation and condensation during solvent regeneration.

The effectiveness of EEMPA has been demonstrated in various tests. As shown in Figure 1 (c), PNNL's 5L laboratory continuous flow system (LCFS) successfully demonstrated a 40 hr steady-state operation with a capture rate above 95% (Zheng et al., 2020). Another test conducted in Research Triangle Institute (RTI) International's 50L bench-scale gas absorption system (BsGAS) (Figure 1(d)) showed EEMPA can acheive a low energy consumption (2.1 GJ/tonne CO_2). The solvent is currently undergoing a 6-month pilot-scale (0.5MW) test at the National Carbon Capture Center (NCCC) in Alabama (Figure 1 (e)), which started in August 2024. 2000 gallons of EEMPA have already been manufactured and delivered to NCCC for the test campaign.

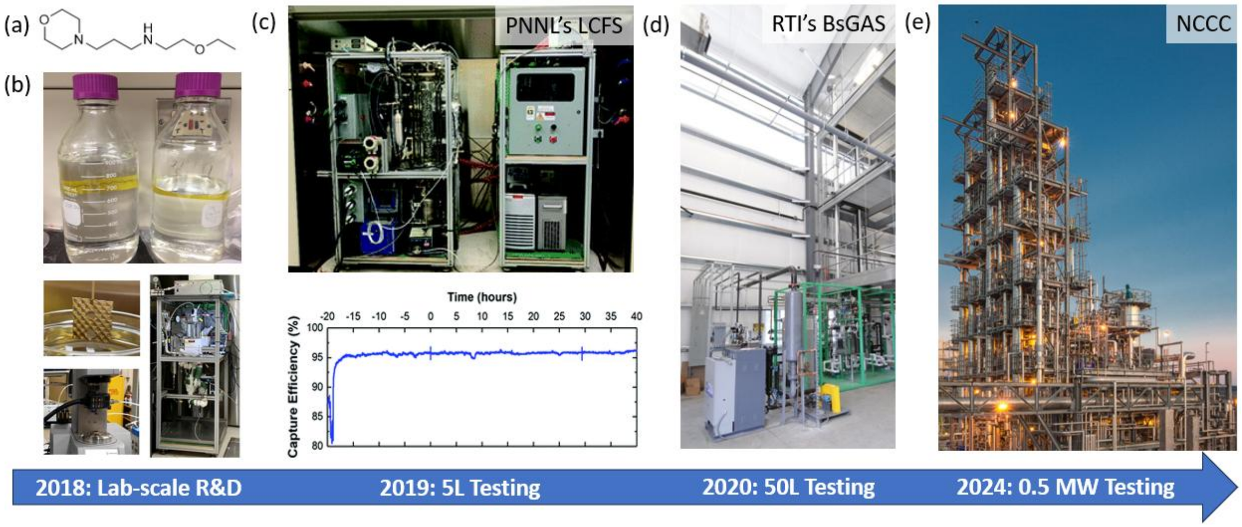

Figure 1. A timeline for EEMPA scale up from lab to pilot scale: (1) chemical structure of EEMPA, (b) synthesis and property measures, (c) continuous flow testing in PNNL's LCFS, (d) continuous flow testing in RTI's BsGAS, and (e) upcoming pilot scale testing in NCCC.

Using experimentally measured property data, Aspen Plus process models validated at both LCFS and BsGAS scales, and NETL fossil energy plant performance baselines (James et al., 2019), a comprehensive TEA further elucidated the energy and cost advantages of EEMPA compared to conventional aqueous amine technologies for capturing CO_2 from coal-fired power plants. As shown in Figure 2, the results suggest that EEMPA enables >20% cost advantage for coal power plant application and >30% energy saving, comparing with aqueous amine solvents. More details of the TEA and process models for coal plant application can be found in Jiang et al. (2021, 2023). To fill the gaps in previous TEAs of water lean solvents, this project focused on evaluating EEMPA application to NGCC power plants at high capture rates.

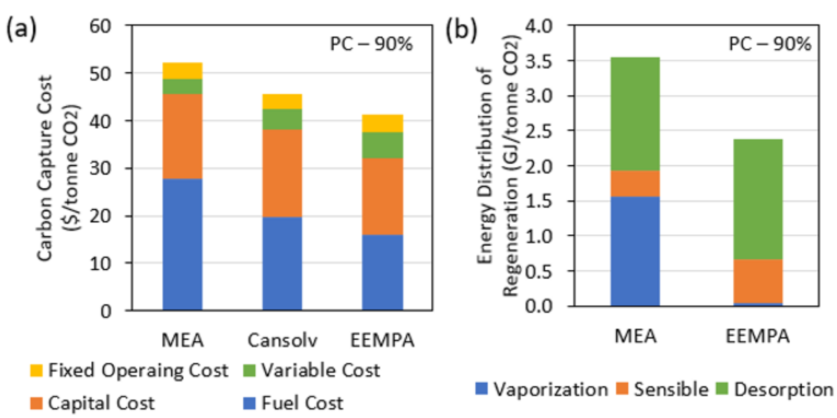

Figure 2. TEA results for using EEMPA for coal-fired power plant carbon capture.

III Project Scope

The revised project scope aims to better assess PNNL's leading CO_2 capture solvent, EEMPA, under natural gas power flue gas conditions. The earlier work on this project was focused on assessing Fluor's advanced solvent technology against the natural gas power flue gas conditions at TCM, which ultimately enabled its testing at the TCM facility. By assessing EEMPA in a similar way, the potential for testing EEMPA at TCM can be better understood and compared against an amine baseline. Further, the scope will include an assessment of the potential for EEMPA to achieve DAC performance, thereby achieving net negative emissions, and modeling support for a pre-proposal for testing EEMPA at TCM. The overall effort will require an upfront TEA effort for EEMPA applied to NETL's natural gas combined cycle baseline case, which will allow for those predictions to formalized and published.

IV Techno-economic Analysis

IV.1 General evaluation basis

Literature approaches and the NETL baseline were used to conduct a TEA based on rigorous process models developed in Aspen Plus, as shown in Figure 3 (Du et al., 2021; James et al., 2022; Van Wagener and Rochelle, 2011). The process model includes two major sections: 1) NGCC power plant, burning natural gas to generate electricity and steam, and 2) CO_2 capture & compression, using utilities from the power plant to capture flue gas CO_2 and produce clean gas and compressed CO_2 product. The operating variables and parameters (i.e., temperature (T), pressure (P), and efficiency (η) of key unit operations such as gas turbine (GT) and steam turbine (ST), pumps, blowers, and compressors) within the NGCC power plant are the same as those outlined in NETL Case B32B (James et al., 2022). Property models used for estimating the vapor-liquid equilibrium (VLE), viscosity, and reactions in the EEMPA carbon capture system were regressed from experimental data (Jiang et al., 2021; Zheng et al., 2020). Note to ensure a consistent economic comparison between the EEMPA capture system and scenarios in NETL Case B32B (James et al., 2022), the inlet natural gas flowrate was maintained at the same level as in NETL Case B32B.

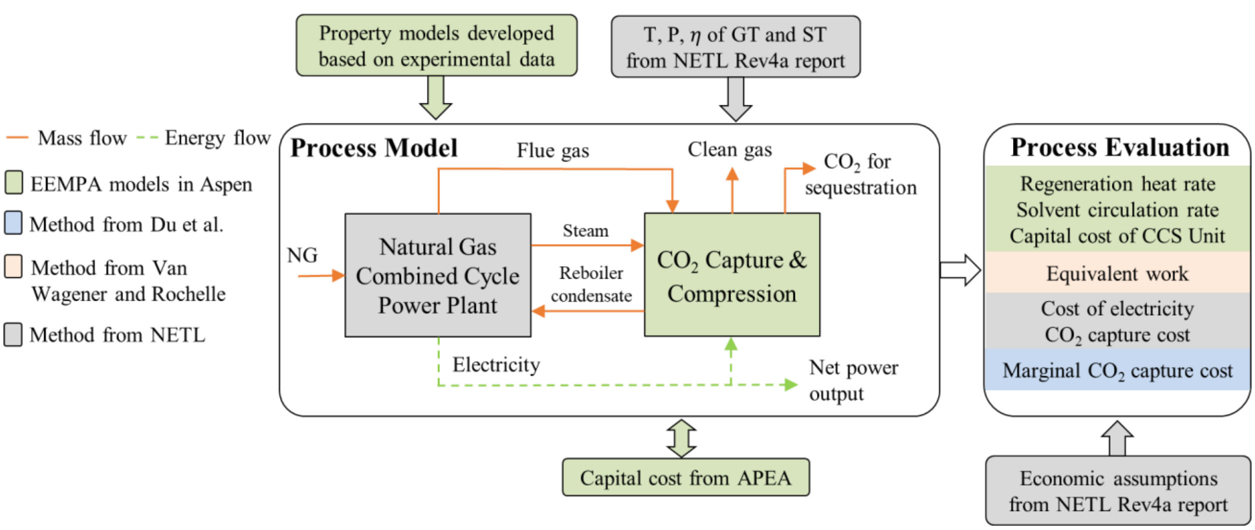

Figure 3. Overview of the general evaluation approach.

To evaluate and compare the EEMPA carbon capture process with different carbon capture technologies (such as MEA and Cansolv, which have the same inlet CO_2 composition in the NGCC flue gas) and DAC, which has a different starting CO_2 composition, two cost metrics were applied in the TEA. These are: 1) carbon capture cost (\$/tonne CO_2) as defined in Equation (1), which represents the cost of integrating carbon capture and storage (CCS) with the NGCC power plant, allowing for comparison between different carbon capture technologies with the same initial CO_2 composition, and 2) marginal capture cost (\$/tonne CO_2) as defined in Equation (2), which reflects the cost increment between two capture rates, useful for comparing CO_2 removal technologies with different starting CO_2 concentrations.

$$C_{CCS} = \frac{(COE_{CCS} - COE_{non-CCS})P}{CO_2\ Captured} \tag{1}$$

$$C_{MCCS} = \frac{C_{CCS,x_2}x_2 - C_{CCS,x_1}x_1}{x_2 - x_1} \tag{2}$$

IV.2 Process configuration and cases

Six carbon capture rates were investigated: three within a normal post-combustion capture range (90%, 95%, and 97%) and three for a zero or negative emissions power plant (with an exhaust gas CO_2 concentration less than 400 ppmv). Two process configurations (Figure) were analyzed in Aspen Plus V14: a) simple stripper (SS) and b) two-stage flash (TSF). The SS process employs a distillation column for CO_2 separation, while the TSF process utilizes two flash vessels operating at different pressures. For these two process configurations, key process design variables such as flue gas chilling temperature, lean solvent loading, and regeneration pressure were determined through sensitivity analyses for each targeted carbon capture rate. Generally, the TSF configuration is thermodynamically unfavorable to achieve high-purity separation as it can only provide one equilibrium stage, while the SS is a multi-stage separator. However, the TSF configuration is efficient when the targeted carbon capture rate is not overly high, as it can reduce downstream CO_2 compression cost and capital investment for solvent regeneration. Therefore, the SS configuration was selected for zero or negative emissions application, and the TSF configuration was selected for normal capture rate application.

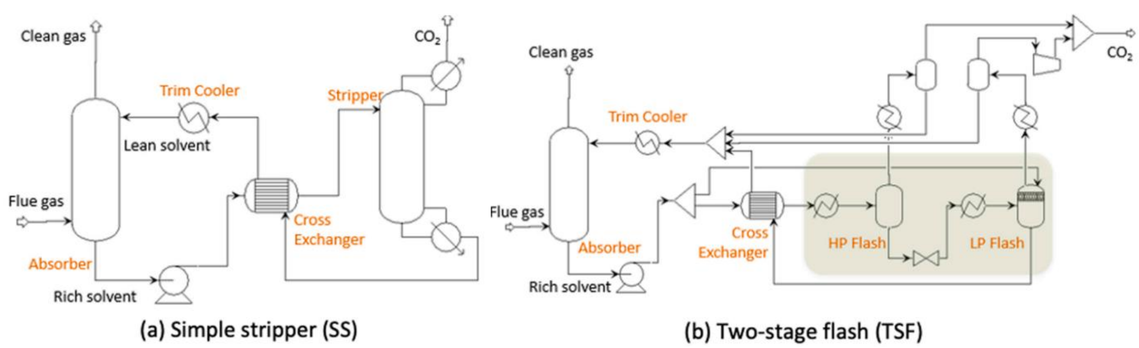

Figure 4. Process configurations for EEMPA carbon capture processes.

IV.3 Solvent performance and estimated carbon capture cost

Table 2 summarizes the key performance and economic measures of EEMPA and Cansolv at normal capture rates, while Figure 5 compares their carbon capture cost with MEA (a representative 1st generation aqueous amine) and Cansolv (a representative 2nd generation aqueous amine). Both EEMPA and Cansolv processes have better economic performance than the MEA process. At 90% carbon capture, the EEMPA process with the TSF configuration exhibits 4% lower carbon capture cost than Cansolv. However, at 97% carbon capture, the EEMPA process requires a 3% higher capture cost than that of Cansolv. Therefore, EEMPA is a favorable carbon capture technology for NGCC flue gas with a carbon capture rate below 95%. For a carbon capture rate above 95%, further research and optimization would be needed to make EEMPA more competitive.

Table 1. Cost estimation and comparison summary for normal capture rate.

Solvent	Cansolv			EEMPA		
Configuration	-	-	-	TSF		
Capture rate	90%	95%	97%	90%	95%	97%
Amount of Captured CO_2 (tonne/hr)	289.3	304.9	311.3	289.3	304.9	311.3
Operating conditions						
Lean loading (mol CO_2/mol solvent)	-	-	-	0.05	0.05	0.038
Rich loading (mol CO_2/mol solvent)	-	-	-	0.197	0.175	0.137
Solvent water loading (wt%)	-	-	-	4.4	4.4	4.4
L/G ratio (wt solvent/wt gas)	-	-	-	2.1	2.6	3.4
Flue gas chilling temperature (°C)	-	-	-	12.6	10.4	10.4
Regeneration pressure (kPa)	-	-	-	521.2, 121.4	521.2, 122.2	521.2, 100.9
Regeneration temperature (°C)	-	-	-	126	126	126
Performance measures						
Net Power, (MW)	883	877	873	907	904	900
Reboiler duty (GJ/tonne CO_2)	2.9	2.9	3	2.7	2.7	3.2
LHV net plant efficiency (%)	54.3	54	53.7	55.9	55.6	55.3
Equivalent work (kJ/mol CO_2)	50.2	50.4	51.6	44.7	46.4	52.9
Reboiler	30.3	30.2	31	23.8	24.3	28.2
Cooling	3.7	3.6	3.6	4.4	4.3	4.6
Refrigeration	-	-	-	3.3	4	4
Pumping / Reclaimer	3.2	3.6	4	1.5	1.7	2.1
Compression	13	13	13	11.8	12.1	14.1
Economic measures (2018 price basis)						
Cost of electricity ($/MW-hr)	61.6	62.5	63.1	60.3	61.5	63.1
Total plant cost of CCS (MM$)	496	517	529	511	558	630
Carbon capture cost ($/tonne CO_2)	56	55.3	55.5	53.7	54.2	57.3

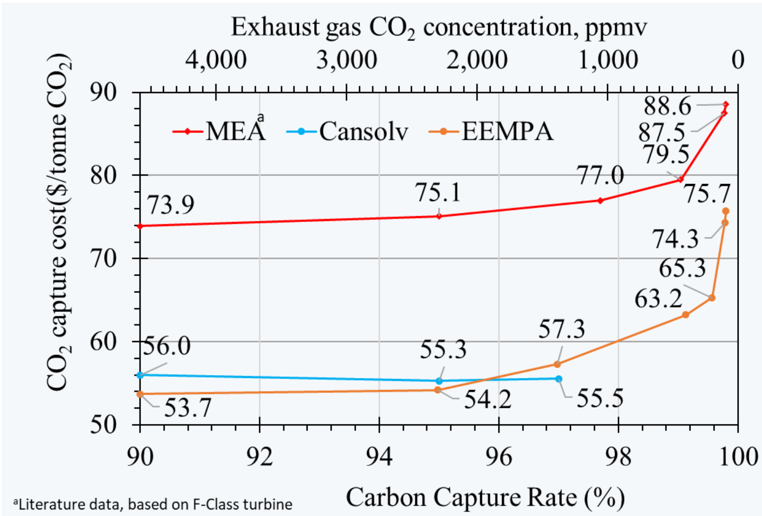

Figure 5. Comparison of carbon capture cost for EEMPA, Cansolv, and MEA.

Table 2 details the EEMPA carbon capture cost estimation at zero and negative emissions, and Figure 5 compares its marginal cost with DAC technologies. When targeting extremely negative emission (100 ppmv CO_2 in the exhaust) even beyond the typical operating range of DAC, the marginal capture cost of EEMPA exceeds 800 $/tonne CO_2, which is a high-end carbon capture cost of DAC technologies (Sievert et al., 2024). However, the marginal capture cost is only $545/tonne CO_2 when aiming for moderate negative emissions (200 ppmv CO_2 in the exhaust, equivalent to capturing 50% of CO_2 from air). This indicates that EEMPA, a post-combustion carbon capture solvent, could be a cost-effective negative emissions technology competitive with current DAC technologies, both capable of reducing CO_2 to 200 ppmv in the exhaust gas at comparable costs.

Table 2. Cost estimation results at zero/negative emissions.

Solvent	EEMPA			
Configuration	SS			
Capture rate	99.14%	99.57%	99.78%	99.8%
CO_2 in exhaust gas (ppmv)	400	200	100	93
Amount of Captured CO_2 (tonne/hr)	327.93	329.35	330.07	330.12
Operating conditions				
Lean loading (mol CO_2/mol solvent)	0.007	0.0045	0.0026	0.0026
Rich loading (mol CO_2/mol solvent)	0.127	0.112	0.099	0.089
Solvent water loading (wt%)	3.2	3.2	3.2	3.2
L/G ratio (wt solvent/wt gas)	2.8	3.1	3.5	3.9
Flue gas chilling temperature (°C)	9.9	11.1	14.1	14.1
Regeneration pressure (kPa)	60.7	50.7	35.2	35.2
Regeneration temperature (°C)	126	121	115	114
Performance measures				
Net power (MW)	863	861	819	817
Reboiler duty (GJ/tonne CO_2)	3	3.2	5.4	5.5
LHV net plant efficiency (%)	53	52.9	50.4	50.2
Economic measures (2018 price basis)				

Cost of Electricity ($/MWe-hr)	66.7	67.7	72.6	73.3
Total plant cost of CCS (MM$)	726	784	903	932
Carbon Capture Cost ($/tonne CO_2)	63.2	65.3	74.3	75.7

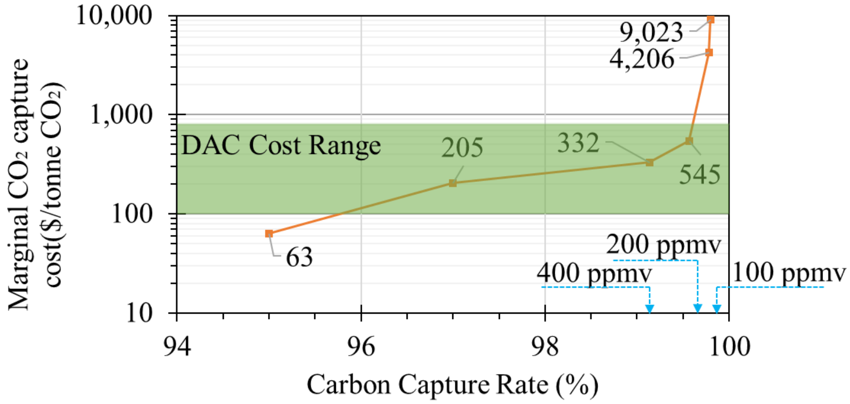

Figure 6. Marginal carbon capture cost of EEMPA and comparison with DAC.

As EEMPA is an emerging solvent that has not been fully commercialized or produced at scale, uncertainties in projected solvent price and solvent loss during the process may impact the cost estimation. Figure illustrates the impact of these variables on the estimated CO_2 capture cost and marginal capture cost. In this sensitivity study, the solvent price varies from $5 to $50 per kilogram based on recent quotes from an amine manufacturer. The solvent loss rate ranges from 25% to 100% of the known MEA loss rate, as the preliminary solvent degradation test at SINTEF suggests that EEMPA is much more stable than MEA. Figure 7(a) shows that higher solvent prices and increased loss rates directly correlate with higher costs. However, EEMPA's lower degradation rate and volatility, approximately five times lower than MEA, could significantly reduce solvent makeup requirements. Assuming an EEMPA makeup rate of 25% of the MEA rate, the impact of solvent price on the estimated carbon capture cost is minimal, with less than a $2/tonne CO_2 increase observed when EEMPA price increases from $5/kg to $50/kg. Figure 7(b) reveals that the marginal capture cost behaves similarly to the carbon capture cost but remains below the DAC upper bound. This further supports the conclusion that EEMPA, despite uncertainties in solvent prices and loss rates, can economically enable negative emissions power plants.

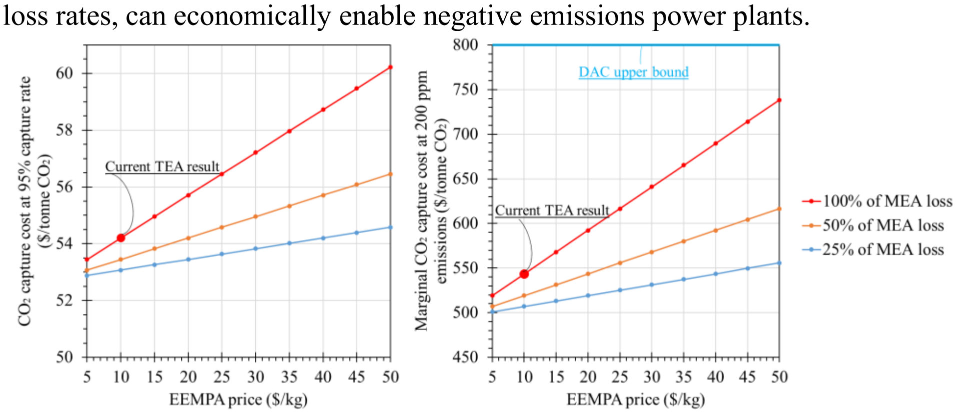

Figure 7. Impact of EEMPA price and solvent loss on key economic measures.

V Modeling and Data Support for TCM Testing Proposal

The introduction call between PNNL and TCM was completed in FY24 Q1. An NDA draft was received from TCM, which is currently under review with the PNNL legal team. Pre-assessment will be kicked-off once an NDA is in place. Data will be collected and shared with TCM, including a preliminary Health, safety and environment (HSE)assessment, plant integrity, test objective & value to CCS deployment, initial technology readiness level (TRL) assessment, preliminary risk identification, and definition of modification. Both PNNL and TCM have completed the first round of NDA reviews. A number of suggestions for edits need to be addressed before signing the NDA and kicking off this subtask. However, due to some disagreements in terms regarding international collaboration, the NDA was still in revision by the end of this project. Per FECM manager guidance, funding allocated for TCM proposal preparation was re-purposed for conducting more TEA and sensitivity studies.

VI Project Outputs

The project conducted a comprehensive techno-economic analysis for applying PNNL's leading EEMPA solvent to NGCC power plant for high capture rates. A detailed final TEA report was submitted to NETL's analysis team for review, and comments were addressed to improve the quality of this work. A manuscript draft was submitted to the International Journal of Greenhouse Gas Control, a peer-reviewed journal. The project team also gave three oral presentations at the 2024 Net-Zero Flexible Power: High Capture Rate Project Review Meeting in Philadelphia, 2024 FECM/NETL Carbon Management Research Project Review Meeting in Pittsburgh, and 2024 American Institute of Chemical Engineers (AICHE) annual meeting in San Diego.

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