U.S. Department of
ENERGY

Multi-Year Program Plan: Point Source Carbon Capture

December 2024

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List of Exhibits

Acronyms and Abbreviations

AI	Artificial intelligence
ARPA-E	Advanced Research Projects Agency–Energy
BiCRS	Biomass carbon removal and storage
BIL	Bipartisan Infrastructure Law
CarbonSAFE	Carbon Storage Assurance Facility Enterprise
CCS	Carbon capture and storage
$CCSI^2$	Carbon Capture Simulation for Industry Impact
CDR	Carbon dioxide recovery
CO_2	Carbon dioxide
DOE	U.S. Department of Energy
FECM	Office of Fossil Energy and Carbon Management
FEED	Front-end engineering design
FLECCS	Flexible carbon capture and storage
FOA	Funding opportunity announcement
FOAK	First-of-a-kind
GJ	Gigajoule
HAP	Hazardous air pollutant
IDAES	Institute for Design of Advanced Energy Systems
IDTC	Industrial decarbonization test center
IEDO	Industrial Efficiency and Decarbonization Office
kta	Kilotons per annum
kW	Kilowatt
LCA	Life cycle analysis
LCOP	Levelized cost of product
MEA	Monoethanolamine
MESC	Office of Manufacturing and Energy Supply Chains
MFiX	Multiphase Flow with Interphase eXchanges
ML	Machine learning
MRV	Monitoring, reporting, and verification
MSW	Municipal solid waste
MW	Megawatt
MWe	Megawatt-electric
MYPP	Multiyear program plan
NCCC	National Carbon Capture Center
NETL	National Energy Technology Laboratory
NGCC	Natural gas combined cycle
NOAK	Nth-of-a-kind
OCED	Office of Clean Energy Demonstrations
R&D	Research and development
RIC	Research and Innovation Center
RNG	Renewable natural gas
SLPM	Standard liter per minute
SMR	Steam methane reforming
tCO_2	Tonne CO_2
TCM	Technology Center Mongstad
TEA	Techno-economic analysis
TRL	Technology Readiness Level

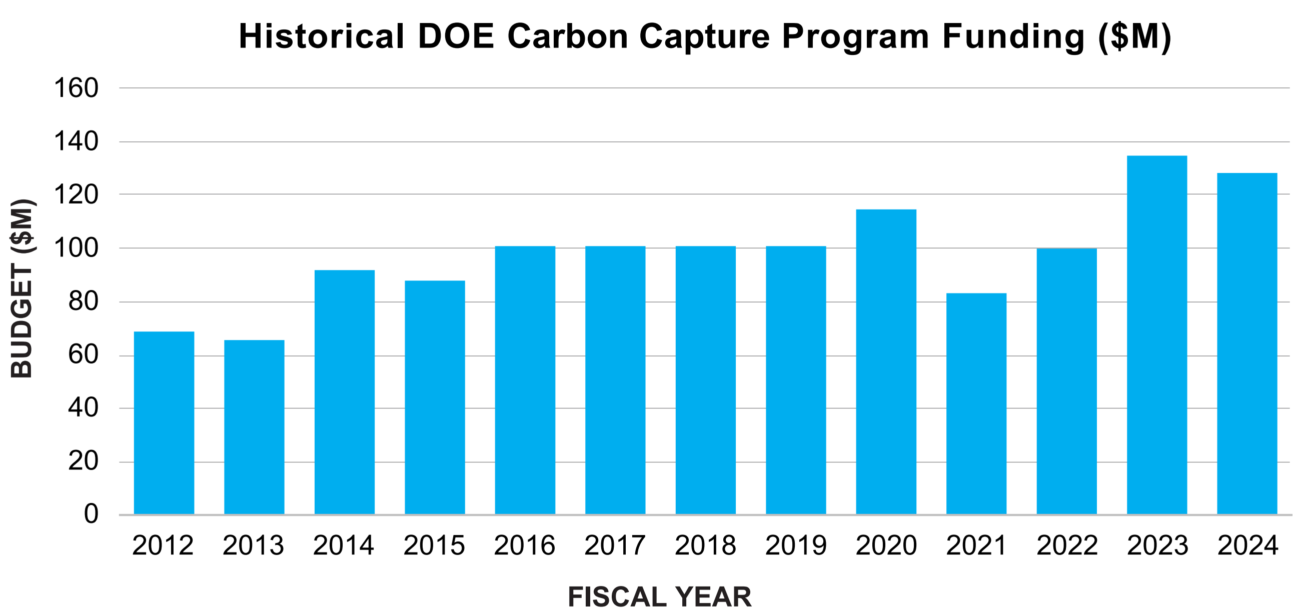
1. Overview

1.1 Introduction and Background

1.1.1 History

Carbon capture research and development (R&D) efforts at the U.S. Department of Energy (DOE)/Office of Fossil Energy and Carbon Management (FECM)/National Energy Technology Laboratory (NETL) were initiated in 1999 with funding from the Carbon Sequestration Program and the Innovations for Existing Plants Program. The Carbon Capture Program was initiated as a distinct entity in 2012 with discrete funding for both pre- and post-combustion technology areas. Program R&D efforts have focused on the development of second-generation and transformational materials (solvents, sorbents, membranes), processes (including hybrid systems), and equipment. As interest in carbon management evolved and expanded, carbon conversion and carbon dioxide removal (CDR) efforts were also included in the Carbon Capture Program portfolio. Eventually, Carbon Conversion and CDR were pulled out as separate Programs in fiscal year (FY) 2020 and FY 2022, respectively, with discrete funding appropriations. In FY 2022, the Point Source Carbon Capture Program was formed with a focus on carbon dioxide (CO_2) capture from power generation and industrial facilities (e.g., hydrogen, petrochemical/chemicals, cement, and steel production facilities). From 2012 to 2024, the Carbon Capture Program invested more than $1.274 billion (**Exhibit 1-1**) to advance carbon capture technologies for both coal- and natural gas-electric generation and industrial sources to support current and future pilot and demonstration testing.

Exhibit 1.1 Carbon Capture Program funding



1.2 Technology Status: Carbon Capture Cost and Technical Performance

As noted in Section 1.1.1, carbon capture R&D efforts at DOE have been conducted for more than 20 years. Early efforts focused on lab- and bench-scale testing to improve the performance of carbon capture processes. Performance targets were established to reduce CO_2 emissions by 90+% and more recently by 95+% at new and existing power plants and industrial facilities.

Pilot-scale testing of solvent-, sorbent-, and membrane-based technologies began in the early 2010s. Since 2009, testing at up to 1-megawatt-electric (MWe) scale has been conducted at the National Carbon Capture Center (NCCC). To date, over 80 technologies have undergone pilot-scale testing at NCCC and an additional 13 are currently in planning. Over that time, capture costs have been reduced by approximately one-third.[1] In addition, four technologies have been tested at large pilot scale (~10 MWe) at Technology Center Mongstad in Norway, and construction has recently been completed for two purpose-built large pilot-scale technologies in the United States.

1.2.1 Progression of Carbon Capture Costs

Reducing capture costs has been a major focus of DOE efforts to accelerate the deployment of carbon capture technologies. The Point Source Carbon Capture Program has developed published guidelines for techno-economic analysis (TEA) that provide a framework for high-level estimation and comparison of system cost and performance on a common basis across technologies and approaches.

TEA-based CO_2 capture costs at coal-fired power plants have decreased from 2015 ($50+/tonne) to the present ($38/tonne) based on continuing R&D. The observed trends suggest that investments made in R&D activities by FECM have enabled an overall cost reduction for carbon capture technology.

TEAs are a valuable tool for assessing comparative costs across various technologies and serve an important function in the design and execution of an R&D program. However, TEA-based capital and operating cost estimates are not reflective of costs associated with actual project deployment conditions that deviate from the design, market, or financial structure assumptions in any way. TEA-based costs can be reflective of nth-of-a-kind (NOAK) systems that benefit from learning-by-doing improvements in reliability that drive down capital cost by eliminating redundancies (e.g., spare adsorber modules), lowering unit costs, and reducing material (e.g., reagents) costs.

First-of-a-kind (FOAK) costs are consistently higher than NOAK costs and are more accurately reflected by cost estimates that are developed through another tool which supports the ultimate deployment of carbon capture technologies: front-end engineering design (FEED) studies. Although capture costs reported for technologies being tested at the lab/bench scale are sometimes lower than TEA baseline values, those at the FEED scale are often higher. This is reflective of the impact of site-specific factors on capture costs (e.g., dry cooling, duct lengths, labor rates, retrofit difficulty).

[1] 10-Year Summary | National Carbon Capture Center.

1.2.2 Progression of Technology Performance: Membrane-, Sorbent- and Solvent-Based Capture

In parallel to a reduction in capture costs, R&D efforts have enabled significant improvements in technical performance of different approaches to carbon capture (e.g., membrane-, solvent-, and sorbent-based). For example, significant reductions in energy requirements have been achieved relative to monoethanolamine (MEA), which suffers from a high parasitic energy penalty due to a high regeneration energy (3.6–3.8 gigajoules (GJ)/tonne CO_2). Nonaqueous or water-lean solvents developed in the FECM R&D program have been successful in lowering regeneration energy, achieving values as low as 2 GJ/tonne CO_2.

Additionally, sorbents offer opportunities to lower the energy consumption of the regeneration step with physisorption-based sorbents exhibiting lower binding energy toward CO_2 than solvents where interactions with CO_2 are based on chemisorption. Recently developed sorbents funded by the program have achieved regeneration energies as low as 1.6 GJ/tonne CO_2 through optimization of sorbent structure and regeneration conditions.

It should be noted that overall advancements in capture technologies cannot be interpreted based on a single parameter. For example, excellent-performing membranes with high permeability and selectivity, or solvents with low regeneration energy, may be more costly to manufacture than lower-performing ones. Additionally, some of the cost reductions achieved can be attributed to innovation in other technical areas (e.g., process intensification, reactor design, advanced manufacturing, etc.) rather than material innovations. However, technical improvements are worth highlighting as indicative of technology progress achieved by R&D funding in the program and are consistent with an overall reduction of cost of carbon capture technology.

1.2.3 Impact Indicators

DOE drove the growth and scale-up of carbon capture technologies (materials, equipment, and processes) toward commercialization by funding laboratory-scale to small- and large-scale pilot testing and FEED studies. In particular, the Carbon Capture Program provided essential support to:

- More than 100 lab/bench-scale technologies.
- 46 technologies validated at Technology Readiness Level (TRL) 6.
- Five technologies validated at TRL 7.
- 40 completed or in-progress FEED studies.

The program has also fostered knowledge advancement, knowledge dissemination, and intellectual property development in the field of carbon capture. In the past 15 years, participants in the program have delivered more than 900 publications (more than 600 of which are peer-reviewed journal articles) and been granted more than 190 patents that explicitly acknowledge FECM's support (**Exhibit 1-2**).

Exhibit 1.2. Historical carbon capture publications/patents from DOE-funded projects[2]

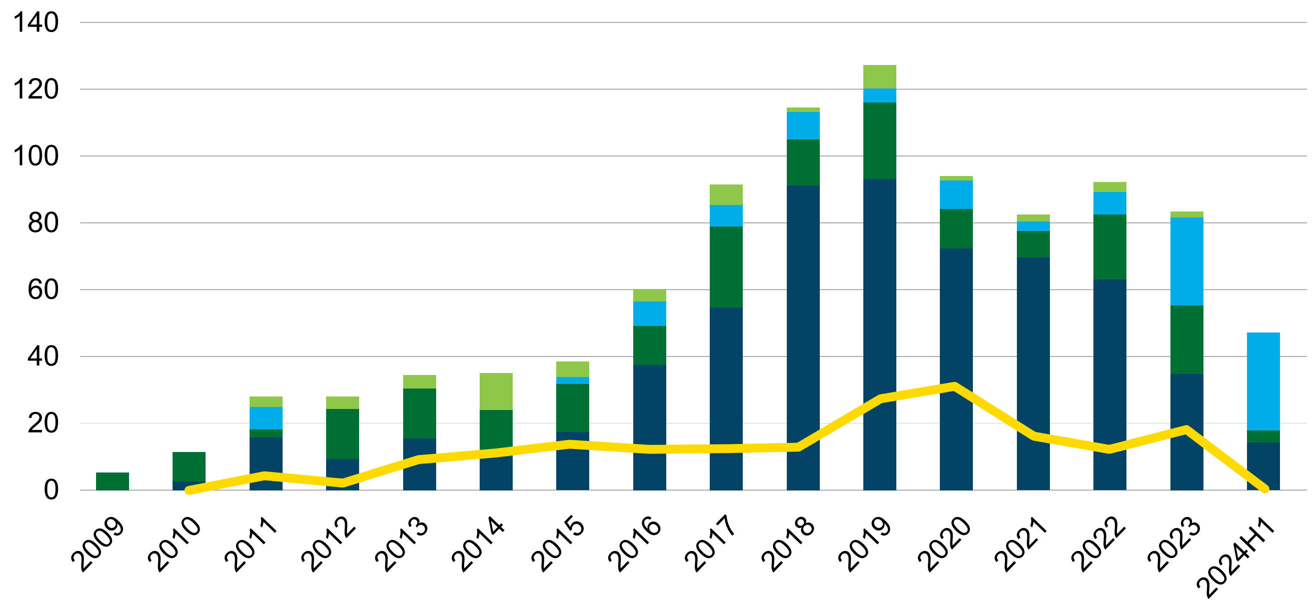
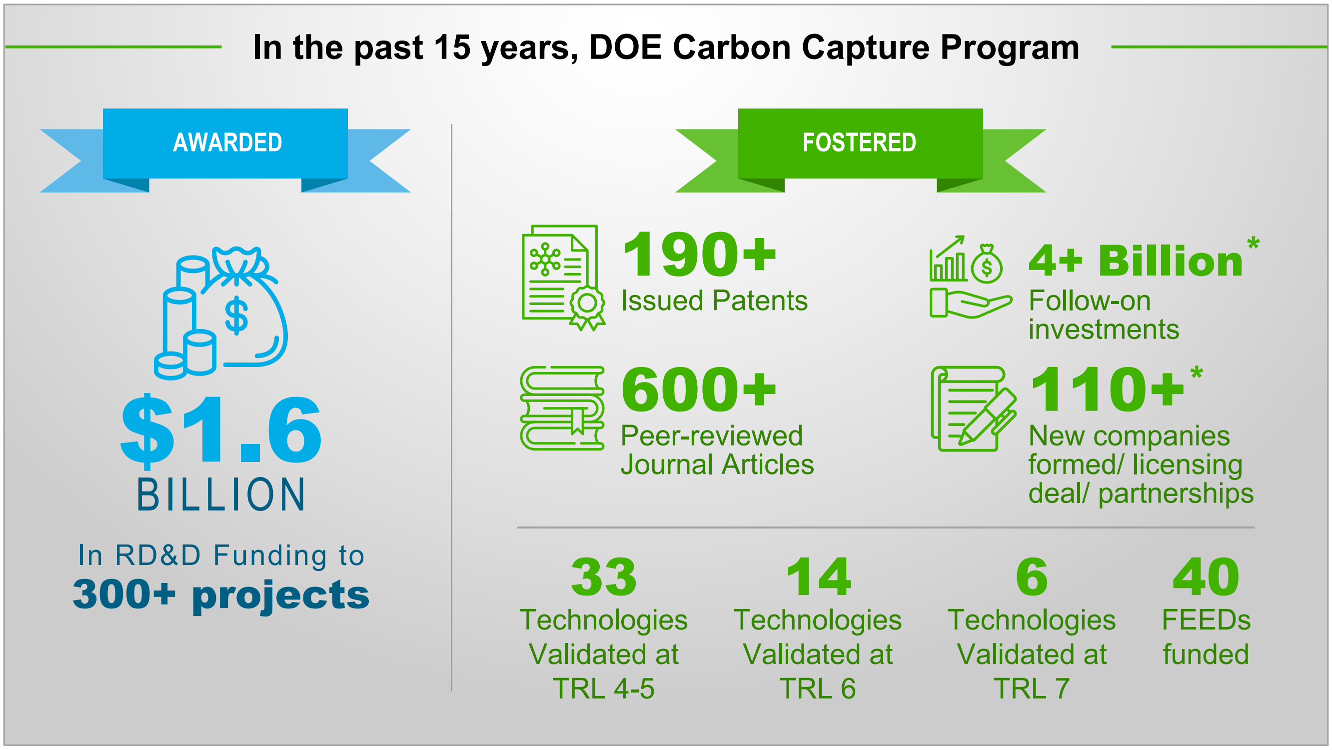


Exhibit 1.3. Carbon Capture Program: Impact Indicators



[2] Data source: OSTI.GOV | U.S. Department of Energy Office of Scientific and Technical Information; Tech Transfer | netl.doe.gov; https://vueproxy.netl.doe.gov/.

1.3 Alignment with DOE and FECM Plans

Vision Statement[3]

Support first-of-a-kind demonstrations of carbon capture on power and industrial sources coupled to dedicated and secure geologic carbon storage, leading to widescale deployment to facilitate a carbon-free economy by 2050, emphasizing robust analysis of life cycle impacts, and understanding air/water quality impacts.

As highlighted in the FECM Strategic Vision,[3] the Point Source Carbon Capture Program will play a key role in decarbonizing emissions associated with the power sector and enabling industrial decarbonization, particularly for industries like cement production that have significant process-related, non-energy CO_2 emissions, in addition to emissions from combustion of fuels. The Point Source Carbon Capture Program will also play a key role in enabling certain types of carbon dioxide removal - particularly biomass carbon removal and storage (BiCRS) - for hydrogen production and power generation. This also complements DOE's Clean Fuels & Products Shot, which targets decarbonizing the fuel and chemical industry.

The technologies that are developed in the Point Source Carbon Capture program will support the achievement of the objectives outlined in the vision statement. This vision emphasizes the need to prepare commercial-scale capture technologies that are flexible (i.e., operable under a variety of conditions with frequent start-up/shut-down cycles) to complement the ever-changing U.S. power grid while simultaneously being capable of complete or near-complete abatement of emission sources.

To support the FECM Strategic Vision and to achieve a target of net-zero greenhouse gas emissions economywide by 2050, carbon capture technology should be integrated with other carbon management technologies (especially carbon transport, storage, conversion, and removal) to foster the creation of sustainable, net-zero regional carbon hubs, as illustrated in **Exhibit 1-4**.

An important element of the Point Source Carbon Capture Program strategy involves support from key provisions of the Infrastructure Investment and Jobs Act,[4] more commonly known as Bipartisan Infrastructure Law (BIL). These provisions are currently being implemented by the Office of Clean Energy Demonstrations (OCED) and supported by FECM. A significant component of FECM support for OCED BIL efforts will be directed toward enabling successful large pilot-scale testing and integrated demonstrations of carbon capture, transport, storage, or conversion technologies applied to coal- and natural gas-based power generation and industrial facilities.

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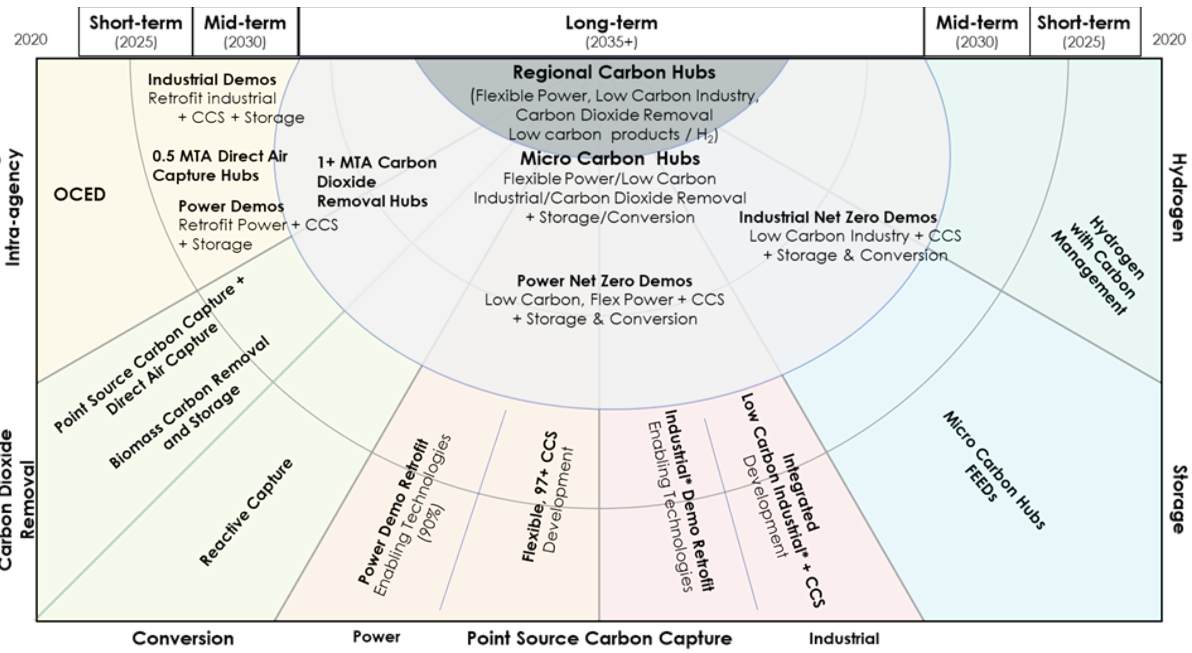
[3] Strategic Vision: The Role of FECM in Achieving Net-Zero Greenhouse Gas Emissions | Department of Energy.

[4] Infrastructure Investment and Jobs Act, Public Law 117-58 (November 15, 2021). https://www.congress.gov/bill/117th-congress/house-bill/3684. This document uses the more common name Bipartisan Infrastructure Law (BIL).

Exhibit 1.4. Key elements contributing to the development of regional carbon hubs



(i) **Short-term**: First-of-a-kind demonstrations of carbon capture technologies in integrated, retrofit, single-source to single-sink carbon capture and storage demonstration projects.

(ii) **Mid-term**: Clusters emerge in which multiple point-source or CO_2 removal sources feed a single high-capacity reservoir while net-zero flexible power and integrated industrial decarbonization approaches are being demonstrated.

(iii) **Long-term**: The clusters will be linked to form a network of regional hubs fed by multiple net-zero power and industrial sources.

The Point Source Carbon Capture Program strategy is built upon efforts in four distinct Focus Areas designated in **Exhibit 1.4:**

- **Focus Area 1: Enabling Technologies for Carbon Capture Demonstrations at Electric Generation Plants:** Technology development to *support* successful demonstration of retrofit CCS projects at electricity generation facilities, with the emphasis of measuring, monitoring, and controlling CCS-related environmental impacts to ensure that deployment also mitigates pollutants beyond CO_2 emissions. (BIL support.)
- **Focus Area 2: Carbon Capture Technologies for Net-Zero, Flexible Power:** Technology development of flexible carbon capture with high capture efficiency at decarbonized thermal generators using lower-carbon fuels (e.g., renewable natural gas [RNG],) to enable Net-Zero Power Demonstration projects.
- **Focus Area 3: Enabling Technologies for Carbon Capture Demonstrations at Industrial Facilities:** Technology development to support successful demonstration of retrofit CCS projects at industrial facilities, with the emphasis of validating technologies at TRL 6 for industrial sources through pilot-scale testing and measuring, monitoring, and controlling CCS-related environmental impacts to ensure that deployment also mitigates pollutants beyond CO_2 emissions. (BIL support.)

- **Focus Area 4: Integrated Low-Carbon Industrial Processes Coupled with Carbon Capture:** Technology development for integrated decarbonized industrial processes coupled with transformational carbon capture technologies to enable Net-Zero Industrial Demonstration projects.

Focus Areas 1 and 3 are aimed at supporting *current* power and industrial pilots and demonstrations, considering the readiness levels of the technologies in these sectors. **Focus Areas 2 and 4** involve work to enable the *next generation* of demonstrations and large pilots. For **Focus Areas 3 and 4,** the targeted industrial sectors include those that are most likely to utilize carbon capture to achieve their deep decarbonization goals, such as mineral production (lime and cement), steel production, hydrogen production from natural gas, hydrocarbon processing (e.g., refineries and petrochemicals), and pulp and paper.

2. Approach, Implentation and Timelines

2.1 Point Source Carbon Capture Program Goal-Setting Efforts

The Point Source Carbon Capture Program will carry out early goal-setting analyses for each targeted sector to ensure that R&D pursued is specific to the needs and characteristics of the sector. Preliminary goals, along with planned efforts to enable goal-targeting analyses specific to each Focus Area, are summarized in **Exhibit 2-1**.

Exhibit 2.1. Current goals and planned program activities supporting refinement/establishment of goals

Focus Area	Current Goals	Planned Future Goal-Related Activities
Enabling Technologies for Carbon Capture Demonstrations at Electric Generation Plants	• Enabling technologies validated at TRL 6 • Validated process model • Support BIL goals, including: ▫ 95% capture ▫ $1,720/kilowatt (kW) (installed capital cost) ▫ Three years stable operation ▫ Unit-wide demo ▫ Carbon storage integration	• Define goals for retrofit, facility-wide CCS installations, NOAK.
Net-Zero Flexible Power	• 97% capture • $1,110/kW (installed capital cost)	• Develop performance and cost targets for flexible, high-capture-rate Natural Gas Combined Cycle (NGCC) applications in high-variable renewable resource environments that include battery energy storage and long-distance transmission based on thermodynamic performance limitations and reasonable forward-looking technology improvement trajectories.
Enabling Technologies for Carbon Capture Demonstrations at Industrial Facilities	• Enabling technologies validated at TRL 6/7 • Validated process model • Support BIL goals, including: ▫ 90% capture ▫ Three years stable operation ▫ 300 kta process slipstream ▫ Carbon storage integration	• Define metrics and values appropriate for determining success in each industrial sector.
Integrated Low-Carbon Industrial Processes Coupled with Carbon Capture	• Progress toward net-zero production • Increased levelized cost of decarbonized product less than 20%	• Generalize the goal formulation framework by including alternative decarbonization methods (e.g., feedstock improvements/substitutions, low-carbon electrification, process or product modifications, plant fuel substitutions) and target to appropriate metrics as established under Focus Area 3.

2.2 Focus Area 1: Enabling Power Demonstrations for Carbon Capture Demonstrations at Electric Generation Plants

Focus Area 1 *will develop technologies to support successful demonstration of retrofit CCS projects at electricity generation facilities, including measuring, monitoring, and controlling for non-CO_2 emissions*

Goals: *Enabling technologies validated at TRL 6, including a process model to support BIL CCS demonstration goals (i.e., 95% capture, $1,720/kW [installed capital cost], three years stable operation, unit-wide demonstration, and carbon storage integration).*

2.2.1 Technology Challenges

As noted above, a significant component of the BIL involves large pilot-scale testing and integrated demonstrations of carbon capture technologies applied to coal- and natural gas-based power generation facilities to facilitate widescale deployment. The focus of FECM point source carbon capture R&D to support these efforts will involve the development of enabling technologies and tools that can enhance the probability of successful demonstrations to support liftoff of CCS.

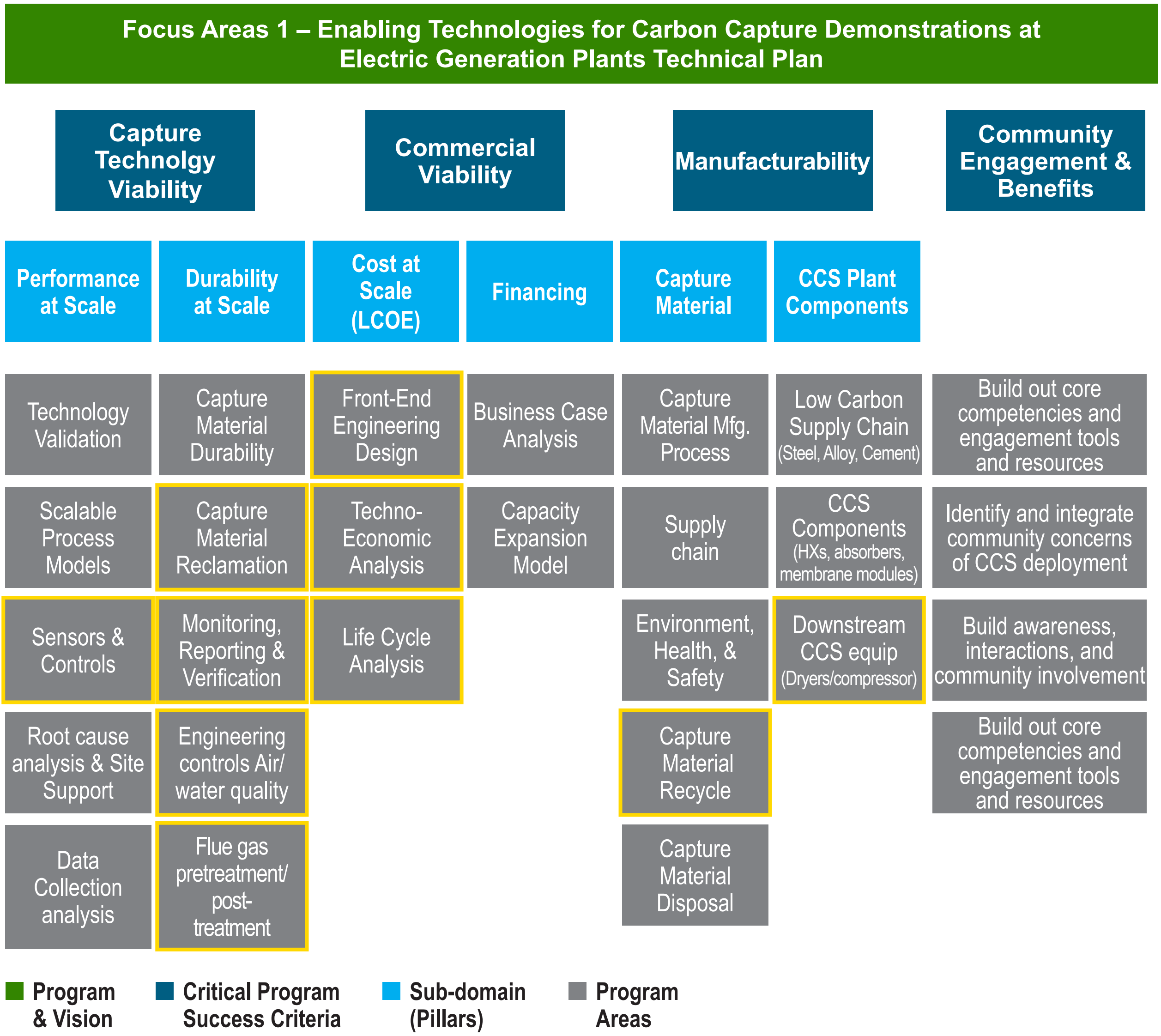
For example, public support for carbon management technologies will require quantification of changes in air pollutant emissions associated with both power production and CO_2 separation. Degradation of capture media during long-term use can impact both costs and secondary emissions of degradation by-products. If it is found that secondary emissions products are being formed, engineering control technologies and approaches will require testing to prevent the release of these emissions. Development and testing of sensors that support long-term operations have the potential to decrease costs and improve reliability in support of build-out of CCS. The efforts needed to address these challenges are described below.

2.2.2 Technical Plan

Successful large pilot-scale testing and demonstrations of CCS technologies in electricity generation applications will require close collaboration across different DOE offices, including FECM, OCED, and the Office of Manufacturing and Energy Supply Chains (MESC). The overall success of the BIL large pilot and demonstration efforts hinges on meeting several critical program success criteria, including (i) technology and commercial viability, (ii) manufacturing readiness, and (iii) community engagement and benefits (**Exhibit 2-2**). Each of these success criteria are in turn supported by subdomain activities focused around performance and durability at scale, cost and financing, and the actual production of capture material and plant components. Program efforts undertaken by FECM, OCED, and MESC each support different aspects of the overall development and deployment process.

Specific FECM Point Source Carbon Capture Program efforts contributing to the success of the BIL large pilots and demonstrations are highlighted in yellow in **Exhibit 2-2** and are described in more detail below. In addition, FECM will provide support to OCED and MESC on the other elements on a “ready-to-serve” basis.

Exhibit 2.2. Enabling Technologies for Carbon Capture Demonstrations at Electric Generation Plants (Focus Area 1): Technical Plan[5]



[5] Specific Point Source Carbon Capture Program efforts contributing to the success of the BIL large pilots and demonstrations are highlighted in yellow. FECM will provide support to OCED and MESC on the other program areas on a "ready-to-serve" basis.

In order to address the challenges associated with supporting large-scale pilot and demonstration testing of carbon capture retrofit technologies, FECM may target the following activities in the short- and mid-term, as part of Focus Area 1 of this MYPP:

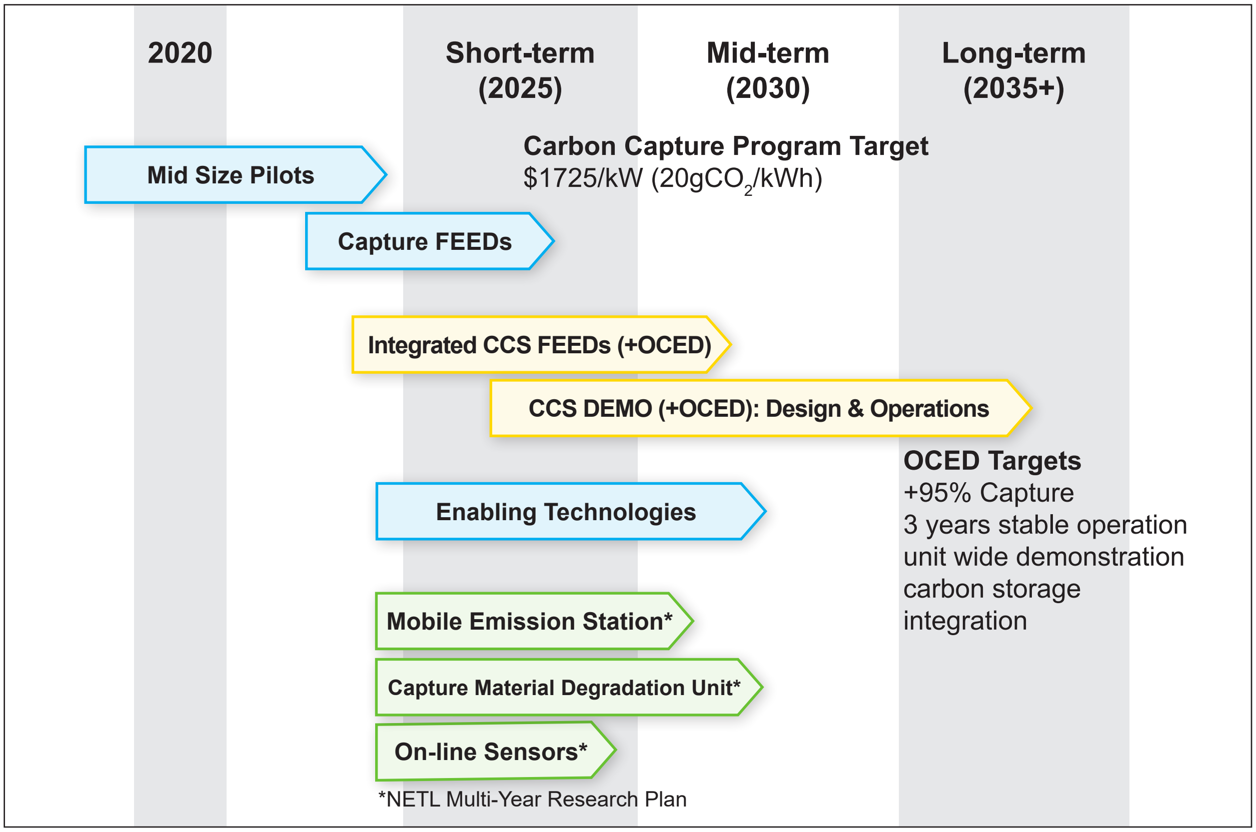
1. Testing and scale-up of engineering control methods/equipment (e.g., pre-treatment, post-treatment acid wash, upstream filters, aerosol controls, corrosion inhibitors) tailored for specific technologies and validated at specific large pilots and demonstration sites.
2. Build mobile testing units to 1) measure emission profiles during testing at specific large pilots and demonstration sites, and 2) evaluate CO_2 product quality to ensure consistent compliance with pipeline, conversion, and storage specifications.
3. Develop a testing framework and associated enabling technologies (e.g., sensors, artificial intelligence [AI]/machine learning [ML]) to evaluate and predict capture media degradation based on the data measured at the specific large pilot and demonstration projects.
4. Develop and validate reuse/recycle processes for capture material deployed at large pilots/demonstration sites.
5. Develop, test, and validate pollutant air dispersion models focused on the transport and fate of criteria pollutants, as well as capture media and capture media degradation products.
6. Develop and deploy online sensors to measure gas- and liquid-phase degradation products during testing at large-scale pilot and demonstration projects.
7. Develop modeling tools to conduct advanced root cause analysis to support technical risk reduction (mitigate impacts of uncertainty in design and deployment).

2.2.3 Implementation Plan

The proposed implementation plan is shown in **Exhibit 2-3**. The elements shown as orange arrows are BIL activities administered by OCED and are not elements of this MYPP. However, all other elements included in **Exhibit 2-3** are explicit components of this MYPP and support the OCED activities shown in orange. The Focus Area 1 Point Source Carbon Capture Program implementation plan includes the following extramural activities:

1. Enabling technology development (monitoring, reporting, and verification [MRV], emissions control, system control, sensors, carbon capture material reclamation, and recycle) and their pilot validation (e.g., mobile units at large-pilot/demonstration sites). (Short- and mid-term.)
2. Complete ongoing capture FEED studies. (Short-term.)

Exhibit 2.3. Enabling Technologies for Carbon Capture Demonstrations at Electric Generation Plants (Focus Area 1): Implementation Plan



In support of the Focus Area 1 implementation plan, in-house NETL-Research and Innovation Center (RIC) activities (shown as green arrows in **Exhibit 2-3**) are integrated with the extramural activities and will develop and execute the following mission-based elements of the RIC Multi-Year Research Plan (MYRP) which will:

1. Develop mobile emissions testing unit(s)/methodologies capable of measuring secondary emissions (e.g., nitrogen containing emissions, hazardous air pollutants [HAPs], aerosols) to be deployed at different large-scale pilot and demonstration projects. (Short-term.)
2. Develop methodology and build carbon capture material degradation mobile unit(s) that can be distributed to different CCS providers to evaluate carbon capture material degradation pathways and products. (Short- and mid-term.)
3. Develop and deploy online sensors to measure liquid-phase degradation products during testing at large-scale pilot and demonstration projects. (Short- and mid-term.)

In addition to directly supporting the R&D outlined above, RIC will also provide "ready-to-serve" technical resources to support broad BIL programmatic activities. The "ready-to-serve" functions are:

1. Provide NETL simulation tool sets (e.g., Carbon Capture Simulation for Industry Impact [CCSI[2]], Multiphase Flow with Interphase eXchanges [MFiX], and Institute for Design of Advanced Energy Systems [IDAES]) for optimization of carbon capture systems.
2. Provide RIC subject matter expertise associated with capture materials development and performance assessment, sensors, and air monitoring to support rapid response to programmatic needs.

2.3 Focus Area 2: Net-Zero/Flexible Power

Focus Area 2 *will develop highly flexible technologies that capture CO_2 efficiently from decarbonized electricity generation facilities to enable the development of Net-Zero Power Demonstration projects.*

Goals: *Flexible duty cycle, 97% capture; $1,050/kW (installed capital cost).*

2.3.1 Technology Challenges

Full decarbonization of the electricity sector while ensuring reliability and minimizing cost will require a combination of renewable resources; energy storage; and reliable, firm, low-carbon, energy generation. Reliable, firm, low-carbon resources such as fossil fuel-based power plants with CCS will lower the cost of decarbonized electricity generation by avoiding significant overcapacity of energy storage and renewable generation relative to peak demand.

However, in an environment with high penetration of renewable sources, it is likely that fossil fuel-based power production will operate differently than it does now. Instead of steady, consistent operation, fossil fuel-based power plants will likely be used to fill gaps associated with intermittent renewable generation, resulting in lower overall usage and frequent start-ups and shut-downs. This flexible power generation will also require flexible operations from associated carbon capture systems and processes. Development efforts to date have focused on carbon capture from steady-state, high-utilization power plant operations that have historically been the norm. Continuing R&D is important to ensure that carbon capture in the anticipated flexible operating environment of the future is reliable and cost-effective.

An important component of this continuing R&D will be the development and testing of approaches that combine carbon capture with altered plant operation procedures that can lead to net-zero power production. For example, significant emissions could be associated with frequent power plant start-ups and shut-downs, during which capture systems can experience suboptimal operations.

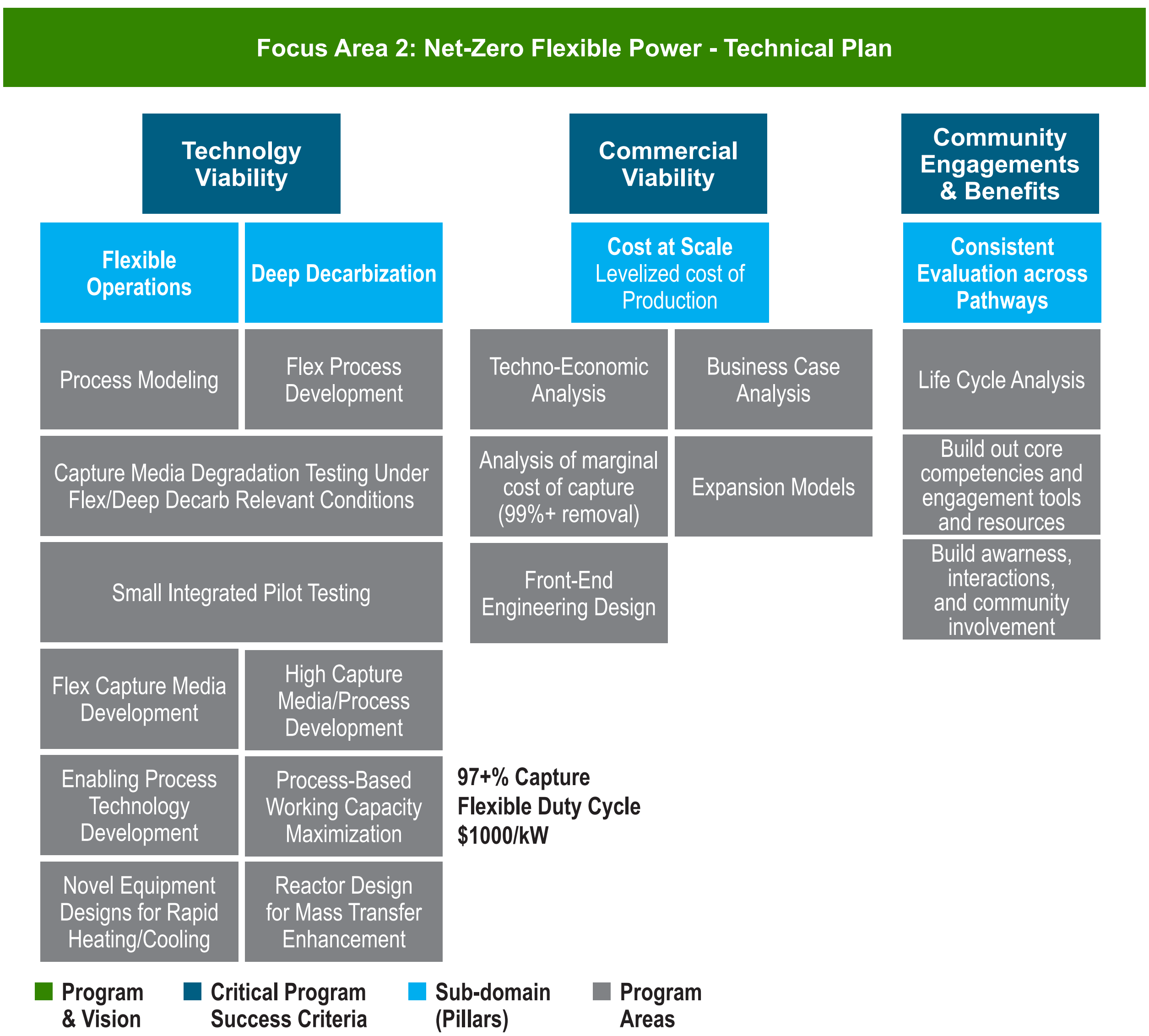
Another important aspect of continuing R&D, given net-zero power production targets, is the requirement that carbon capture technologies operate very efficiently (i.e., greater than or equal to 95% capture efficiency), notwithstanding low-utilization factors. Recent analyses associated with ongoing Point Source Carbon Capture Program R&D efforts show varying cost impacts associated with increases in carbon capture efficiency significantly above 95% and decreases in utilization factor depending on specific characteristics of the capture system and the flue gas being treated,[6] especially when applied to natural gas power plant flue gas. Also, the dilute concentration of CO_2 in natural gas power plants (4% compared to approximately 12% for coal-fired units), as well as higher water and oxygen content in the natural gas flue gas, makes CO_2 capture from natural gas power plants more technically and economically challenging than coal.

[6] 2023 FECM / NETL CARBON MANAGEMENT RESEARCH PROJECT REVIEW MEETING - Point source carbon capture - PROCEEDINGS | netl.doe.gov.

2.3.2 Technical Plan

Demonstration of a flexible carbon capture system at a net-zero carbon electricity generation facility will need to meet critical program success criteria, including technology and commercial viability, and community engagement and benefits (**Exhibit 2-4**). To support these success criteria, the subdomain activities of the program will focus on validation of flexible operation at high capture efficiencies, demonstration of cost at scale, and development of a consistent plan to evaluate community benefits during technology development and demonstration. The technologies underpinning flexible, net-zero power generation are at an earlier stage of development than those proposed for retrofit applications supported by BIL activities. Given this developmental stage, all of the program areas described in **Exhibit 2-5** below are elements of the FECM Point Source Carbon Capture Program.

Exhibit 2.4. Net-Zero, Flexible Power (Focus Area 2): Technical Plan



In support of the net-zero flexible power demonstrations, Focus Area 2 of this MYPP will target the following investments in the short- through long-term:

1. Foster crosscutting projects (i.e., within FECM and within DOE) to scale-up carbon capture technologies at advanced fossil fuel-based power plants utilizing lower-carbon fuels (i.e., natural gas with RNG) integrated with secure carbon storage, CO_2 conversion, and energy storage.
2. Support development and scale-up of flexible carbon capture technologies, including carbon capture media and processes; novel equipment design for rapid heating and cooling; and unit operations with improved mass- and heat-transfer that leverage low-carbon supply chains.
3. Expand capabilities in dynamic process modeling, TEA, and life cycle analysis (LCA) to quantify changes in carbon intensity associated with the implementation of innovative technologies and better understand and quantify total system economics.
4. Develop enabling technologies, including:
   a. Emissions monitoring, reporting and verification, validated at pilot scale.
   b. Engineering control methods/equipment (e.g., pre-treatment, post-control acid wash, upstream filters, aerosol controls, corrosion inhibitors) tailored for specific technologies and validated at pilot scale.
   c. AI-based control systems.
5. Invest in additional carbon capture FEED studies. Future FEED studies will be focused in areas where clusters of electricity-generating units are found within proximity to other opportunities for carbon capture and removal that can leverage shared transport and storage infrastructure.
6. Support the development of materials, processes, and equipment capable of maintaining high annual capture efficiency despite frequent start-up/shut-down cycles anticipated in response to grid modernization efforts.

2.3.3 Implementation Plan

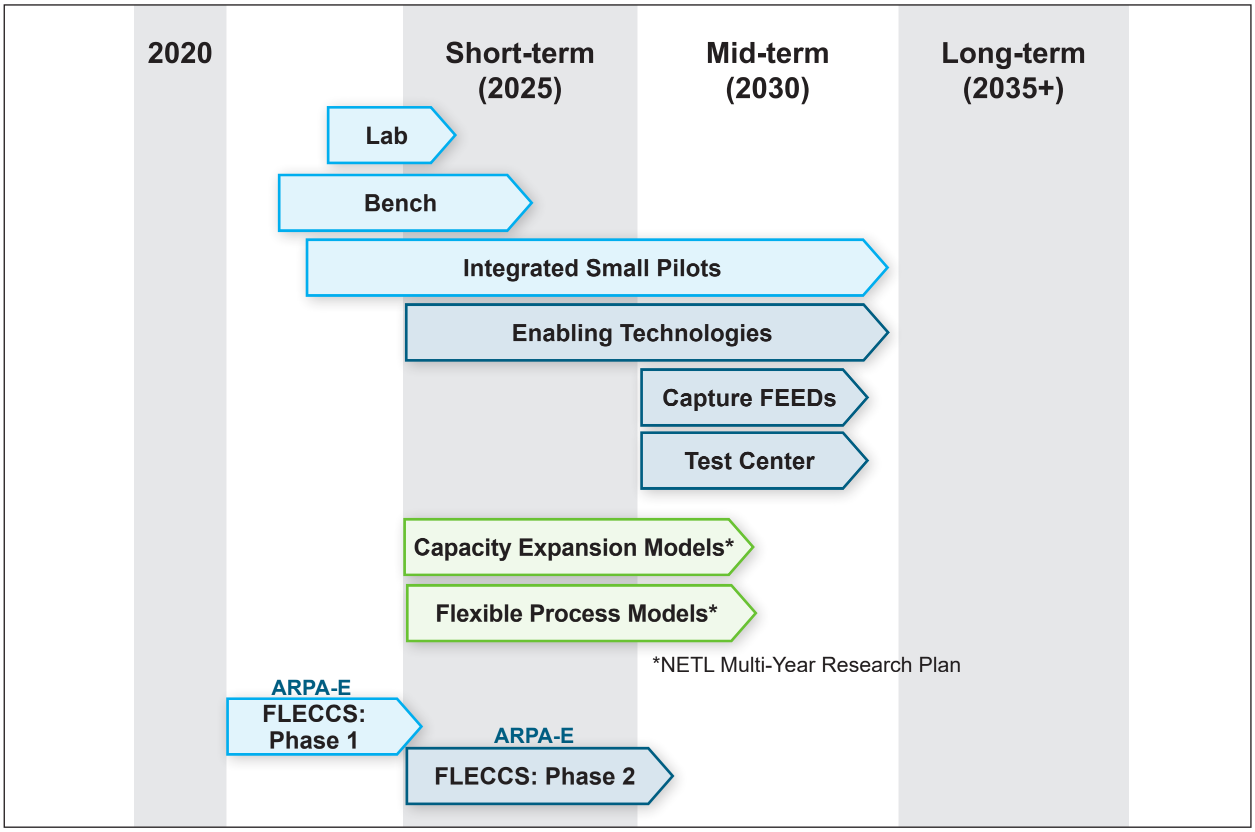
The proposed Focus Area 2 implementation plan includes the following extramural development steps (**Exhibit 2-5**):

1. Lab- and bench-scale validation of the individual flexible and/or highly efficient components developed as part of previous FECM efforts and/or Advanced Research Projects Agency–Energy (ARPA-E) flexible CCS (FLECCS) projects. (Short-term.)
2. Small pilot-scale validation of highly efficient/FLECCS processes with actual flue gas in small integrated pilot systems (less than 3 tonne CO_2/day) (e.g., integration of CCS and flexible components such as thermal or chemical energy storage). (Short- and mid-term.)
3. Enabling technology development (e.g., MRV, emissions control, system control). (Short- and mid-term.)
4. FEED studies coupled with Carbon Storage Assurance Facility Enterprise (CarbonSAFE) projects. (Short- and mid-term.)

In support of the Focus Area 2 implementation plan, in-house NETL-RIC activities will develop and execute mission-based elements of the RIC MYRP which will:

1. Leveraging Carbon Capture Simulation for Industry Impact (CCSI2), develop integrated, multi-hierarchical modeling tools/platforms which will be used to improve predictive capabilities; and reduce risk for process design, piloting, and scale-up activities for extramural projects.
2. Develop an electricity system capacity expansion model framework that will help perform net-present value analysis for extramural technologies developed under Focus Area 2.

Exhibit 2.5. Net-Zero, Flexible Power (Focus Area 2): Implementation Plan



2.4 Focus Area 3: Enabling Technologies for Carbon Capture Demonstrations at Industrial Facilities

Focus Area 3 *will develop technologies to support successful demonstration and large pilot-scale testing of CCS approaches applied to industrial facilities, with the emphasis of validating technologies at TRL 6 for industrial sources through pilot-scale testing, including measuring, monitoring and controlling CCS-related environmental impacts. Targeted industrial sectors include mineral production (lime and cement), steel production, hydrogen production from natural gas, hydrocarbon refining/petrochemical production, and pulp and paper. (BIL support.)*

Goals: *Technologies validated at TRL 6, including a process model to support BIL CCS demo goals (e.g., 90% capture, three years stable operation, 300+ kta pilot, carbon storage integration).*

2.4.1 Technology Challenges

As with the power sector applications discussed in Section 2.2, a significant component of the BIL involves large pilot-scale testing and integrated demonstrations of carbon capture technologies applied to industrial facilities to facilitate wide deployment. Given the relatively short-term nature of the BIL-focused efforts, industrial decarbonization efforts are expected to involve retrofit applications of capture technologies that do not necessarily include alterations to basic production processes. Longer-term industrial decarbonization may include changes to production processes and practices along with carbon capture that have the potential to alter the way carbon capture is implemented. Efforts supporting these longer-term industrial decarbonization approaches will be discussed in Section 2.5.

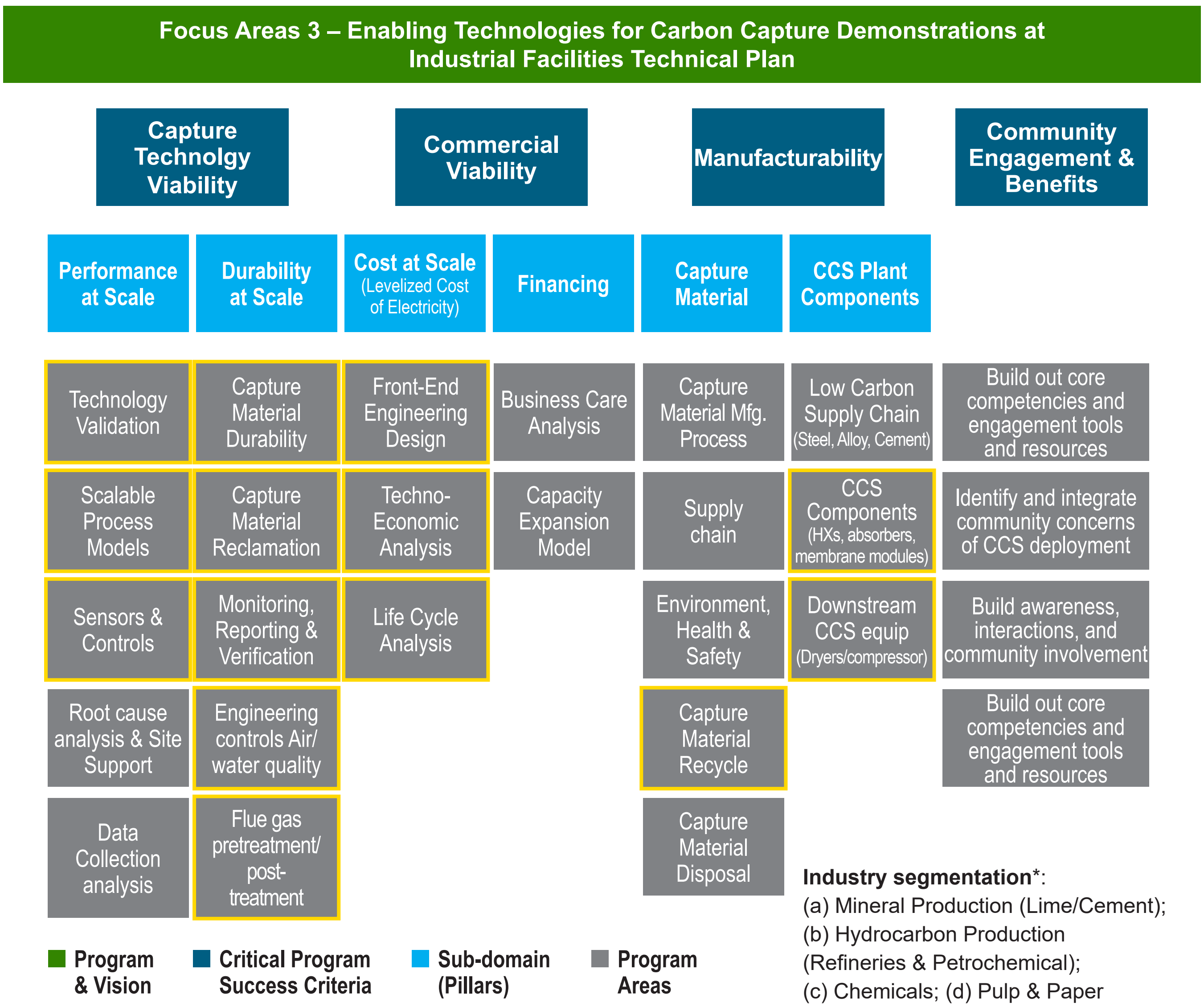
The Point Source Carbon Capture Program is laying the groundwork to enable the commercial implementation of second-generation and transformational CCS systems and retrofits at U.S. industrial facilities.

However, because Point Source Carbon Capture Program activity on industrial systems has only recently begun, the key feature differentiating Focus Area 1 (i.e., Section 2.2) from the Industrial Demonstration Focus Area 3 is the relative scarcity of projects supporting pilot and demonstration activity in each of the industrial sectors. Each industrial sector generates flue gas streams that have differing CO_2 concentrations and, just as importantly, differing gas composition profiles that can influence the performance of a capture system, as well as quantities and characteristics of secondary emissions. The practical impact of these differences is that capture technologies that have been tested at a specific TRL for power generation applications may be at a lower TRL for industrial applications. The earlier developmental stage of capture technologies for industrial applications will have some impact on the focus of future R&D efforts. The ability to perform pilot-scale testing at multiple sites can support wide deployment of CCS as it demonstrates the viability of capture technology at a specific site to operators and investors before committing the resources required for commercial implementation.

2.4.2 Technical Plan

The broad nature of the technology challenges associated with support for large pilot-scale testing and demonstration of industrial carbon capture technologies is similar to those noted for fossil fuel-based power generation in **Exhibit 2-6.** The overall success criteria, the subdomain activities, and the broad program areas are all the same, but the specific FECM Point Source Carbon Capture Program efforts contributing to the success of the BIL large pilot and demonstrations for industrial systems (highlighted in yellow in **Exhibit 2-6**) are different due to the earlier developmental stage of capture technologies for industrial applications. For Focus Area 3, more small pilot-scale testing is important to derisk large pilots and demonstrations. It is anticipated that industrial small pilot-scale testing will include testing of enabling technologies and tools that can enhance the probability of successful widescale deployment of CCS in multiple industrial sectors.

Exhibit 2.6. Enabling Technologies for Carbon Capture Demonstrations at Industrial Facilities (Focus Area 3): Technical Plan[7]



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[7] Specific Point Source Carbon Capture Program efforts contributing to the success of the BIL large pilots and demonstrations are highlighted in yellow. FECM will provide support to OCED and MESC on the other elements on a "ready-to-serve" basis.

In order to address the challenges associated with supporting large pilot-scale and demonstration testing of carbon capture retrofit technologies, Focus Area 3 of this MYPP will target similar investments to those noted for Focus Area 1 (i.e., Section 2.2) in the short- to long-term, with the following notable additions:

1. Develop capability to conduct pilot-scale testing at multiple sites with varying flue gas characteristics to better define operating challenges and requirements for emissions mitigation approaches (i.e., mobile pilot testing skids).
2. As part of the small pilot-scale testing to be conducted, critical information will be developed to validate technologies and evaluate capture material durability given the unique characteristics of the flue gases generated in different industrial applications and sectors. In addition, the development/refinement of scalable process models will be a key outcome of the small pilot-scale testing.

2.4.3 Implementation Plan

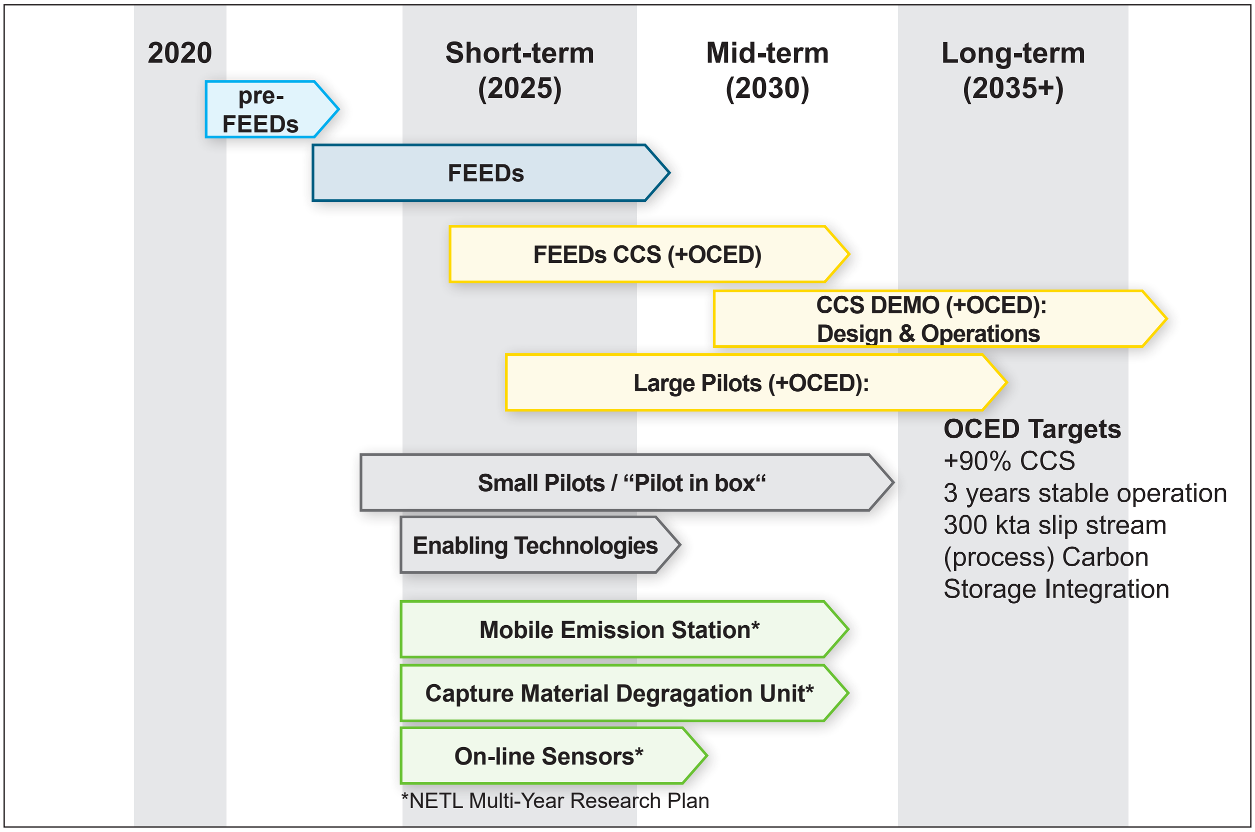
The proposed implementation plan is shown in **Exhibit 2-7**. The elements shown as orange arrows are BIL activities administered by OCED and are not elements of this MYPP. However, all other elements included in **Exhibit 2-7** are explicit components of this MYPP and support the OCED activities shown in orange. The Focus Area 3 Point Source Carbon Capture Program implementation plan includes the following extramural activities:

1. Enabling technology development (MRV, emissions control, system control, sensors). (Short- and mid-term.)
2. Build mobile pilot testing units ("pilot in a box") and test technologies to validate process models, performance, and capture material durability under conditions specific to industrial sites/sectors. (Short- and mid-term.)
3. Complete previously funded capture FEED studies. (Short-term.)
4. FEED studies for integrated CCS systems at industrial facilities. (Short- and mid-term.)

The work from the DOE Joint Strategy Team (JST) and Science and Energy Technology Team (SETT) on industrial decarbonization and Pathways to Commercial Liftoff: Industrial Decarbonization report will be leveraged to prioritize the industrial sectors where CCS can play a critical role to realize significant emissions reduction potential.[8]

[8] Pathways to Commercial Liftoff: Industrial Decarbonization (energy.gov)
Pathways to Commercial Liftoff: Low-Carbon Cement (energy.gov)
Pathways to Commercial Liftoff: Decarbonizing Chemicals & Refining (energy.gov)

Exhibit 2.7. Enabling Technologies for Carbon Capture Demonstrations at Industrial Facilities (Focus Area 3): Implementation Plan



RIC activities in support of the Focus Area 3 implementation plan are shown in green in **Exhibit 2-7** and will be the same as those noted for support of Focus Area 1 (Section 2.2.3).

2.5 Focus Area 4: Integrated Low-Carbon Industrial Processes Coupled with Carbon Capture

Focus Area 4 *will develop highly efficient carbon capture technologies integrated with low-carbon industrial processes to enable Net-Zero Carbon Emissions Industrial Demonstration projects. Targeted industrial sectors include aluminum, ammonia, cement, glass, iron-steel, lime, petrochemicals, paper refining, soda ash, and liquified natural gas (LNG).*

Goals: *Progress toward net-zero production with less than 10% impact on cost of product.*

2.5.1 Technology Challenges

Achieving net-zero carbon emissions by 2050 for the industrial sector will require implementing a variety of approaches, including, but not limited to increased process energy efficiency, utilization of low- or zero-carbon fuels, electrification, and transformational carbon capture systems. The target industrial processes (aluminum, ammonia, cement, glass, iron-steel, lime, petrochemicals, pulp and paper, refining, soda ash, and LNG) for Focus Area 4 include sectors where a significant portion of the CO_2 emissions are addressable with advanced carbon capture technologies.

Industrial processes that generate process- and combustion-based CO_2 emissions represent an opportunity for the application of carbon capture technologies along with other decarbonization techniques. However, there are aspects of industrial processes that provide unique challenges compared to prior R&D efforts on carbon capture. **Exhibit 2-8** provides a summary of some of the challenges.

Exhibit 2.8. Focus Area 4: Technology Challenges

Variety of Industrial Sources and Process/Flue Gas Compositions	• Multiple fuels utilized (coal, natural gas, biomass, etc.). • Process emissions affect CO_2 concentrations. • Pressure/concentration of CO_2-containing streams vary by industry and even within a single facility in some sectors (e.g., refineries).
Wide Range of Process/ Flue Gas Emissions Rates	• On average, flue gas flow rates are smaller than those in the power sector. • Industrial capture quantities range from approximately 100,000 to 3 million tonnes CO_2 per year depending on sector.

Insufficient Integration	• Future industrial facilities may alter their feedstocks, production processes (e.g., chemistries, process equipment/technologies) and fuel sources
	  ▫ Alternate low-carbon fuels for lower emissions profiles, including biomass, hydrogen, municipal solid waste (MSW), etc.
	  ▫ Alternate industrial processes, such as:
	    ▪ Steel production through electric arc furnace and direct reduced iron.
	    ▪ Oxy-combustion for cement production (results in concentrated CO_2 stream from process emissions that can be readily separated).
	    ▪ Electrochemical cement production.
	    ▪ New feedstocks/reaction pathways for chemical production.

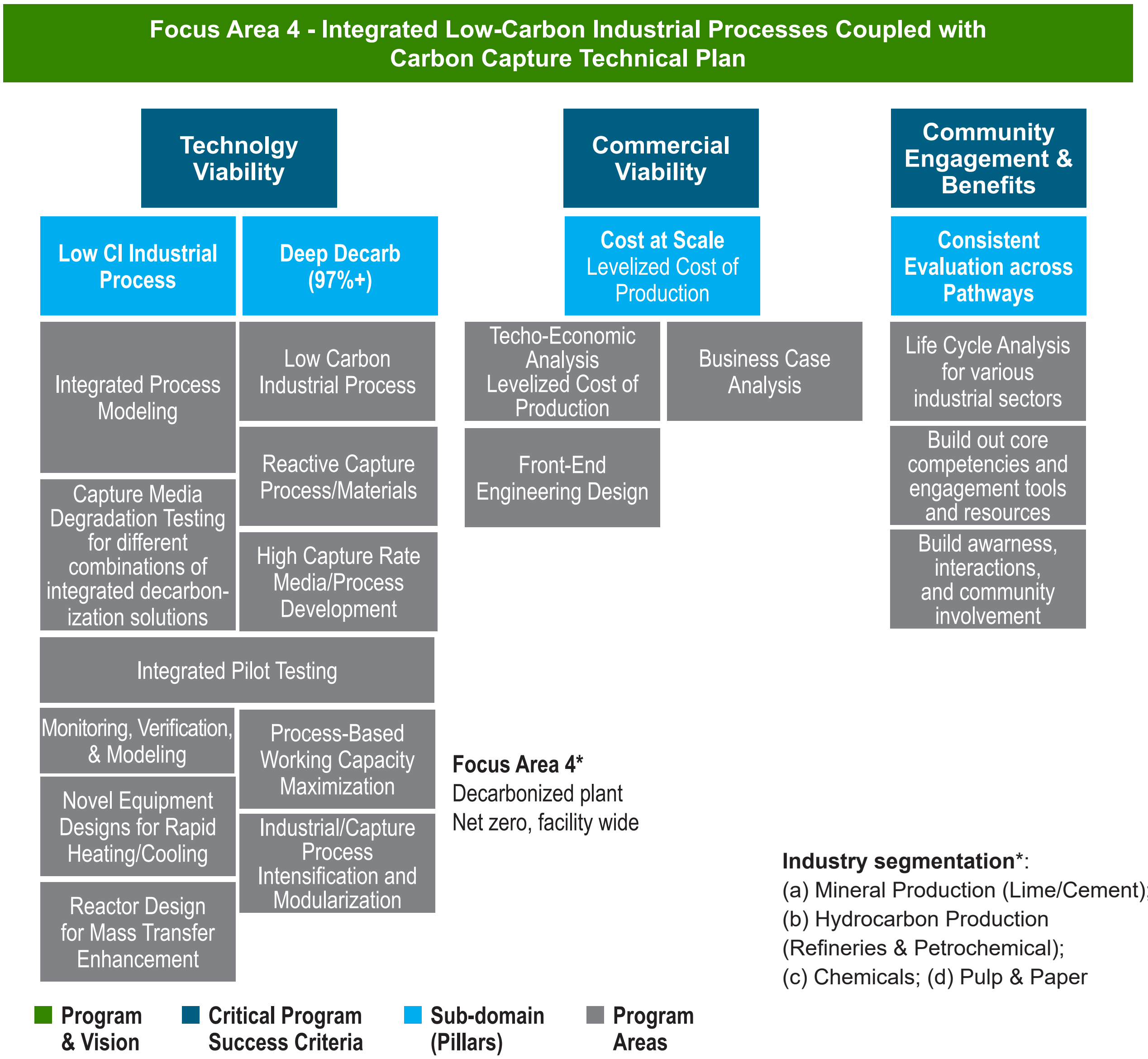
Goals Need to be Developed for Each Industrial Sector	• Current information/goals analysis is limited to those included in the industrial capture report. • Need to create cases for each sector that address the base plant as well. • Effect of integrated alternate decarbonization solutions and CCS on product prices is vital; however, information on production costs is difficult to obtain. • Goals currently based on CO_2 capture; unclear how goals relate to decarbonization. • Need to evaluate scaling versus modularization.

2.5.2 Technical Plan

The critical program success criteria for the development and eventual deployment of integrated low-carbon industrial processes coupled with carbon capture are similar to those noted for net-zero, flexible power: technology and commercial viability and community engagement and benefits. To support these success criteria, the subdomain activities of the program will focus on development and testing of low-carbon-intensity industrial processes coupled with capture technologies capable of achieving deep decarbonization; demonstration of cost at scale; and development of a consistent plan to evaluate potential changes in air, water, and solid waste emissions associated with both changes in process characteristics and installation of carbon capture technologies, as well as community benefits during technology development and demonstration. Given the relatively early developmental stage of the technologies needed to achieve net-zero industrial CO_2 emissions, all program areas noted in **Exhibit 2-9** are elements of the FECM Point Source Carbon Capture Program.

The technical plan for addressing the challenges identified in Section 2.5.1 requires development efforts across a wide range of TRLs in order to address long-term decarbonization goals (i.e., net-zero). As such, the plan includes lab/bench-scale development of materials, processes, and equipment that can be integrated and scaled through small pilot-scale testing. As new technologies mature, the plan includes FEED studies to derisk demonstration and eventual deployment. As pilot-scale testing advances, it is anticipated that the need for enabling technologies will become evident, and these will be developed and tested in conjunction with pilot-scale testing efforts. Throughout the technology testing, integration, and scale-up processes, the development, application, and refinement of process simulation models will be key to derisking the technologies.

Exhibit 2.9. Integrated Low-Carbon Industrial Processes Coupled with Carbon Capture (Focus Area 4): Technical Plan



Investments needed to overcome the technical challenges noted above for Focus Area 4 include the following:

1. Industrial decarbonization test centers (IDTCs) for development of integrated net-zero industrial processes: Initial efforts will be focused on establishing an IDTC at a cement facility to conduct bench-

scale and small pilot-scale testing of different transformational carbon capture technologies (e.g., advanced sorbents/membranes, intensified processes [e.g., rotating bed reactors], chemical looping, reactive capture) integrated with low-carbon decarbonization process options (e.g., low carbon fuel switching and feedstock substitutions, indirect heating of kiln or kiln electrification, process or energy efficiency improvement). It is anticipated that this approach can be extended to other industrial sectors such as pulp and paper or petrochemicals at some point in the future.

2. Carbon capture material degradation testing: Examine the impact of integration of new low-carbon industrial processes on the performance, degradation, and emissions of transformational carbon capture materials.
3. Enabling technologies, including:
    a. Emissions MRV (analytical methods, testing equipment) validated at pilot scale.
    b. Engineering control methods/equipment (e.g., pre-treatment, acid wash, upstream filters, aerosol controls) tailored for specific technology to control emissions during dynamic operations and/or operation with low-carbon fuels

1. Expand capabilities in process modeling, TEA, and LCA for the targeted industrial processes to build levelized cost of product (LCOP) as a function of process carbon intensity for FOAK low-carbon industrial processes (such as those noted above) integrated with carbon capture to drive to net-zero operations.

4\.

Invest in additional FEED studies for industrial plants, coupled with CarbonSAFE projects. Future FEED studies will be focused in areas where clusters of industrial plants are found with proximity to potential CO_2 storage sites along with CO_2 pipelines to provide support for development of CCS hubs.

5. Integrate top-down insights from economy-wide decarbonization studies (e.g., Rapid Energy Policy Evaluation and Analysis Toolkit [REPEAT]; the Electric Power Research Institute [EPRI] U.S. Regional Economy, Greenhouse Gas, and Energy [REGEN] model) and apply these to bottom-up regional and local industrial decarbonization (low-carbon industrial process and carbon capture) studies.

6\.

a. Regional hub studies of specific industries to assess the feasibility of low-carbon industrial processes and CCS: Cost and availability to switch fuels/electricity, to transport and store CO_2.
b. Analyze regions with high CCS activity (e.g., Class VI permits) and assess potential for regional CCS hub development from a low-carbon industry perspective.
c. Participate in the development of standards for low-carbon cement and concrete, iron and steel, and fuels and chemicals.

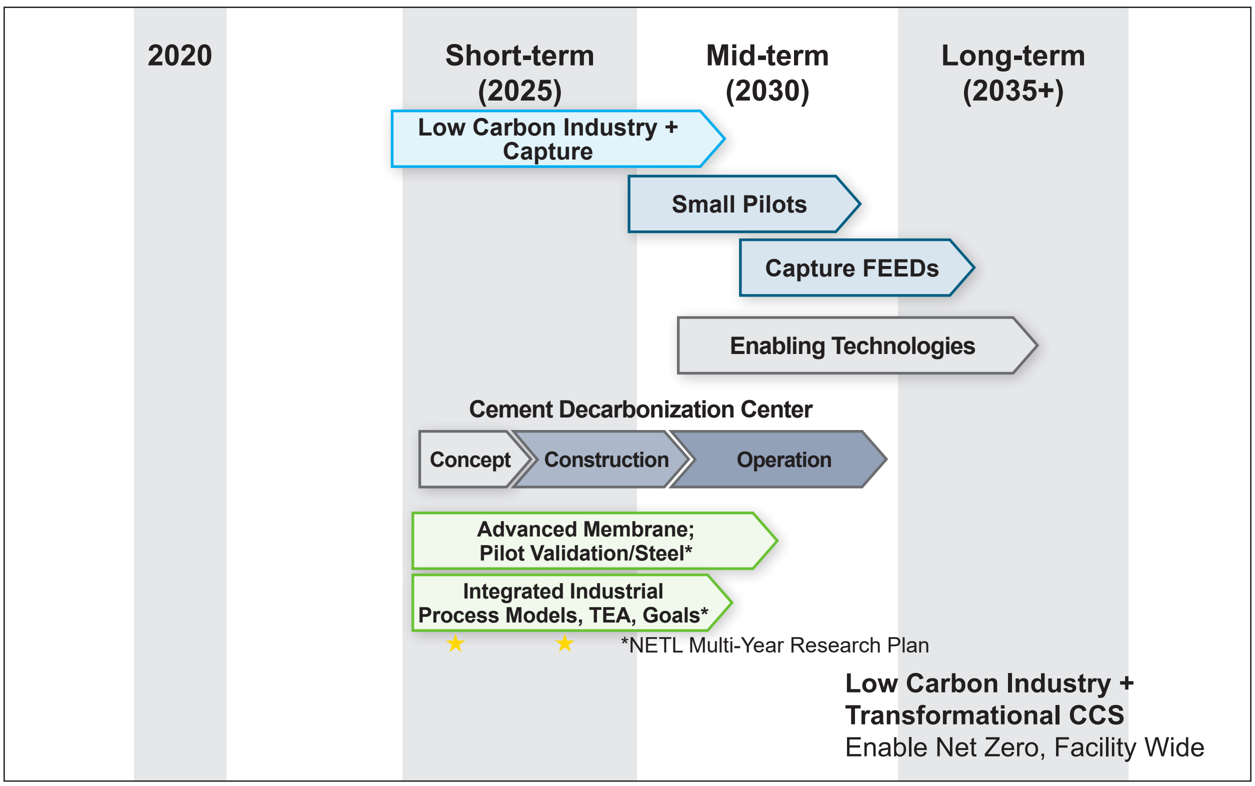
2.5.3 Implementation Plan

Lab/bench-scale development of integrated industrial decarbonized processes (e.g., low-carbon fuel, materials substitution) and capture (e.g., reactive capture, BiCRS, chemical looping, etc.) will be funded. The work from the DOE Joint Strategy Team and Science and Energy Technology Team on industrial decarbonization and Pathways to Commercial Liftoff: Industrial Decarbonization report will be leveraged to identify appropriate combinations of manufacturing process-oriented decarbonization approaches (e.g., fuel switching, input materials substitution) that, when integrated with CCS, have the potential to lead to net-zero production processes.

The proposed implementation plan (**Exhibit 2-10**) includes the following extramural activities:

1. Lab- and bench-scale validation of individual low-carbon emissions industrial processes/components integrated with transformational carbon capture (e.g., chemical looping, reactive capture, advanced membranes/sorbents, oxy-combustion). (Short-term.)
2. Development, construction, and operation of a cement decarbonization test center. (Short- and mid-term)
3. Small pilot validation of integrated low-carbon industrial CCS processes with actual flue gas in small integrated pilots (purpose-built and testing center, less than 3 tCO_2/day). (Short- and mid-term.)
4. Enabling technology development (e.g., MRV, emissions control, system control). (Short- and mid-term.)
5. FEED studies coupled with CarbonSAFE projects. (Short- and mid-term.)

Exhibit 2.10. Integrated Low-Carbon Industrial Processes Coupled with Carbon Capture (Focus Area 4): Implementation Plan



(I) Industrial Sectors: Mineral Production, Cement, Steel, Pulp & Paper, Petrochemical/Refineries

In support of the Focus Area 4 implementation plan, in-house activities will develop and execute mission-based NETL-RIC MYRP goals that will:

1. Validate the NETL advanced membranes system (rubbery polymer, thin film composite membrane/flat sheet membrane modules) in a purpose-built small pilot system at a steel plant (30 standard liter per minute [SLPM] slipstream; parametric and long-term testing under flexible industrial operations).
2. Develop first principles models of different industrial plant designs to ensure representation of decarbonization strategies beyond and/or integrated with CCS. Develop models of alternative decarbonization strategies, such as, but not limited to, electrification, biomass cofiring, and process alternatives. Integrate these models into base plant models to capture the effect of integration on product prices and quality.
3. Perform TEA (Class 4-5 AACE) and LCA for net-zero carbon emissions reference plants and develop curves of LCOP as a function of carbon intensity for cement, pulp and paper, petrochemical/refineries, and steel.

2.6 Other Programmic Focus/Priorities

2.6.1 Mobile sources

The Point Source Carbon Capture Program includes support for low-TRL efforts in CO_2 capture in newer areas (e.g. mobile transport and reactive capture). Capture from mobile sources, such as heavy duty vehicles and shipping, involves unique challenges compared to the previously outlined stationary sources. This includes relatively low concentrations of CO_2 in exhaust gas (9% for heavy-duty trucks and 4.5% for ships); transient operating conditions; size and weight constraints; and elevated exhaust gas temperatures (450˚C for heavy-duty trucks and 220˚C for ships). This calls for an assessment of the feasibility of technologies that are already in the Point Source Carbon Capture Program portfolio for these applications, as well as the development of new materials and processes.

To support the development of approaches to carbon capture that are suitable for mobile applications, the program will target the following investments:

- Conceptual design to prove the initial feasibility of proposed approaches for mobile carbon capture. These studies will include detailed TEA, LCA, and engineering designs to enable comparison with other decarbonization alternatives that could be applied to mobile sources (e.g., electrification, hydrogen fuel cells). Technology-gap analysis will also be conducted in this phase to identify aspects of the capture process that should be the focus of future R&D in the lab- and bench-scale phase. In FY 2024, the Point Source Carbon Capture program awarded nine (9) Small Business Innovation Research (SBIR)/Small Business Technology Transfer (STTR) projects in this area.
- Bench-scale R&D validation of selected concepts.

2.6.2 Artificial Intelligence for Emissions Forecasting and Control

The Point Source Carbon Capture Program supports efforts to develop machine learning (ML) tools that can forecast emissions of solvents and their degradation products into the atmosphere, which has been identified as one of the main environmental challenges associated with amine-based CO_2 capture.[9, 10] These efforts will be particularly important for flexible operations (Focus Area 2), where emissions profiles may vary significantly. Capabilities of these models should include real-time prediction of future emissions given historic test campaign data and emissions forecasting in scenarios of plant operation with different emissions mitigation controls online (e.g., pre-treatment, post-control acid wash, upstream filters, aerosol controls, corrosion inhibitors). These ML models will initially be developed to predict emissions from most studied solvents (MEA) under steady-state operation and will then be extended to second-generation solvents and more non-steady-state operation.

To support the development of ML tools for emissions forecasting, the program will target the following investments:

- Conceptualization of ML models for emissions forecasting given historic MEA test campaign data.
- AI-based tool development and implementation across pilot-scale testing capture projects for emissions forecasting and design of process control algorithms.

In FY 2024, the Point Source Carbon Capture Program awarded six (6) SBIR/STTR projects in this area.

2.7 Themes Across Focus Areas

There are two topics, discussed briefly below, that are common to all of the Focus Areas that will be included in all solicitations that emerge from this MYPP:

1. Measuring, monitoring, and controlling potential environmental impacts associated with installation of carbon capture technologies.
2. An extension of the focus of FEED studies to maximize both CCS performance and quantify emissions of secondary and primary pollutants generated by the power or industrial facility.

2.7.1 Measuring, Monitoring and Controlling CCS-Related Emissions

As noted in Section 2.2.1, the application of carbon management technologies has the potential to lead to changes in pollutant emissions associated with power and industrial production. Installation of carbon capture equipment often requires removing sulfur and nitrogen compounds that can impact the performance of the capture media. This results in decreases in total emissions of these compounds, improving air quality compared to the situation prior to installation of CCS. At the same time, degradation of capture media during long-term use can impact secondary emissions of degradation by-products. Efforts to quantify the reduction in pollutants associated with production processes, as well as formation of secondary pollutants, will be a significant component of future solicitations, as summarized in **Exhibit 2-11**.

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9 Towards Commercial Scale Post Combustion Capture of CO_2 with Monoethanolamine Solvent: Key Considerations for Solvent Management and Environmental Impacts | Environmental Science & Technology (acs.org).

10 Human and Environmental Impact Assessment of Post combustion CO_2 Capture Focusing on Emissions from Amine-Based Scrubbing Solvents to Air | Environmental Science & Technology (acs.org).

Exhibit 2.11. Efforts associated with quantification and control of emissions associated with installation of CCS

Focus Area	Item	Focus Area
R&D	✓Validate the safety of solvent emissions; MRV. ✓Engineering control systems tailored for power and industrial applications (including measurement of particulates, SO_x and NO_x, if relevant). ✓Advanced emissions control (e.g., water-wash) systems. ✓Solvent reclamation processes.	Focus Areas 1 and 3
Project Implementation	**Small/Large Pilots:** ✓Install emissions measurement systems (e.g., Proton Transfer Reaction — time-of-flight mass spectrometry [TOF-MS], Fourier-transform infrared spectroscopy [FTIR]). ✓Install/test emissions control systems. ✓Mobile emissions testing units. ✓Third-party emissions testing. ✓Measure reductions in product process emissions. ✓Develop emission forecasting models.	Focus Areas 2, 3 and 4
	FEEDs: ✓Include emissions quantification. ✓Account for reductions in product process emissions.	Focus Areas 2 and 3
Communications	✓R&D results. ✓Distill information for nonscientific communities.	Focus Areas 2, 3 and 4

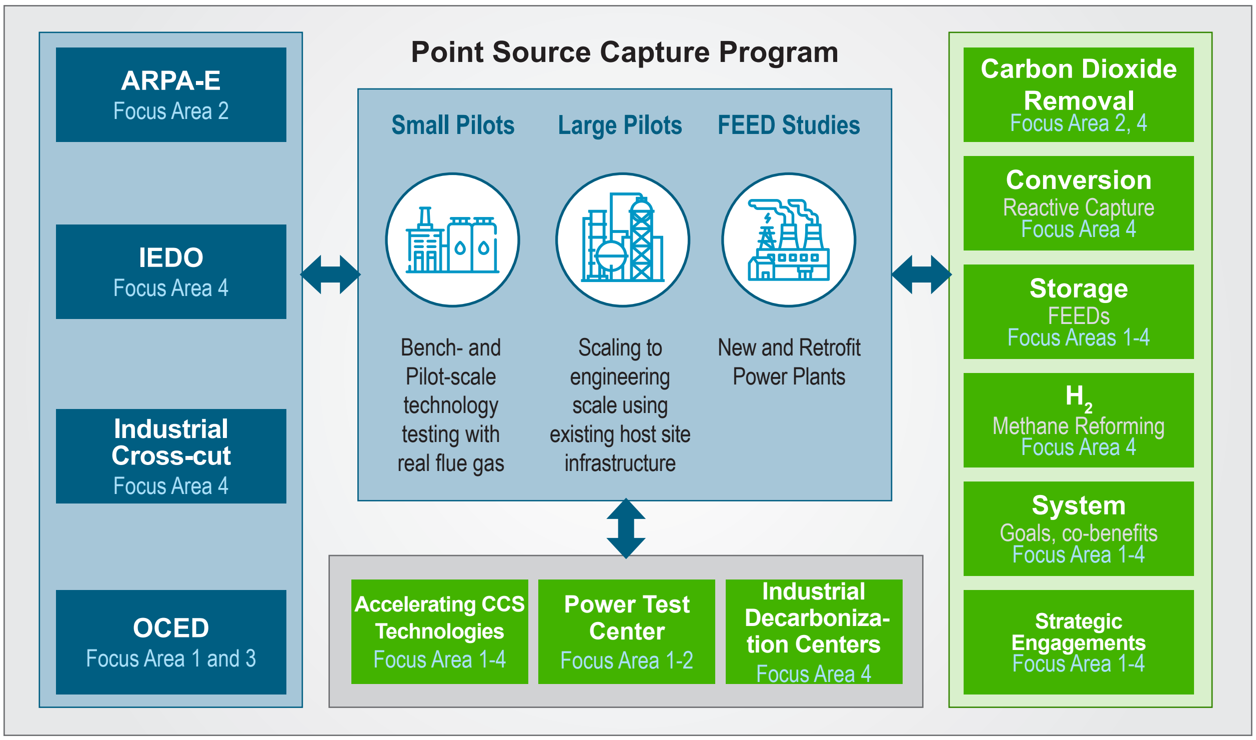
2.7.2 Extension of FEED Study Focus

FEED studies have been an important element in advancing capture technologies toward demonstration and ultimate deployment. Historically, the focus of FEED studies has been on maximizing the performance of subject capture technologies and approaches while minimizing cost. With the enhanced focus of future efforts on quantification and control of emissions, future FEED studies will explicitly account for emissions. Specifically, future FEEDs will focus on (1) addressing existing technical uncertainties (e.g., long-term performance and operational aspects related to solvent degradation and reclamation); (2) examining optimal host plant and capture system integration (e.g., mitigating air ingress upstream of the point of CO_2 capture and comparing host plant steam extraction source and condensate return configurations); (3) enabling capture system design optimization to provide the maximum environmental benefit while minimizing cost; and (4) FEED studies that integrate CCS technologies with other low-carbon technologies used on industrial sources.

2.8 Engagement Crosscutting Intra- and Interdepartmental Activities

Collaboration across multiple FECM program areas, other DOE offices and elements, and with international partners/entities, is an essential element to support Point Source Carbon Capture Program goals, as illustrated in **Exhibit 2-12**.

Exhibit 2.12. Point Source Carbon Capture Program Engagement



Focus Areas 1 and 3 are designed to support large pilot and demonstration activities conducted by OCED, as well as by private industry. The Point Source Carbon Capture Program has already provided technical support to OCED via assistance with solicitation development, reviews of concept papers and full applications, and contract negotiations. That support is expected to continue and possibly expand in the future. Interaction with the Industrial Efficiency and Decarbonization Office (IEDO) and the Industrial Cross-cut Joint Strategy Team have also been initiated and are expected to expand to support Focus Area 4. ARPA-E's FLECCS Program is directly relevant to Focus Area 2 and is anticipated to develop technologies that can be transferred to the Point Source Carbon Capture Program for further development and scale-up.

Interaction with other FECM programs includes co-funding of biomass carbon removal and storage and reactive capture technologies with the Carbon Dioxide Removal and Carbon Conversion Programs, respectively. The Carbon Transport and Storage Program, Systems Analysis group, and Strategic Engagements cut across all Point Source Carbon Capture Program Focus Areas by supporting FEED studies, helping with the establishment of goals, quantifying co-benefits, and supporting community benefits plan development. Interaction with the Hydrogen Program involves Point Source Carbon Capture Program support of the capture component of steam methane reforming (SMR) and autothermal reforming technologies to identify challenges to the deployment of low-carbon industrial processes with CCS.

Ongoing DOE international collaboration helps to accelerate the maturation of CCS. Multiple international projects that the Point Source Carbon Capture Program funded through the Accelerating CCS Technologies (ACT) consortium along with the Clean Energy Transition Partnership (CET Partnership) help DOE and stakeholders better understand the entire chain of amine-based emissions — from source pre-treatment and processing in the absorber, through the water-wash section, and finally what mitigation measures may be available. These projects focus on:

- Control, monitoring and mitigation of amine-based emissions.
- Sustainable operation of post-combustion capture plants.
- Lowering absorption process uncertainty, risks and costs by controlling amine degradation.

FECM also collaborates with Technology Center Mongstad (TCM) via technology testing at TCM's 10-megawatt (MW) pilot-scale facility. This facility is equipped with state-of-the-art equipment, and technology developers benefit from the expertise of the plant operating personnel.

In closing, the FECM Point Source Carbon Capture Program has a significant amount of work to do in the next decade to both support the short-term deployment of CCS on the power and industrial sectors and to develop advanced deep decarbonization technologies that can be deployed in next decade to facilitate near-zero emissions from both the power and industrial sectors. This work requires FECM collaboration with not only external stakeholders, but also across the department with OCED, MESC, IEDO and ARPA-E.

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