Low-Energy, Low Cost Production of Ethylene by Low Temperature Oxidative Coupling of Methane

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Siluria Technologies
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Project Objective

- **Overall Objective:** To develop a new catalytic process for distributed production of ethylene via low-temperature oxidative coupling of methane using the advanced OCM catalyst developed by Siluria Technologies.

- Distributed small-scale production of ethylene enables on-demand ethylene applications such as on-site generation of high-value derivatives with the potential to reshape and condense the national manufacturing value chain, from raw material to finished goods.

- The current design developed and commercialized by Siluria shows excellent scalability between 100 and 1,000 KTA (KiloTons per Annum). However, the specific operating and capital costs sharply increase for smaller capacities.

- Among key drivers for poor scalability at smaller scale are:
  - Product recovery and purification train - utilizes typical cryogenic separation systems that show poor scalabilities at small-scale.
  - Technical limitations and minimum capital expenditures.
  - Separation section (and other process areas to a lesser extent) hits baseline costs and are cost challenged at capacities below 100 KTA.

- The project aims to overcome the above hurdles and enable economically attractive small scale OCM design.

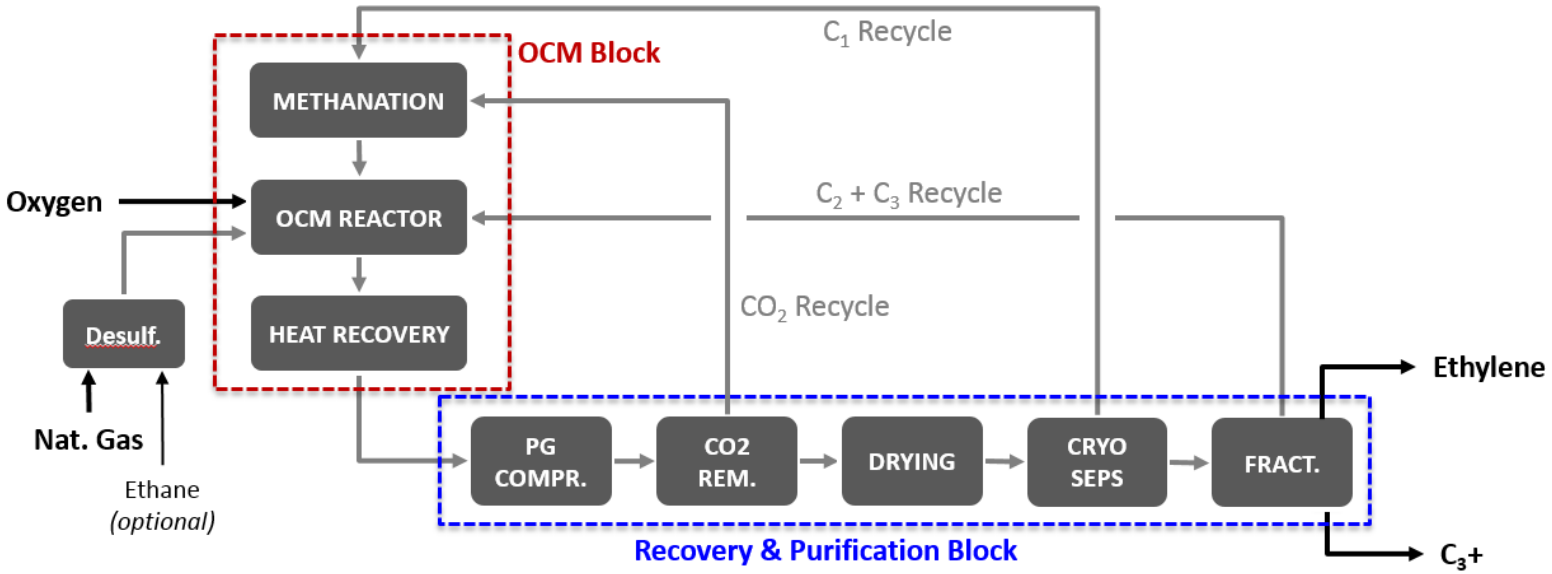
Technical Innovation

- **Ethylene Crackers:** Currently primarily produced by steam cracking of ethane, propane or naphtha
  - Utilizes mega scale crackers whose minimum efficiency scale is currently above 500 KTA.
  - Operate at very high temperatures and are extremely energy and capital intensive.
- **Siluria's New OCM Technology:**
  - Proprietary, revolutionary technology enables direct conversion of all components of natural gas to higher value petrochemical products.
  - Simple exothermic OCM process design (as currently developed by Siluria) enables excellent scalability for a wider range of capacities than steam cracking.

OCM Reaction:

$2CH_4 + O_2 \rightarrow C_2H_4 + 2H_2O + heat$

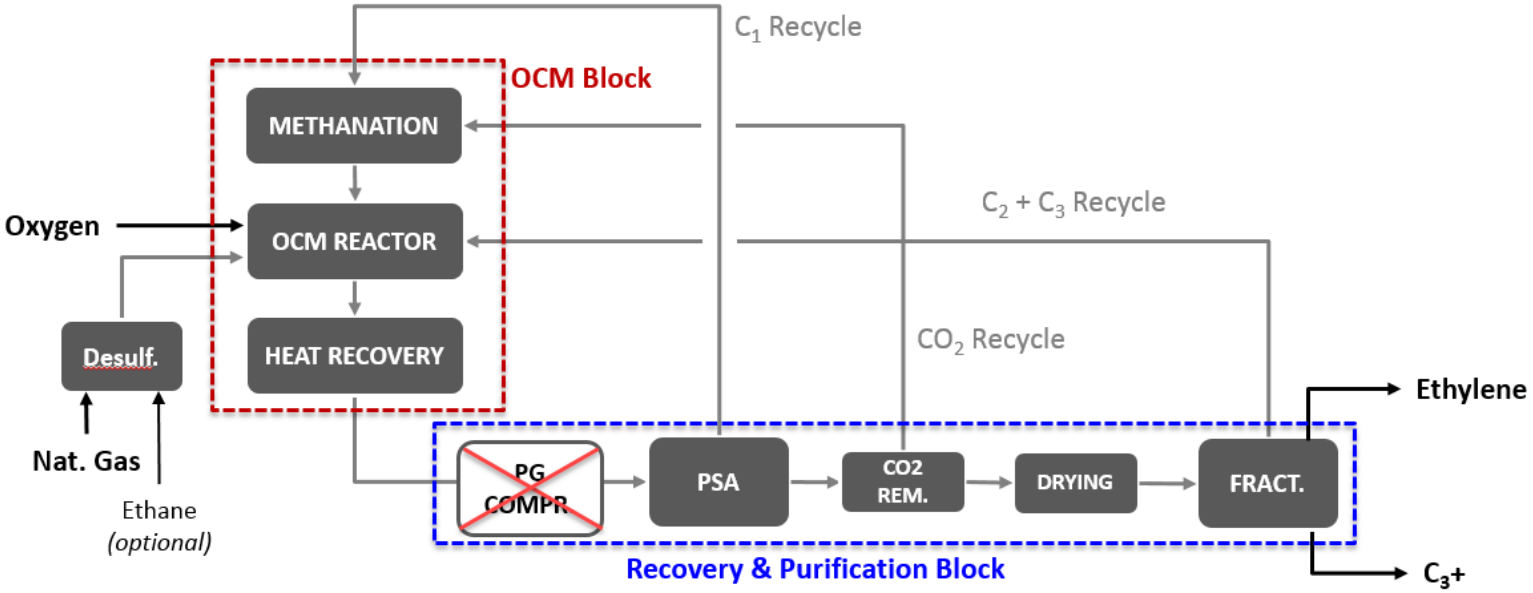
- **Replacing Cryogenic Separations with Alternative Advanced Separations:**
  - Development of advanced olefin separation technologies (the main scope of this project) would further expand the scalability of the OCM process.



Technical Innovation

Novel Adsorbent Based Separation Process:

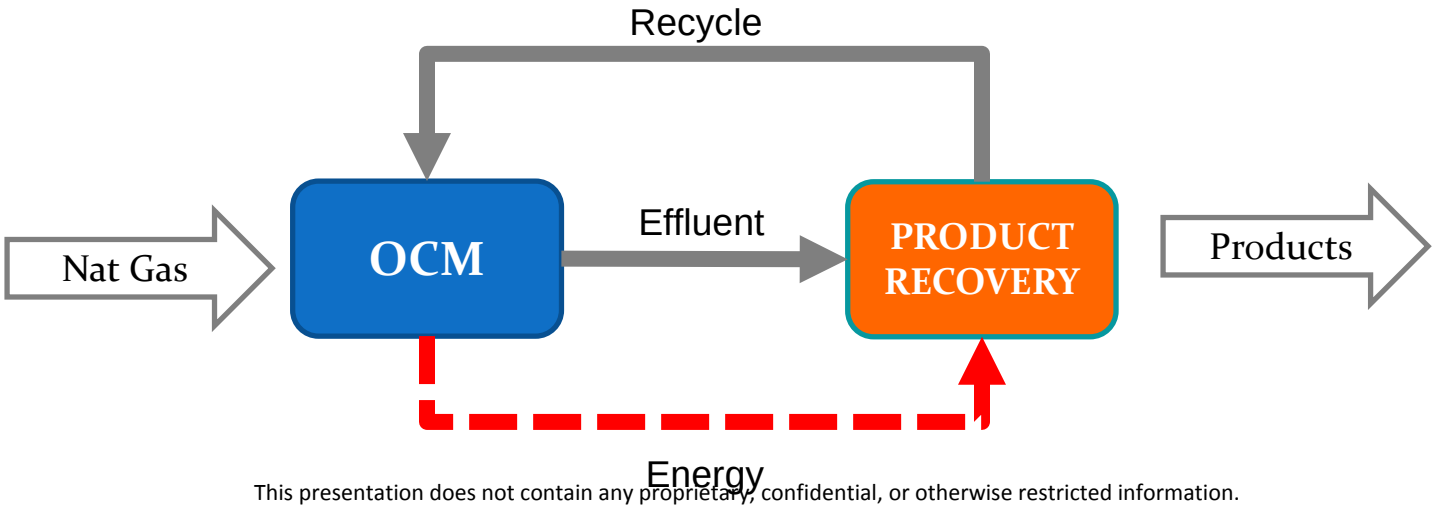
- Certain zeolite and Metal Organic Framework materials' very high selectivity for ethylene facilitates effective olefin separation.
- High capacity of certain Metal Organic Framework materials enables practical implementation of PSA for these separations.
- Development of optimized process configuration(s) would aid the deployment of such materials.



Technical Approach

Identify and resolve roadblocks to small-scale implementation of Siluria's OCM process by exploring out-of-the box and innovative solutions for olefin separations and other key process areas.

- Evaluated Siluria's current OCM ethylene design for small-scale deployments and identified critical bottlenecks to scalability (separations).
- Researched and developing optimal alternative unit operations / process schemes to energy intensive cryo based separations that limit the overall down scalability of the process.
- Investigating techno-economic viability of alternative designs.
- Conducting experimental validation and final configuration design.



Technical Approach

Siluria's world class team:

Vision and competence to translate ideas into implementation

- State-of-the-art high throughput screening platform for catalyst discovery and development.
- R&D and pilot facilities specifically developed for OCM and incorporating new separation technologies.
- Extensive process engineering and technology development experience.
- Techno-economic analysis & commercialization expertise.
- First of a kind (world's largest) OCM unit co-located with Braskem operating polymer plant in La Porte, TX.

Materials and Process testing - RTI International (Partner)

- Material development and testing capabilities - sorbent development for separation studies.
- Process development - strong competence in developing, designing and constructing separation systems for novel applications.

Novel Adsorbent Materials – UC Berkeley (Partner)

- World leading Metal Organic Framework (MOF) research capabilities.
- Invented multitude of MOF materials with excellent relevant properties.

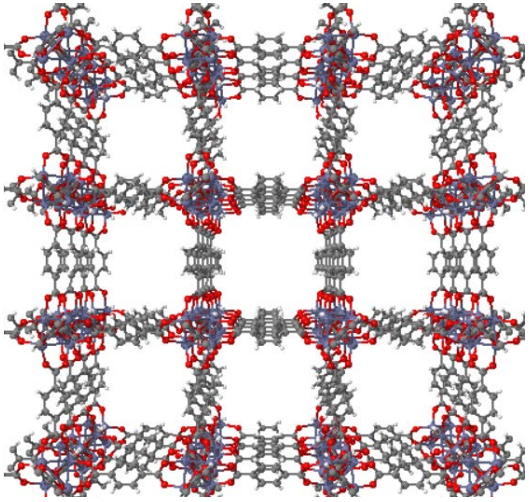
Modeling of Adsorbent Systems – Norton Engineering (Partner)

- Decades of experience in conceptual design of PSA systems.

Transition (beyond DOE assistance)

Developing the fundamental knowledge and understanding of alternative separation processes to fit the mega trends in the US olefin market

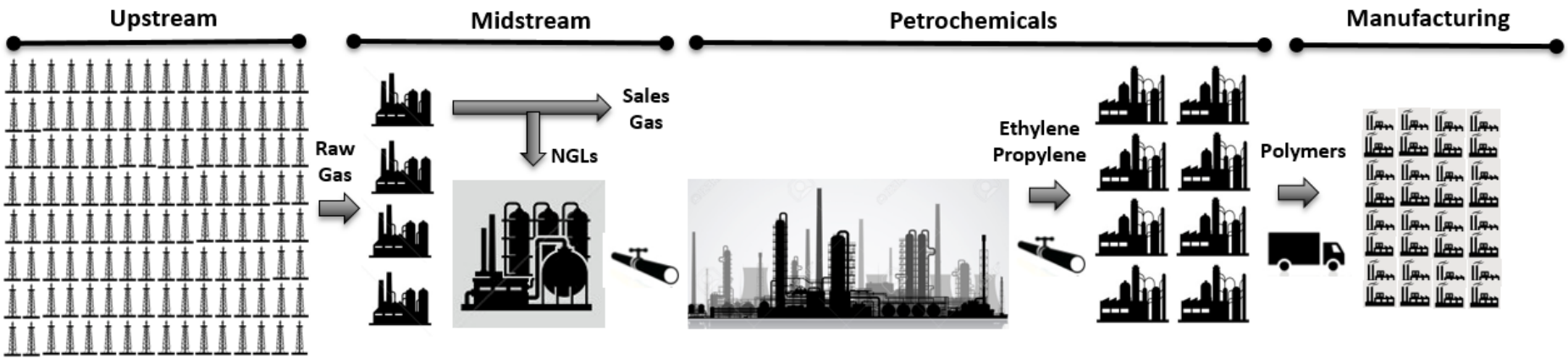
- Understanding the interactions of olefins on various adsorbent material structures, and ways in which the affinity of olefins to the adsorbent materials can be enhanced.
- Designing the optimal materials to achieve the properties required for separation performances and fit with commercially relevant operations.
- Conceiving process schemes that maximize the benefits of using these materials in commercial olefin separation applications.



Transition (beyond DOE assistance)

Mega Trends in US olefin Market - *Scale, location, and infrastructure*

- American natural gas and ethane is being produced in growing quantities, in geographies far removed from petrochemical hub in the US Gulf Coast (infrastructure constrained).
- Scale of ethane crackers requires 60 to 80 MBPD of ethane to be delivered to each US Gulf Coast cracker.
- Scale of ethane crackers dwarfs ethylene derivatives facilities.
- These drivers are pushing raw materials like natural gas and ethane to export, rather than adding value domestically through manufacturing.

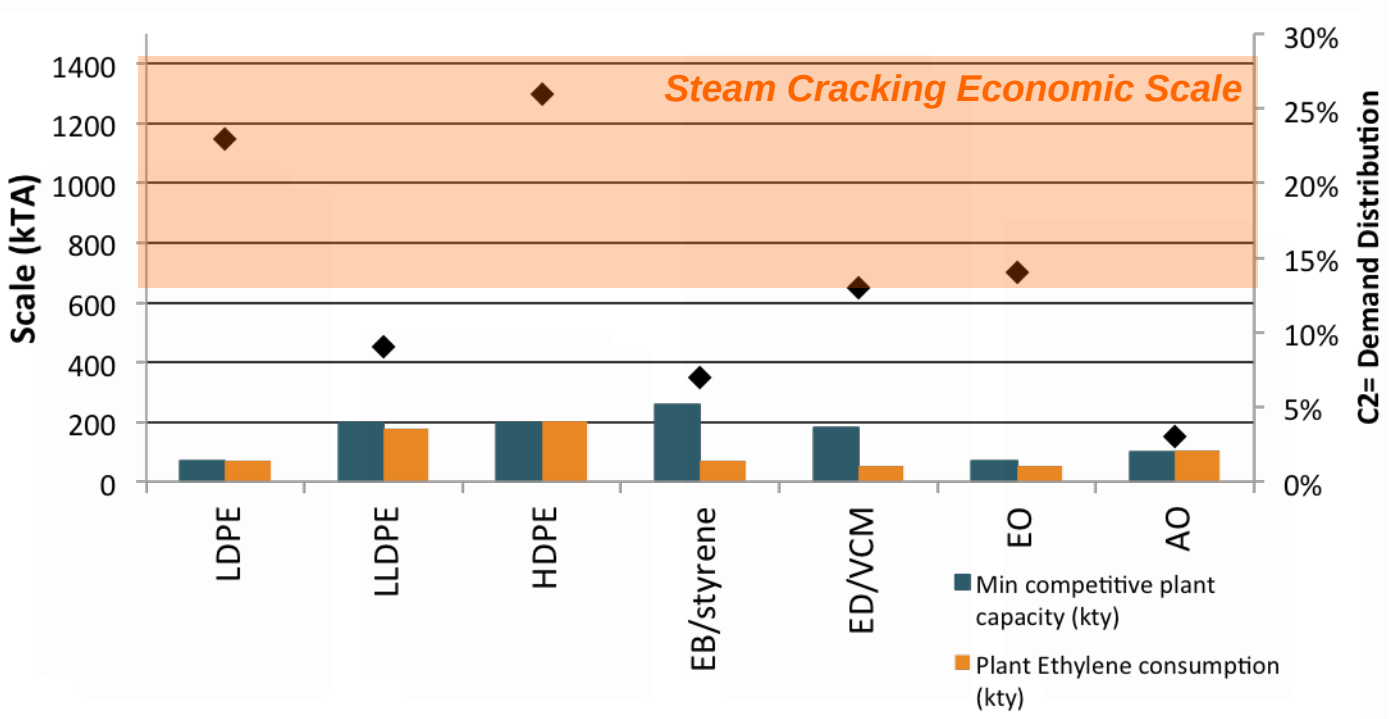


Measure of Success

Cracker / Derivatives Scale Mismatch

Scale range of OCM w/ conventional seps

Scale range of OCM w/ advanced seps



Siluria's OCM can enable distributed-scale production of high value products like polymers from ubiquitous natural gas, radically disrupting the resource-to-manufacturing value chain

Source: Internal Siluria, IHS Chemicals Commissioned Research

Project Management & Budget

Project Duration: 24 months

Task	Description	Duration	Status
1.0	**Detailed Process Analysis** • **Milestone 1:** Target list of unit ops and/or process steps providing roadblocks to small scale implementation (Q1)	**Q1**	**Complete**
2.0	**Process Design and Development** • **Milestone 2:** Identify alternative process concepts (Q2) • **Milestone 3:** Preliminary alternative process concepts, validated w/experimental data (Q3) • **Milestone 4:** Refined alternative process concepts, validated w/experimental data (Q6)	**Q2 to Q6**	**Complete**
3.0	**Refined Conceptual Design & Techno-Economic Modeling** • **Milestone 5:** One or more process concepts for small-scale OCM ethylene production (Q7)	**Q6 to Q7**	**In Progress**
	Internal Go/No-go Decision Point: Techno-economic analysis for one or more process concept for small-scale	**Q7**	**In Progress**
4.0	**Project Management and Reporting** • **Milestone 6:** Draft final report (Q7) • **Milestone 7:** Submit final report (Q8)	**Q1 to Q8**	

Total Project Budget	
DOE Investment	$2,000,000
Cost Share	$500,923
Project Total	$2,500,923

Results and Accomplishments

- **Accomplishments:** Completed Milestones 3 and 4 (currently in Q7)
  - Identified novel adsorbents that can treat multicomponent stream of the OCM effluent.
  - Developed process concepts that can operate at moderate pressure and temperature conditions, thus enhancing scalability.
  - Developed simulation models to predict behavior of such complex multicomponent adsorbent based system.

Illustrative Selectivity Data

Component	Selectivity
C_2H_4/CH_4	50
C_2H_4/C_2H_6	5
C_2H_4/CO	5
C_2H_4/CO_2	6
C_2H_4/H_2	$>10^8$

- **Current Work:**
  - Fine tuning of shortlisted adsorbents to identify technically and economically most effective material(s).
  - Determining the most optimum process concept(s).
    - Modeling the final process configuration to determine the cycles
    - Integration with the overall OCM process.
- **Schedule:**
  - Final set of experimental testing and modeling → Techno-econ analysis for final process configuration(s)