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TL1: Alternative Light Olefin Production through Methane Diluted Cracking, Turboquenching, and Electric Cracking Reactors

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PURDUE UNIVERSITY

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PURDUE UNIVERSITY | THE UNIVERSITY OF NEW MEXICO | Northwestern University | UNIVERSITY OF NOTRE DAME | TEXAS The University of Texas at Austin | NSF

THRUST 4 TEAM

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Process Synthesis, Separation

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Process Synthesis, Optimization

Jennifer Dunn
Modeling, LCA

David Allen
(Co-Lead)
Modeling, LCA

Jeffrey Siirola
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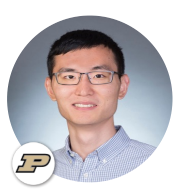
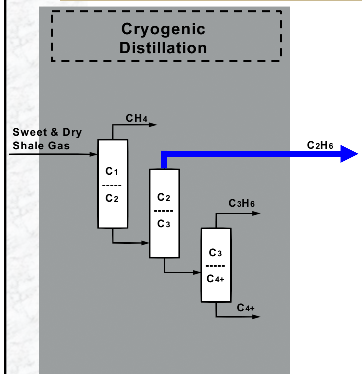
Gary Sawyer
Process Synthesis, Economics



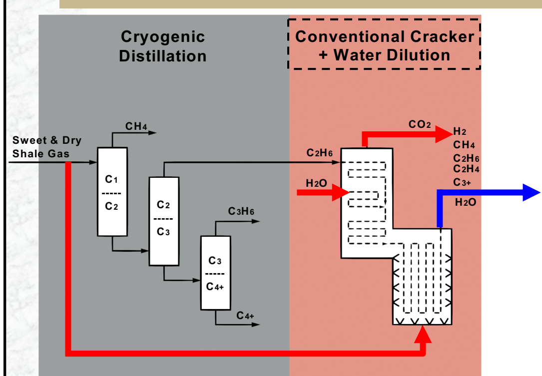
Can Li
Process Optimization and Design

David Bernal
Process Optimization and Design

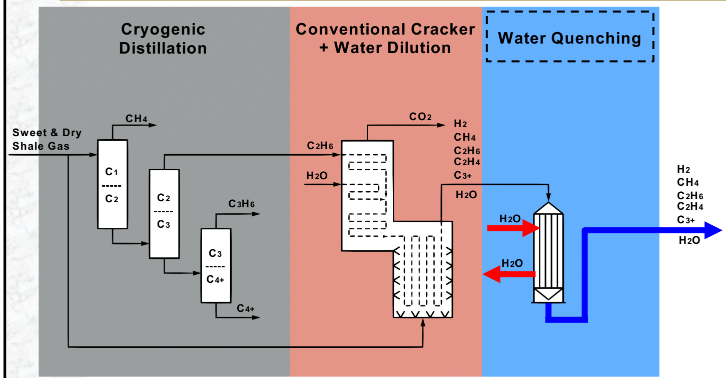
Conventional Shale Gas Processing Begins With Cryo. Separation



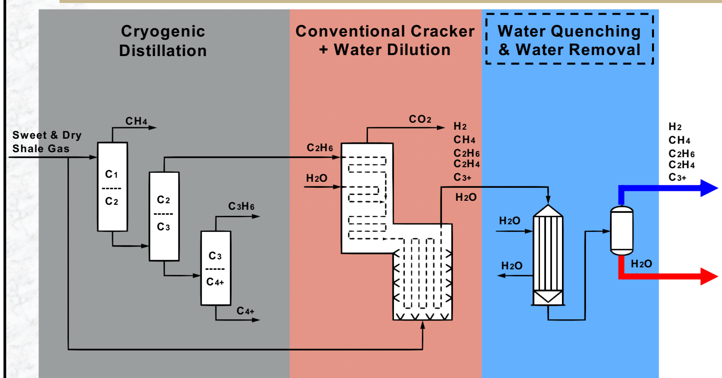
Conventional Crackers Burn Fossil Fuels and Generate CO_2



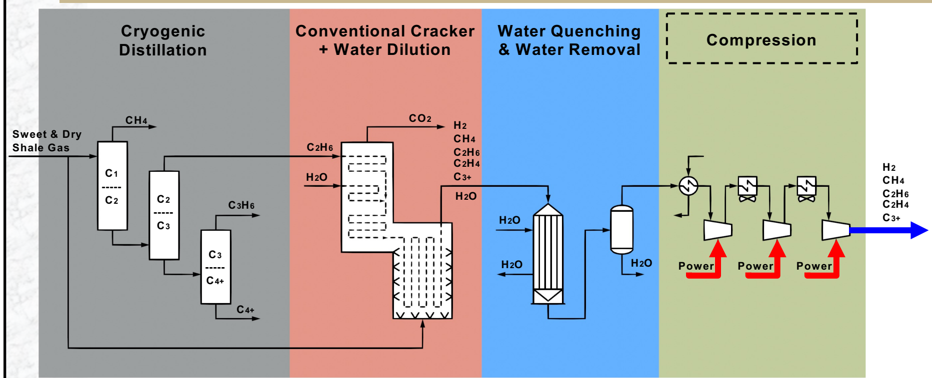
Reaction Product Is Rapidly Cooled to Avoid Secondary Reactions



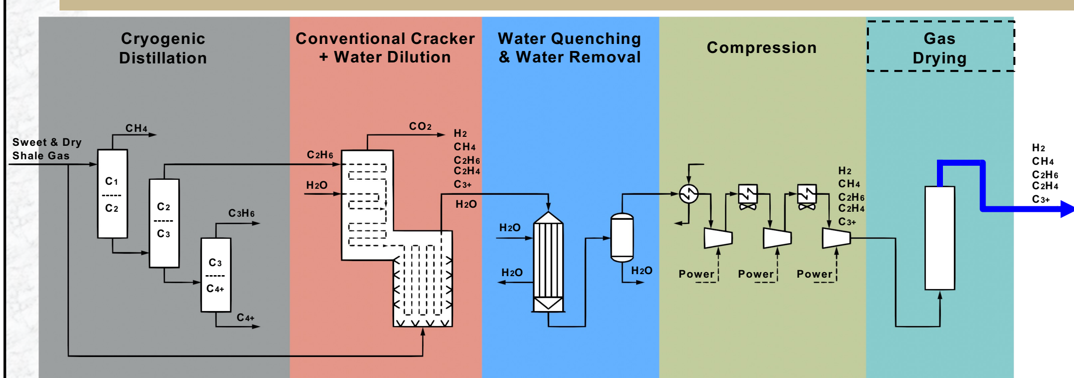
Dilution Water Must Be Removed After Reaction



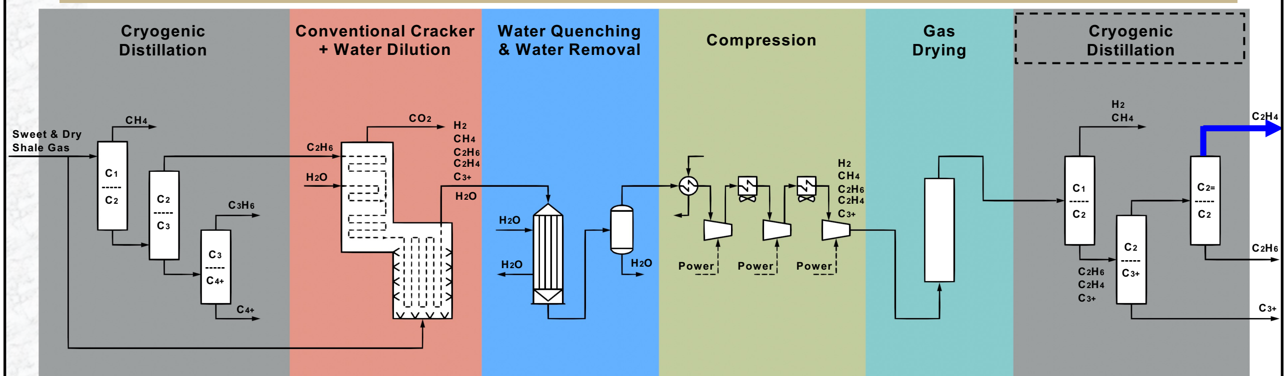
Product Is Compressed Using External Electric Power



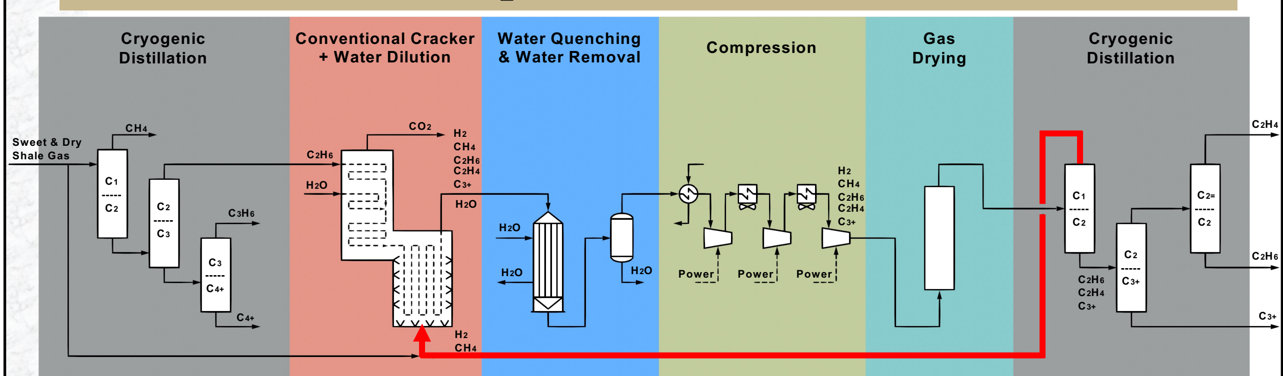
Gas Drying Removes Remaining Water



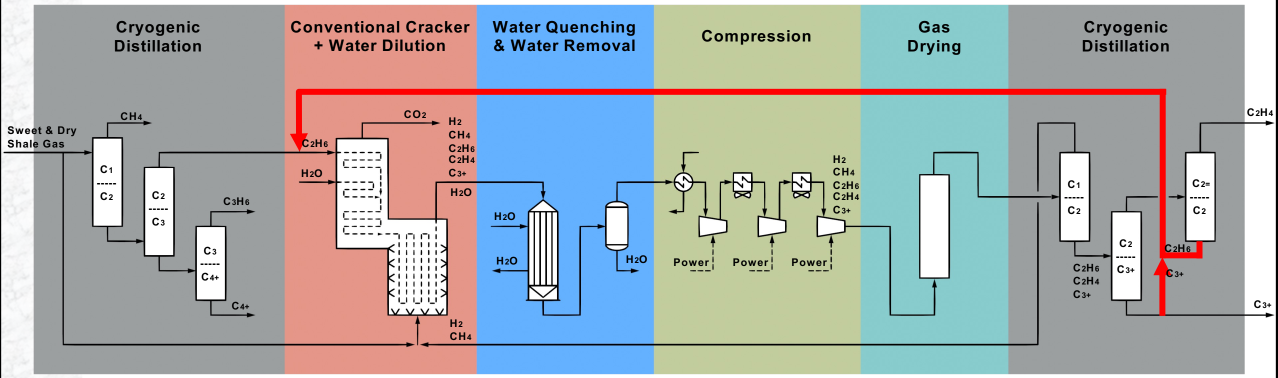
Cryogenic Separation Recovers Ethylene



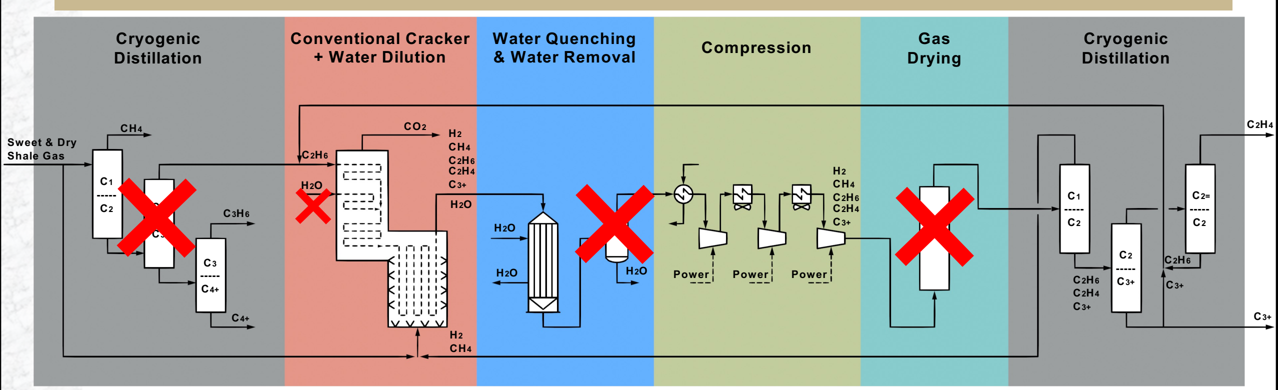
Typically, Methane and H_2 Are Burned In the Cracking Reactor



Unreacted Ethane and C_{3+} Can Be Recycled Back to Reactor

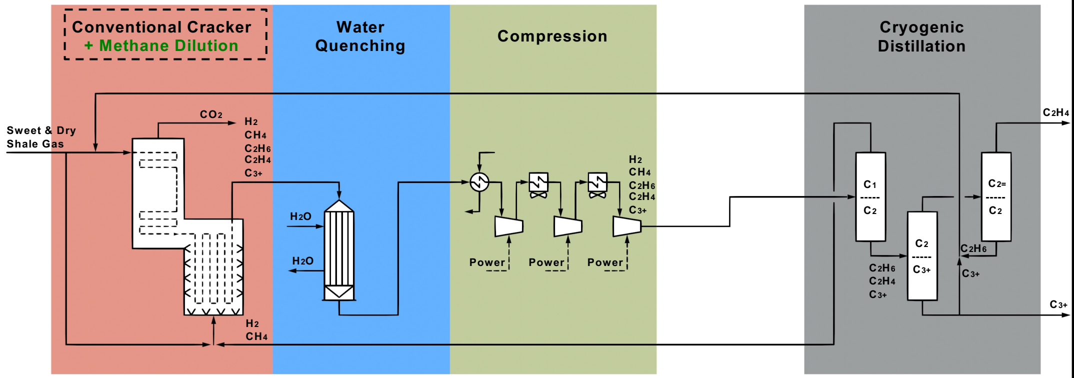


Methane Is Inert - No Initial Separation or Water Dilution Is Needed



Agrawal R., Li, Y. US Patent 11,339,104 B2.
Agrawal, R. and Oladipupo, P. US Patent 11,267,768 B2.
Chen, Z., Li, Y., Oladipupo, W. P., Gil, E. A. R., Sawyer, G., & Agrawal, R. Cell Reports Physical Science, (2021)

Methane Dilution Dramatically Simplifies the Process



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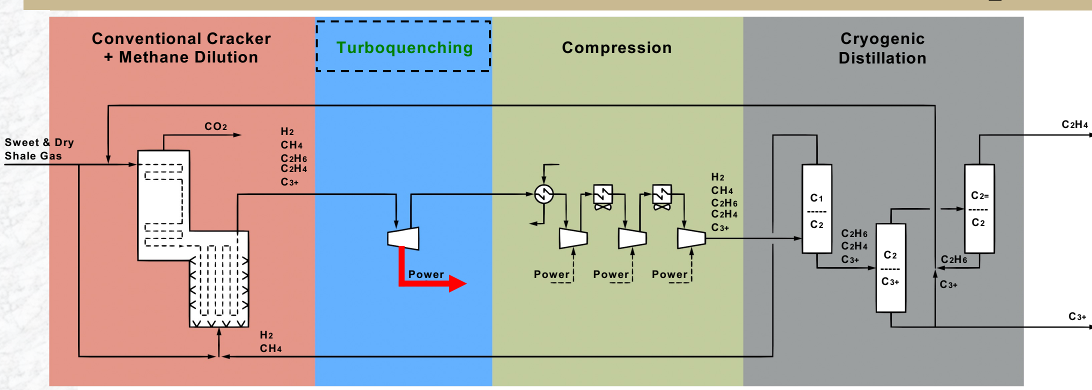
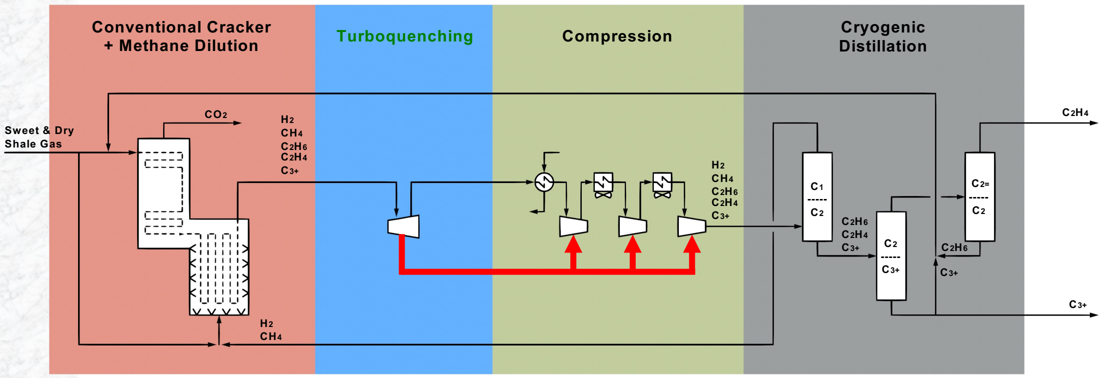
Quenching by Expansion Generates Power & Reduces H_2O Consumption



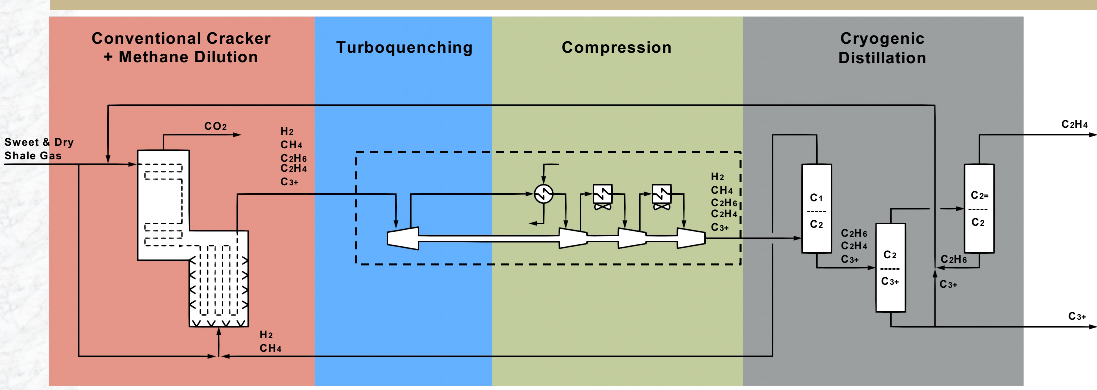
Agrawal, R. and Rodriguez, E. (2022). Turboquenching, U.S. Provisional Patent Application No. 63/347,759.

Power From Turbo-Quenching Can Be Used for Compression



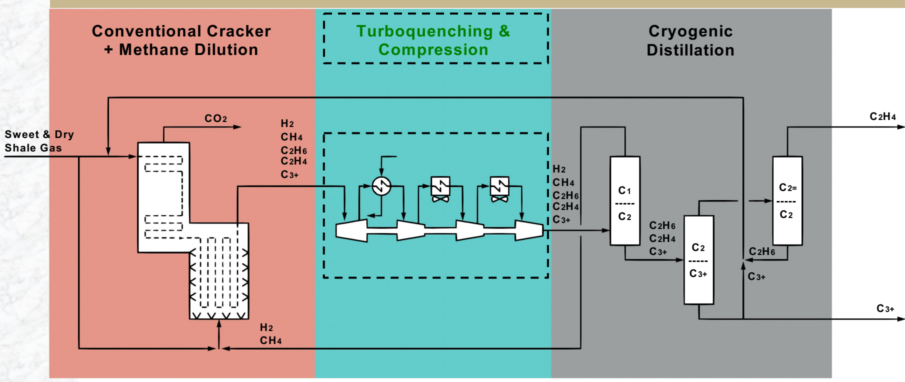
Agrawal, R. and Rodriguez, E. (2022). Turboquenching, U.S. Provisional Patent Application No. 63/347,759.

A Single Shaft Drive Simplifies the Process



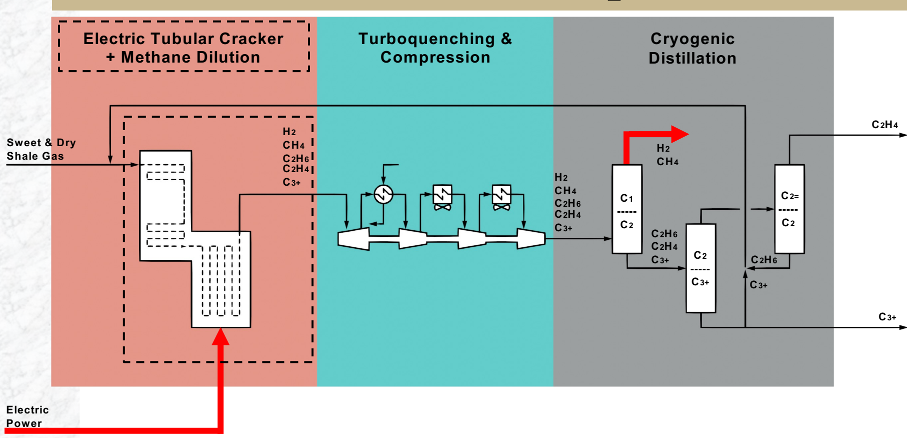
Agrawal, R. and Rodriguez, E. (2022). Turboquenching, U.S. Provisional Patent Application No. 63/347,759.

Turboquenching & Compression Are Combined Into a Single Process



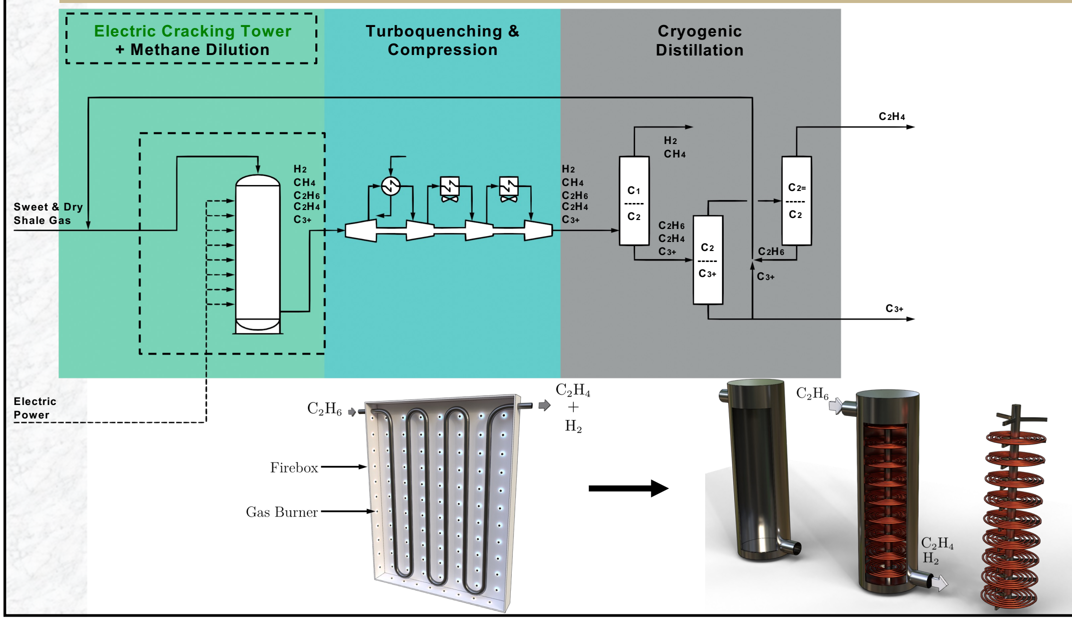
Agrawal, R. and Rodriguez, E. (2022). Turboquenching, U.S. Provisional Patent Application No. 63/347,759.

Electric Cracking Eliminates CO_2



Agrawal, R., Chen, Z., Oladipupo, P. (2023) Electrically Heated Dehydrogenation Process. US11578019B2
Chen, Z., Rodriguez, E., Agrawal, R. Industrial & Engineering Chemistry Research, (2022)

Electric Cracking Towers Enhance Cracking Process



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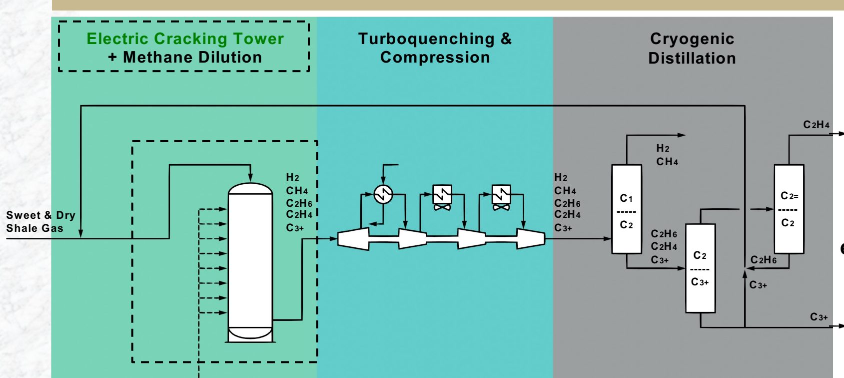


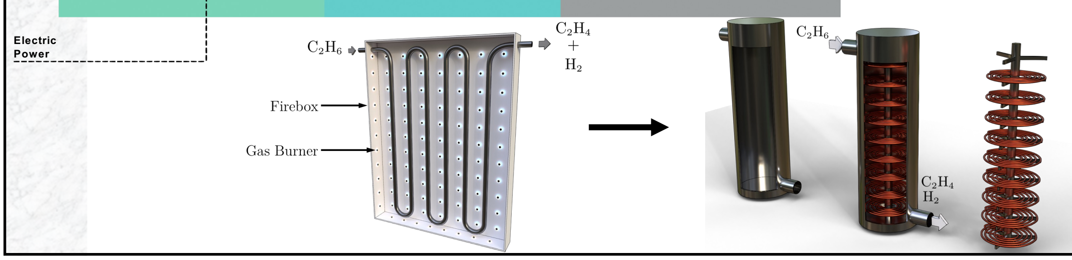
Electric Cracking Towers

- Enable Precise Temperature Control

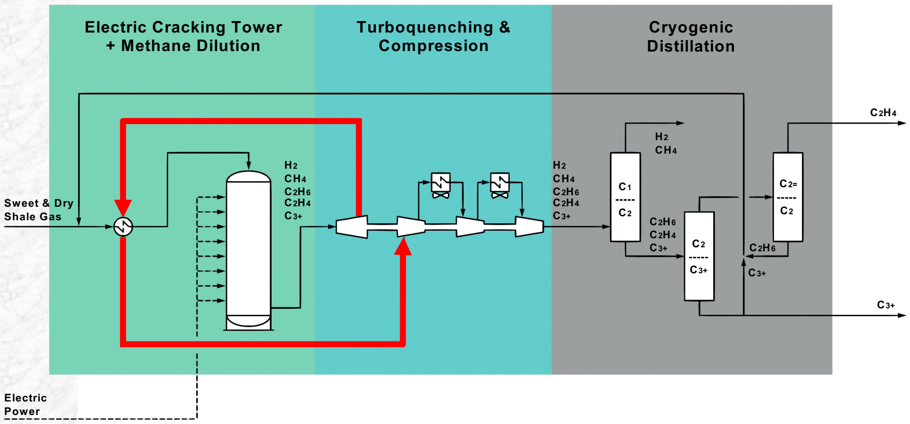
- Eliminate the Need for Parallel Tubes for Scaling

- By tailoring the amount of heat at each element, ethylene yield can be maximized, while undesired side reactions and hot spots reduced

Modular Construction Could Simplify Construction And Maintenance



Heat Integration Reduces External Heating Demand



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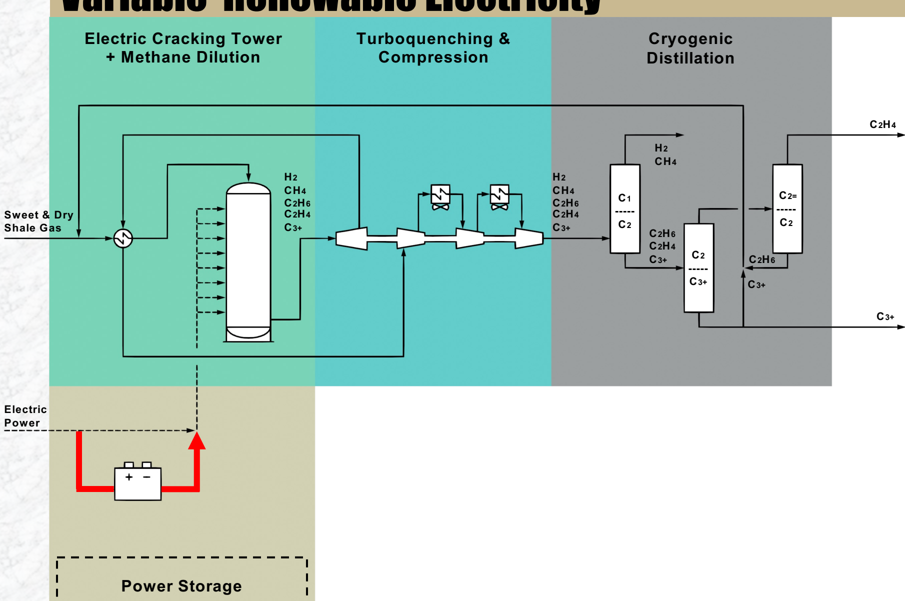
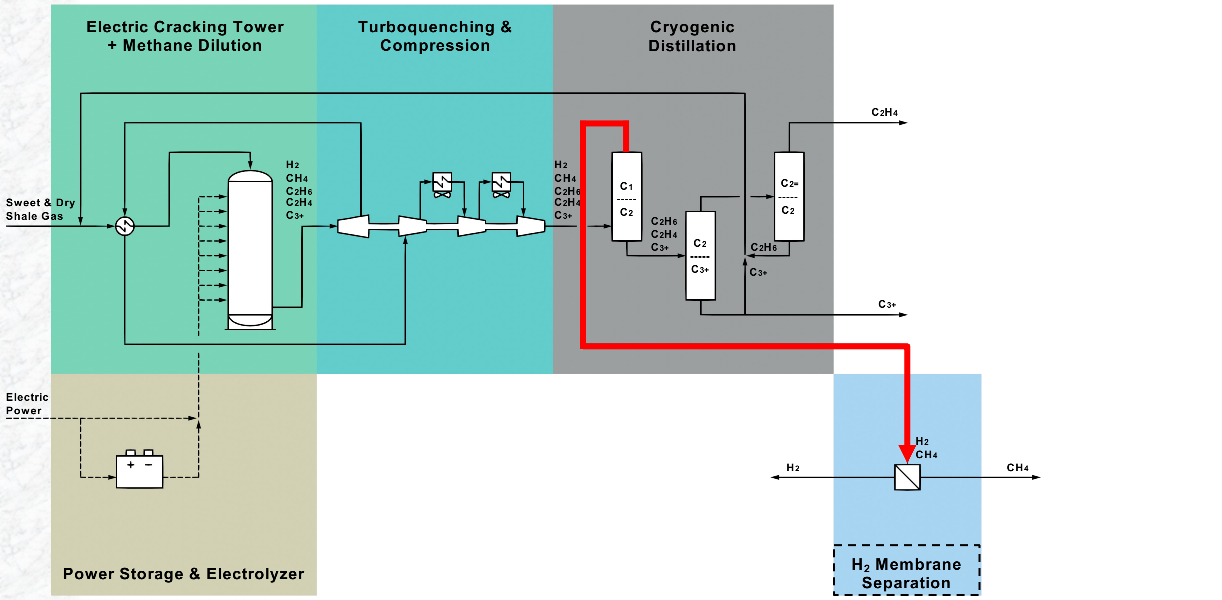
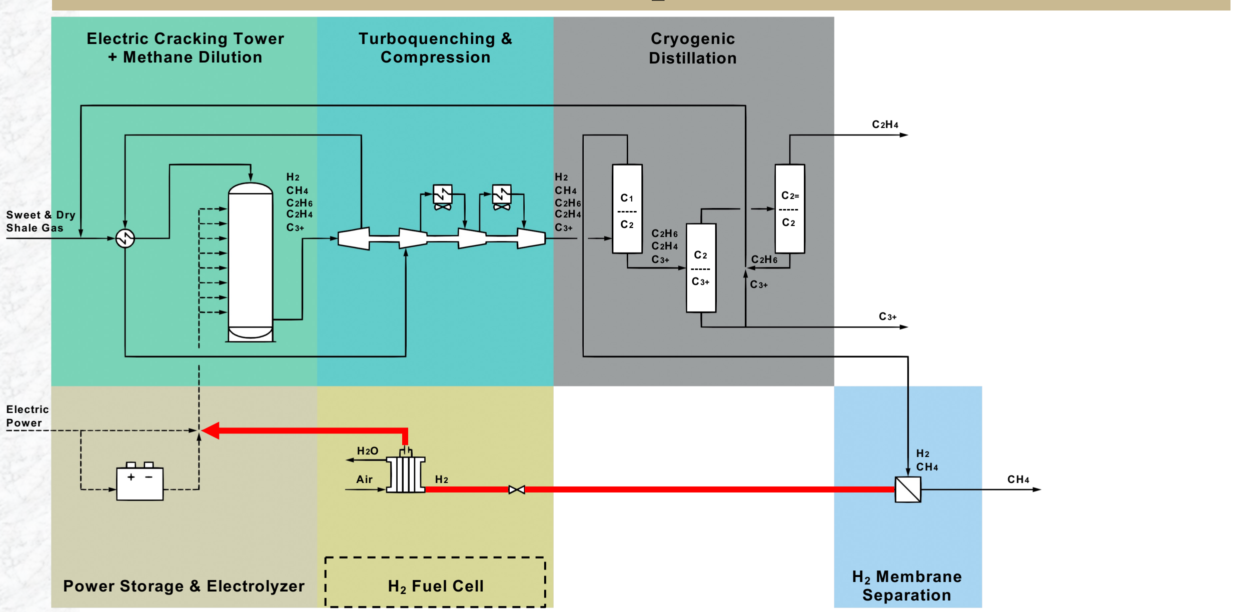
Energy Storage Enables Around-the-clock Operation With Variable Renewable Electricity



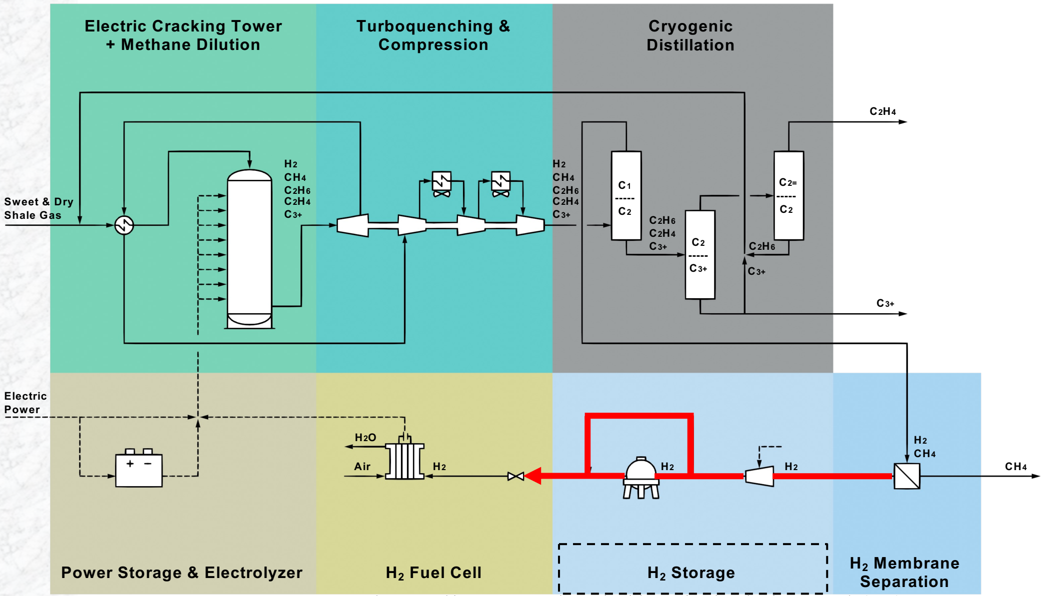
Membrane Separation Recovers Coproduced H_2



A Fuel Cell Uses the Coproduced H_2 to Produce Electricity

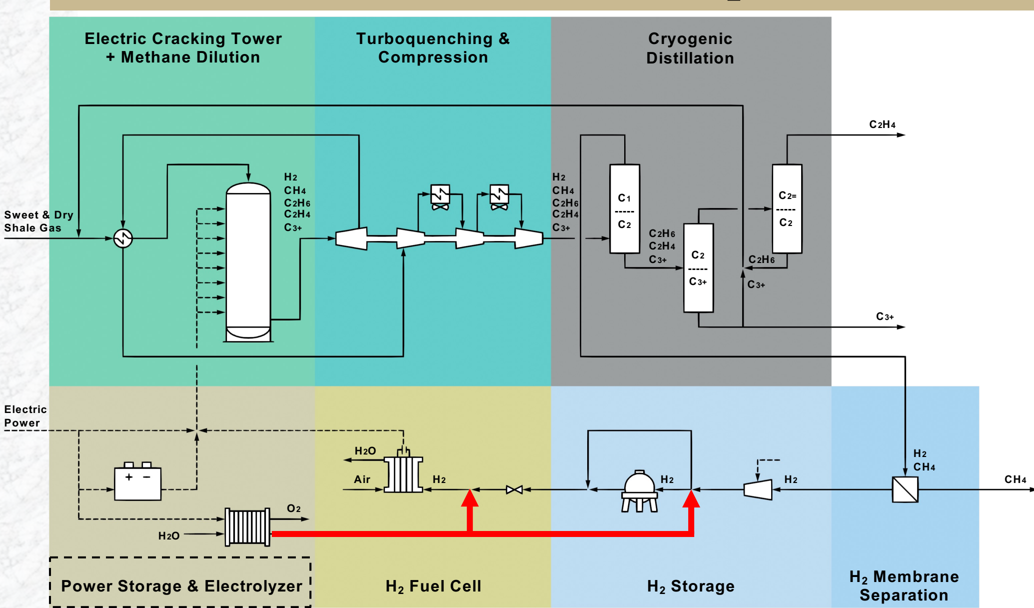


H_2 Can Be Stored As Energy Reserve



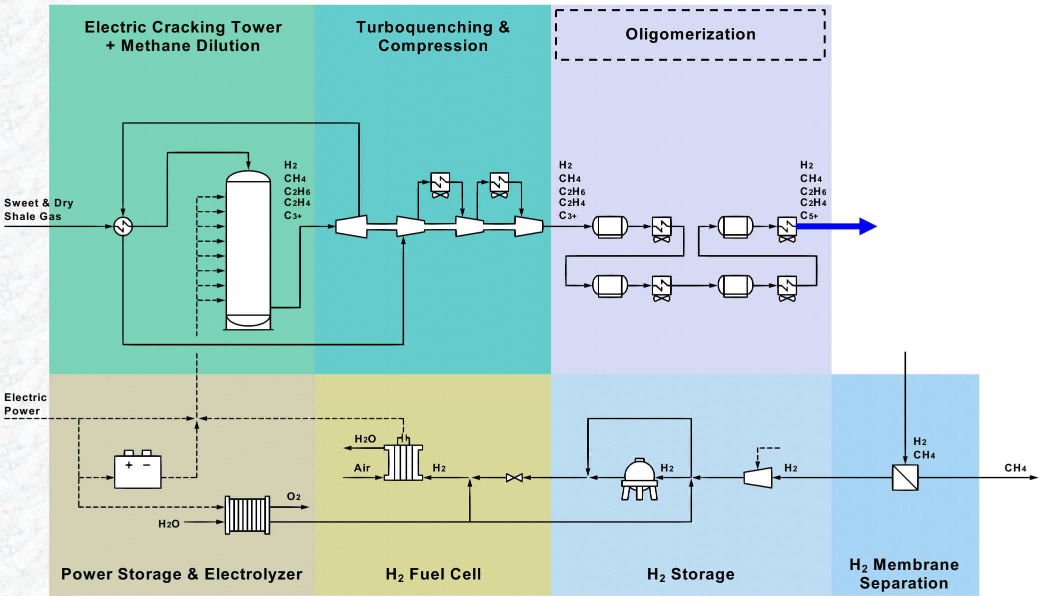
Chen, Z., Rodriguez, E., Agrawal, R. Industrial & Engineering Chemistry Research, (2022)

Electrolyzer Can Generate Additional H_2 During Strategic Hours

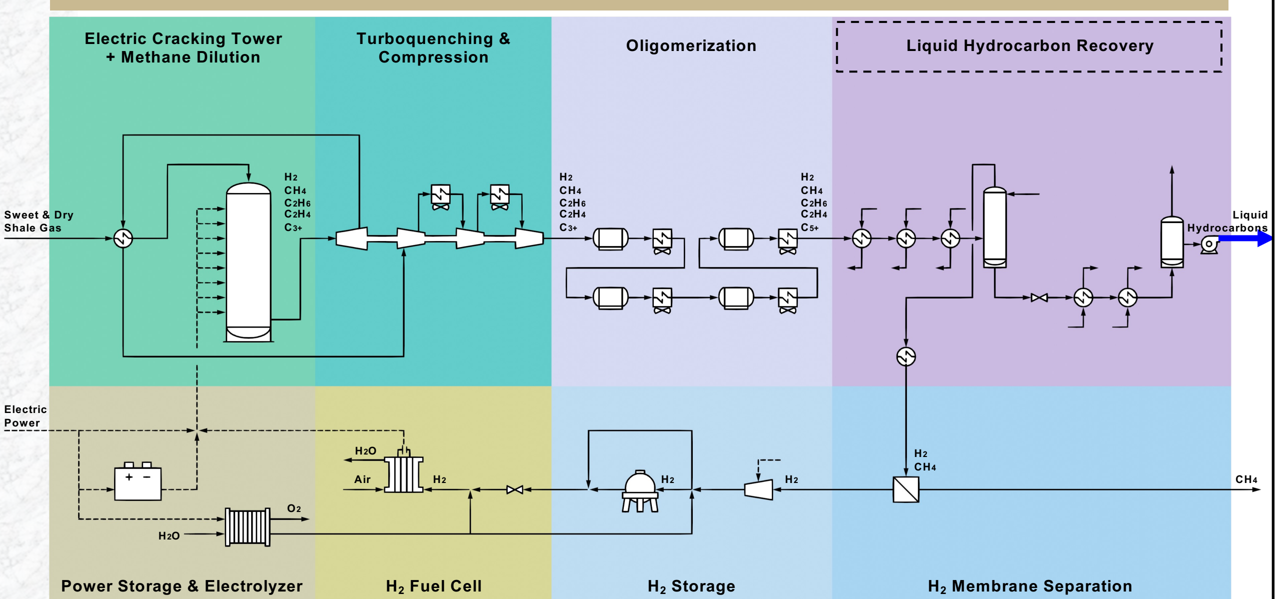


Chen, Z., Rodriguez, E., Agrawal, R. Industrial & Engineering Chemistry Research, (2022)

If Liquid Hydrocarbons Are Desired, An Oligomerization Unit is Used

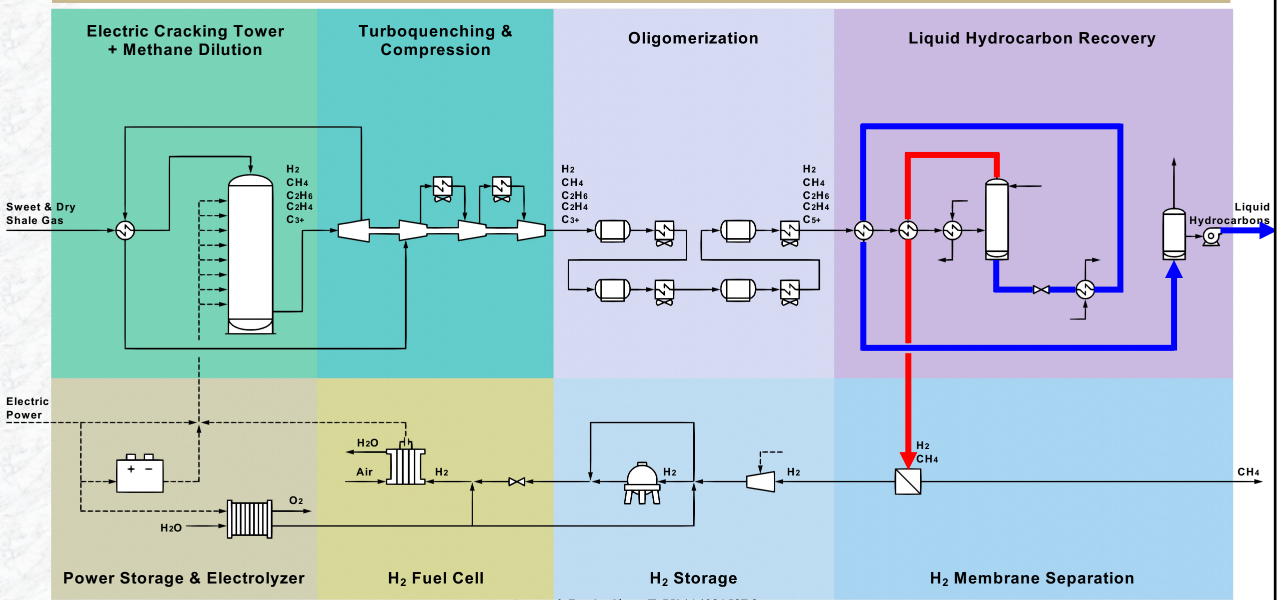


An Absorption-Flash System Recovers Liquid Hydrocarbons



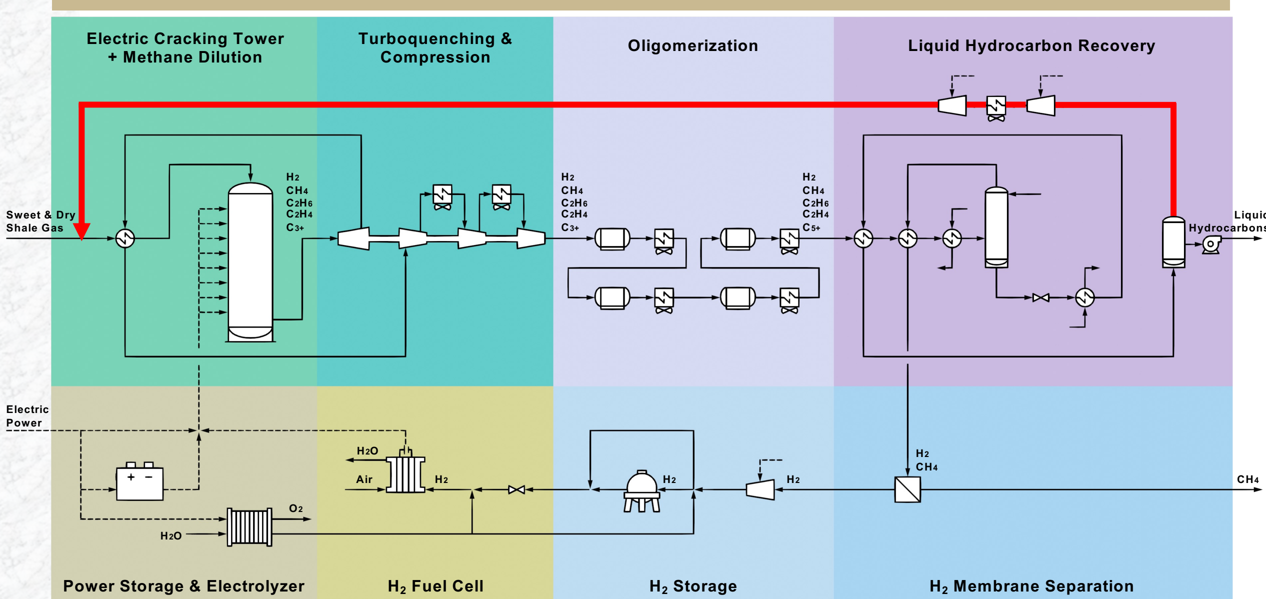
Agrawal, R., &; Chen, Z. US11402153B2.

Heat Integration Reduces Demand for External Utilities



Agrawal, R., &; Chen, Z. US11402153B2.

Unreacted Molecules Are Recycled to the Electric Cracking Tower



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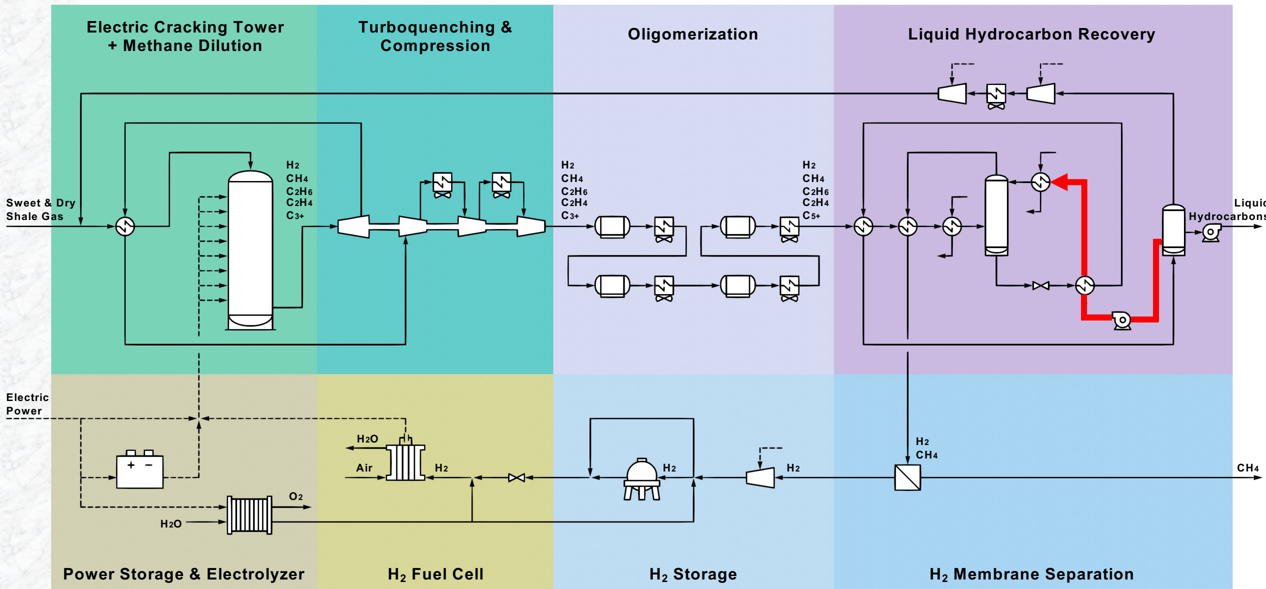
A Portion of the Product Can Be Used As Absorption Agent



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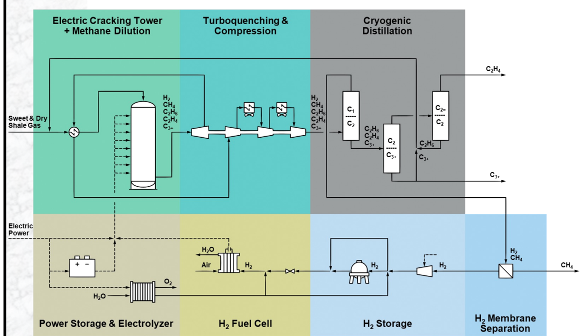
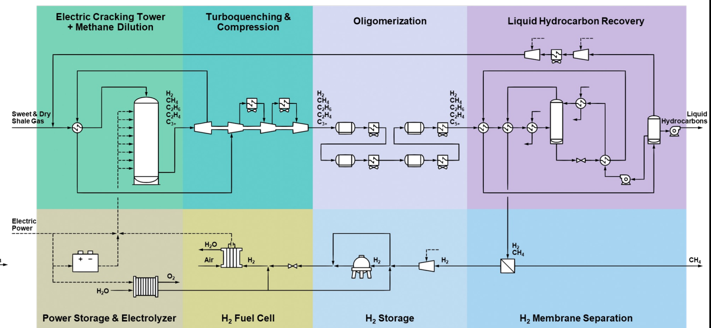
In Summary

Both Ethylene and Liquid Hydrocarbons Productions Are Decarbonized



CISTAR 2023 Process for Modular and Decarbonized Ethylene Production

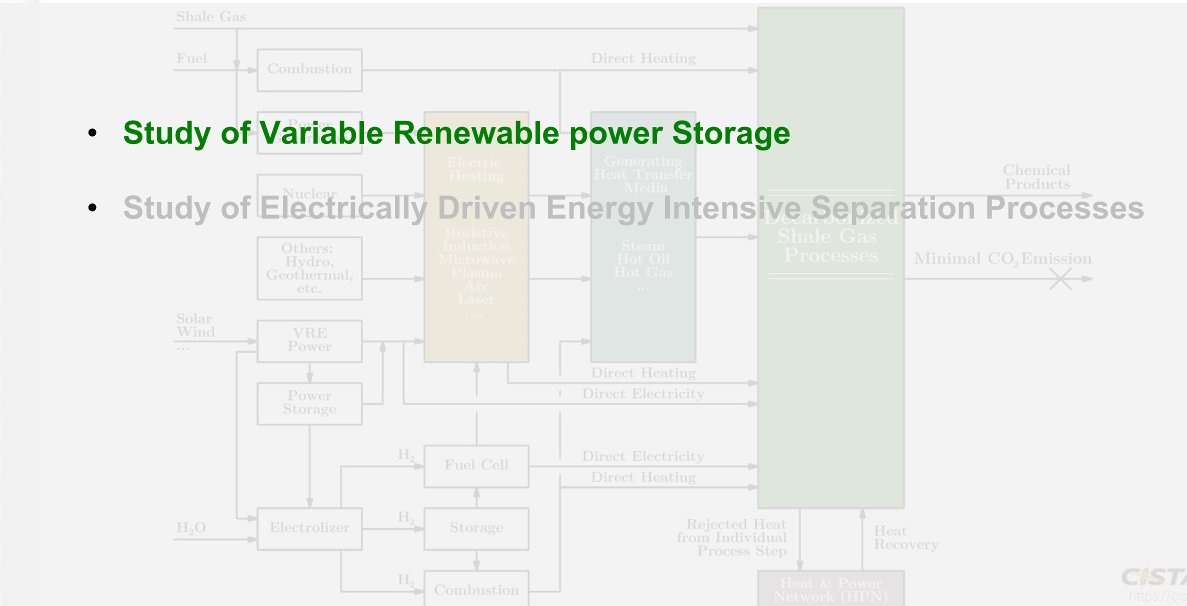


CISTAR 2023 Process for Modular and Decarbonized Liquid Hydrocarbon Production

- Agrawal, Li, US Patent 11,339,104 B2; ●Agrawal, Oladipupo, US Patent 11,267,768 B2.
- Agrawal, Chen, US11402153B2; ● Agrawal, Chen, US11434184B2.
- Agrawal, Chen, Oladipupo, US11578019B2; ● Agrawal, Rodriguez, U.S. Provisional Patent Application No. 63/347,759.

Part 2

We Are Moving Towards Decarbonization of Shale Gas Processes



- **Study of Variable Renewable power Storage**
- Study of Electrically Driven Energy Intensive Separation Processes

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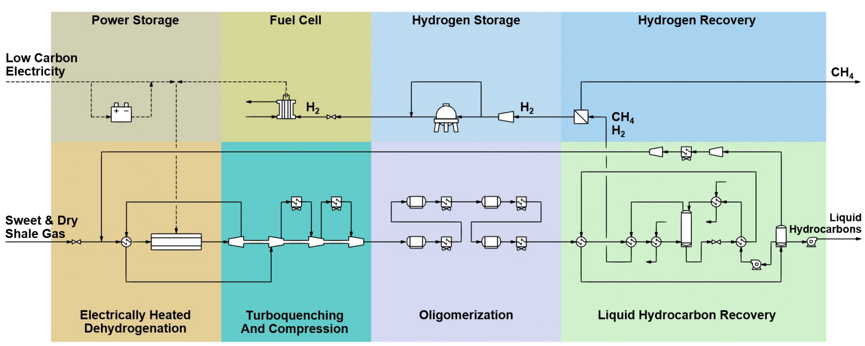
Bakken Field: Energy Storage for Variable PV Power the Average Sunlight Scenario



At Bakken Field, 10 MMSCFD Plant Electricity Requirement: 11.6 MW
Byproduct H_2 can provide 3.33 MW of power

Battery Storage Based on Average Availability: 158.8 MWh

	CH_4	C_2H_6	C_3H_8	C_4H_{10}	C_5H_{12}	CO_2	N_2
Bakken shale gas basin composition (mol%)	57.82	19.98	11.35	3.79	1.26	0.57	5.23

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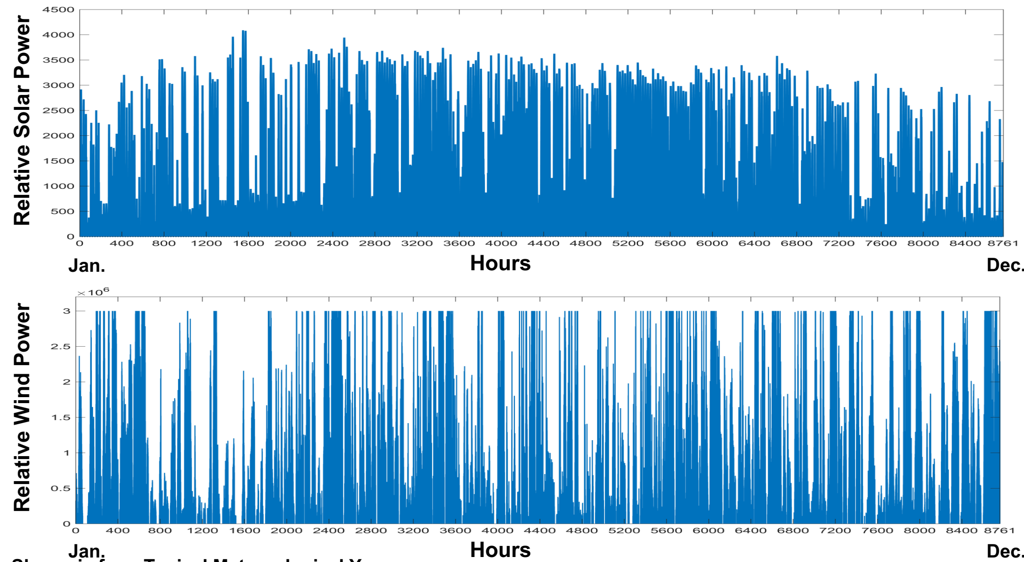
However, Sunlight and Wind Show Diurnal and Seasonal Variability

Bakken Field



Data Shown is for a Typical Meteorological Year

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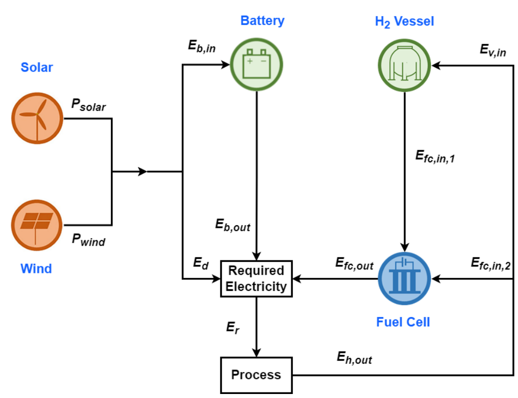
Calculating Storage While Accounting for Variability



Energy Balance Equations are written and storage minimized over the entire year.

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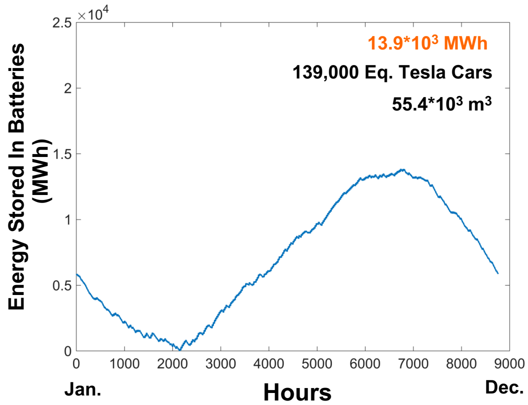
Calculating Storage While Accounting for Variability

Solar Power Only @ Bakken Field

- Annual average solar power = 9.5 MW

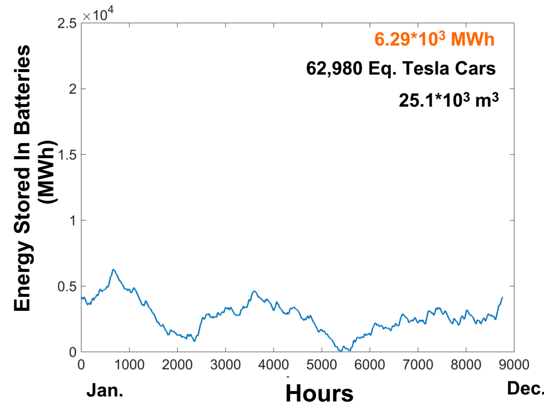
Battery Storage



Wind Power Only @ Bakken Field

- Annual average wind power = 9.1 MW

Battery Storage



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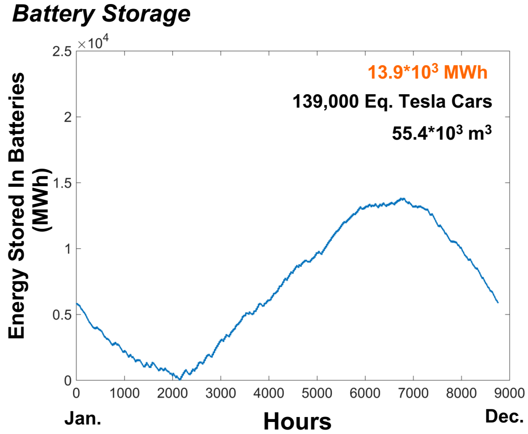

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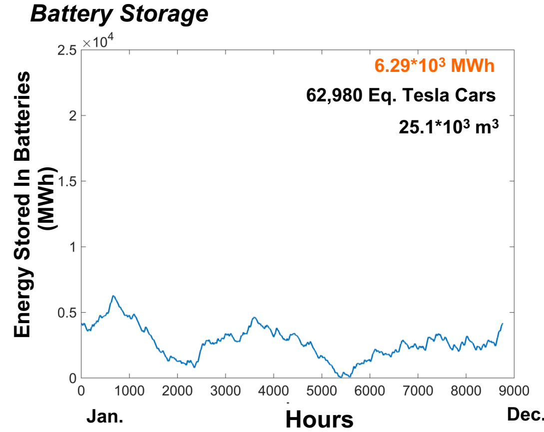
Battery Storage



Actual Battery Storage Is 40 to 90 Times the Average Day Based Battery Storage of 159 MWh

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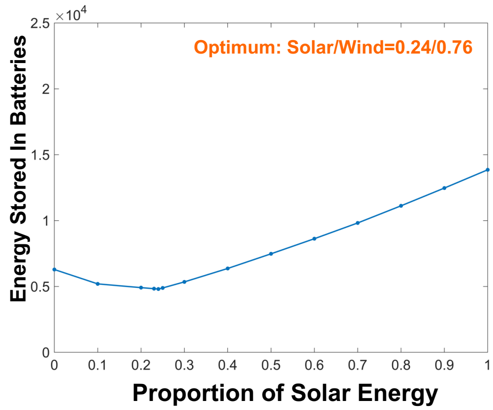
Co-Use of Solar and Wind Reduces Battery Storage

Hybrid Power Combining Solar and Wind Power @ Bakken Field

- At Optimum: Annual average solar power = 2.2 MW; Annual average wind power = 6.8 MW

Battery Storage as Proportion of Solar



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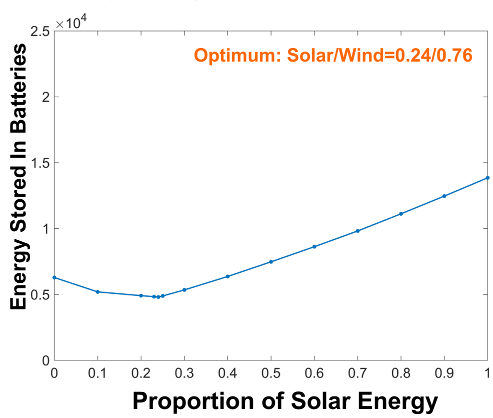
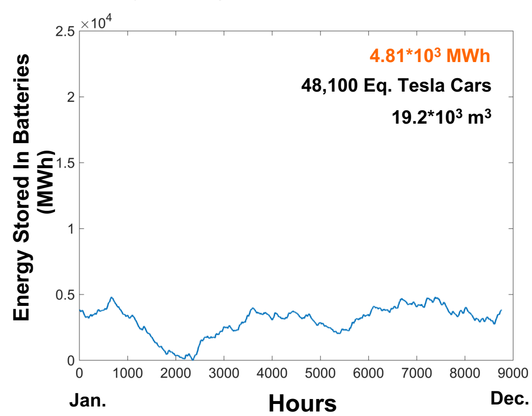


Battery Storage at Optimal Combination



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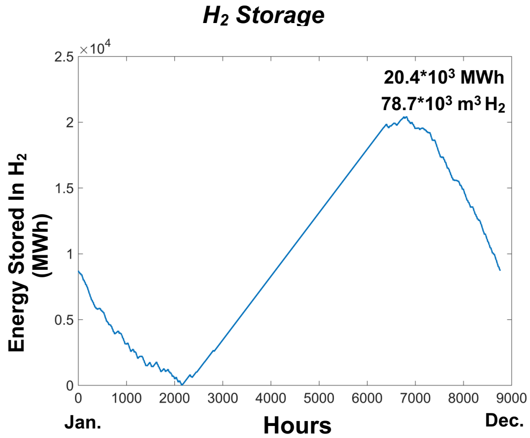
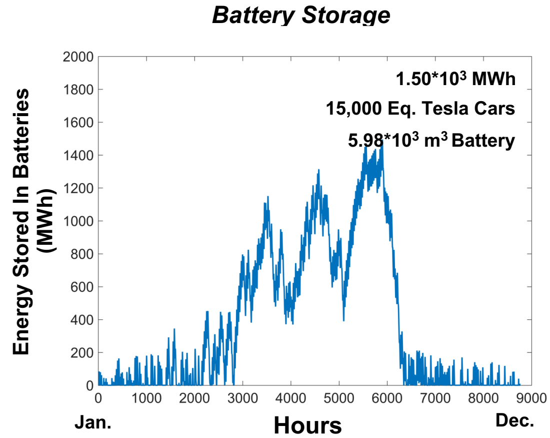
Storage of Co-Product Hydrogen Greatly Reduces Battery Storage

Solar Power @ Bakken Field

- Annual average solar power = 9.6 MW





Hydrogen Storage Greatly Reduces Battery Storage

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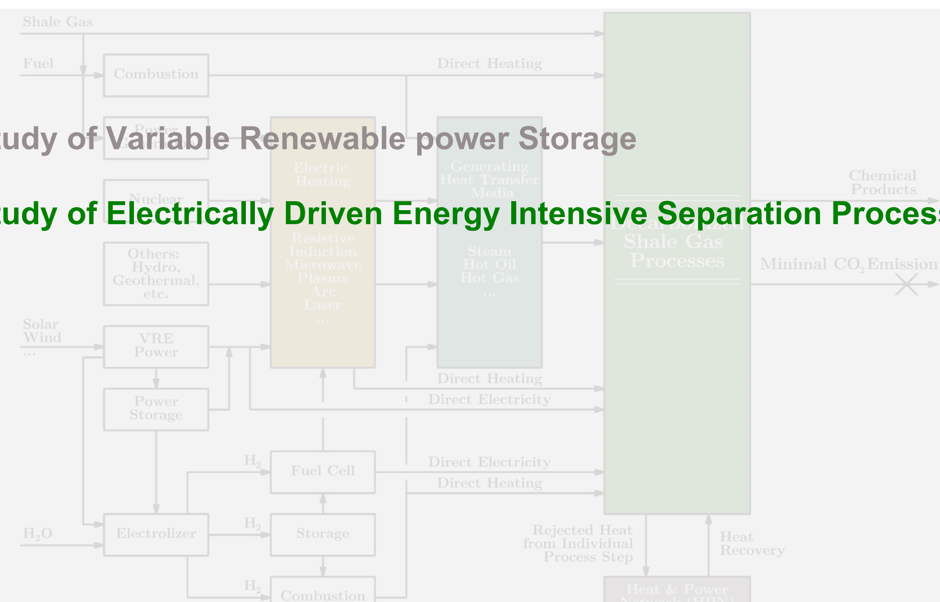
We Are Moving Towards Decarbonization of Shale Gas Processes



- Study of Variable Renewable power Storage
- **Study of Electrically Driven Energy Intensive Separation Processes**

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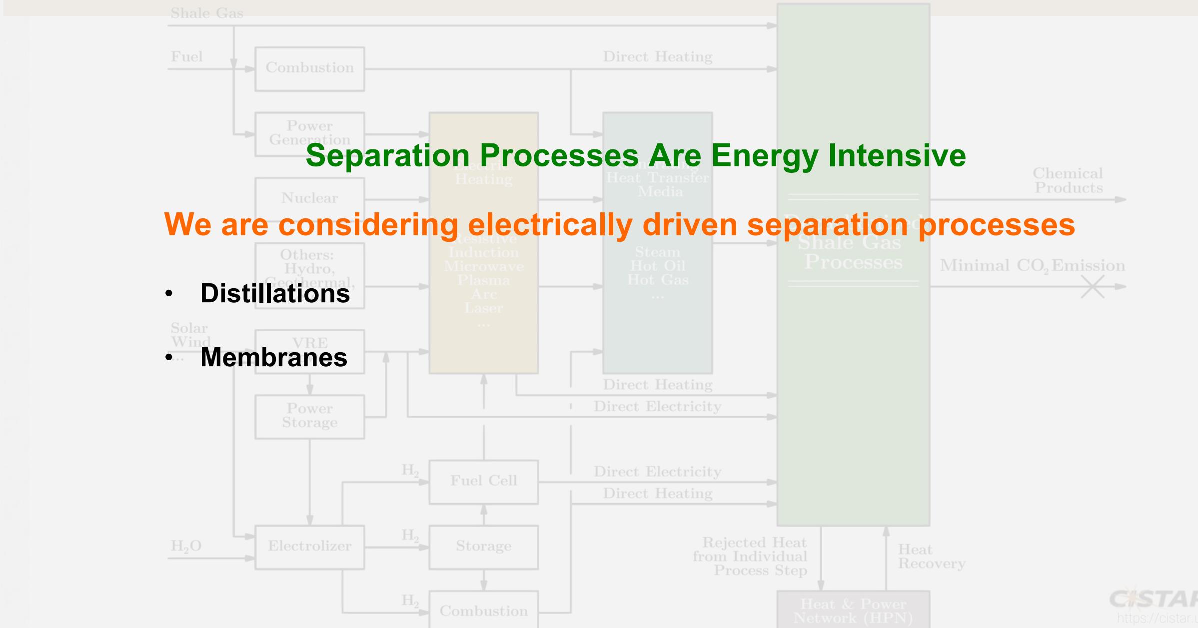
Study of Electrically Driven Energy Intensive Separation Processes



Separation Processes Are Energy Intensive

We are considering electrically driven separation processes

- **Distillations**
- **Membranes**

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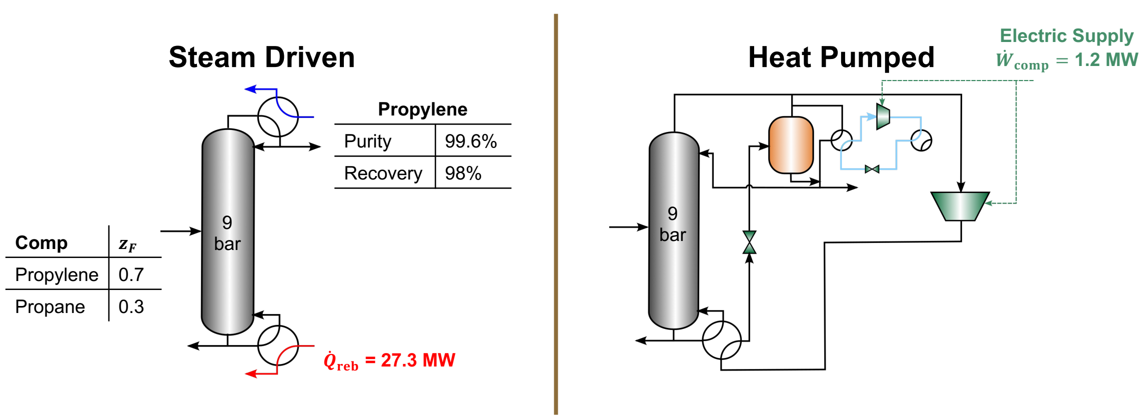
Steam Driven vs Heat Pumped Distillation

A Propylene-Propane Separation Case Study



Feed	α (Rel. Vol)	T_{reb} (C)	T_{cond} (C)	$\dot{Q}_{reb}$ (kW)	$\dot{W}_{comp}$ (kW)
0.7	1.16	22.9	15	27,300	1,225

46

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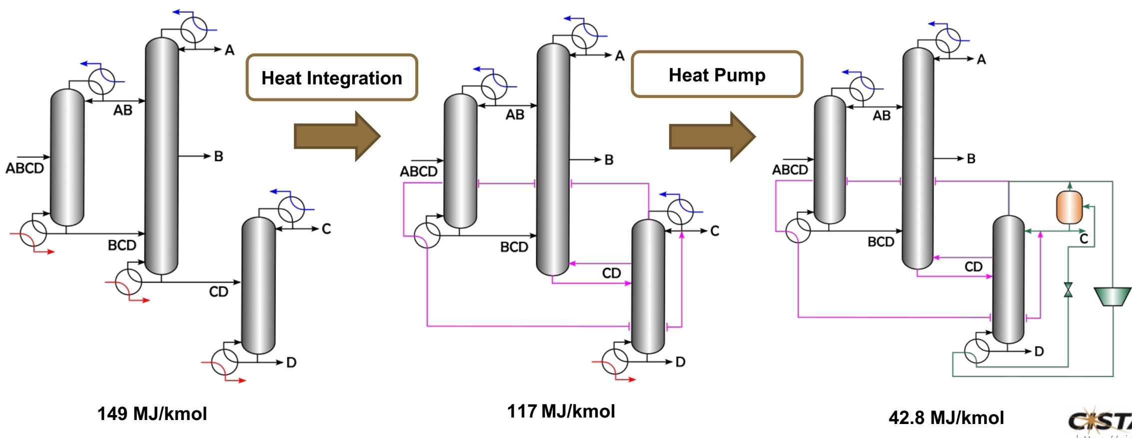
Heat Pumps in Multicomponent Systems

Case Study - Aromatic Separation			
Benzene (A)	**Toluene (B)**	**P-Xylene (C)**	**O-Xylene (D)**
55%	15%	15%	15%



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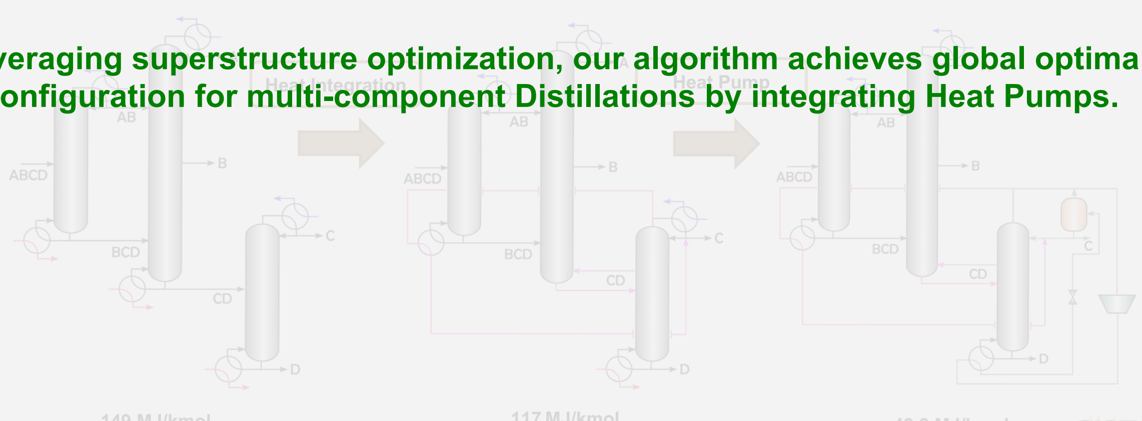
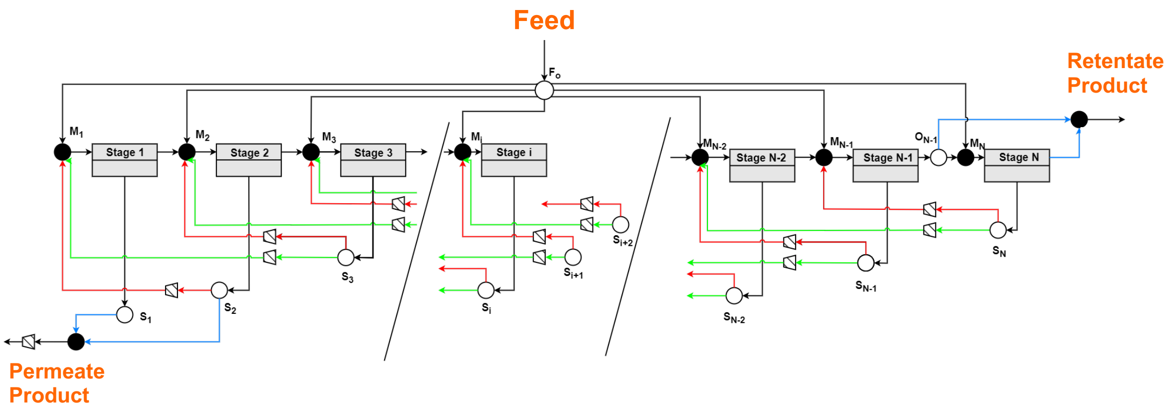
Heat Pumps in Multicomponent Systems

Case Study - Aromatic Separation			
Benzene (A)	Toluene (B)	P-Xylene (C)	O-Xylene (D)
55%	15%	15%	15%

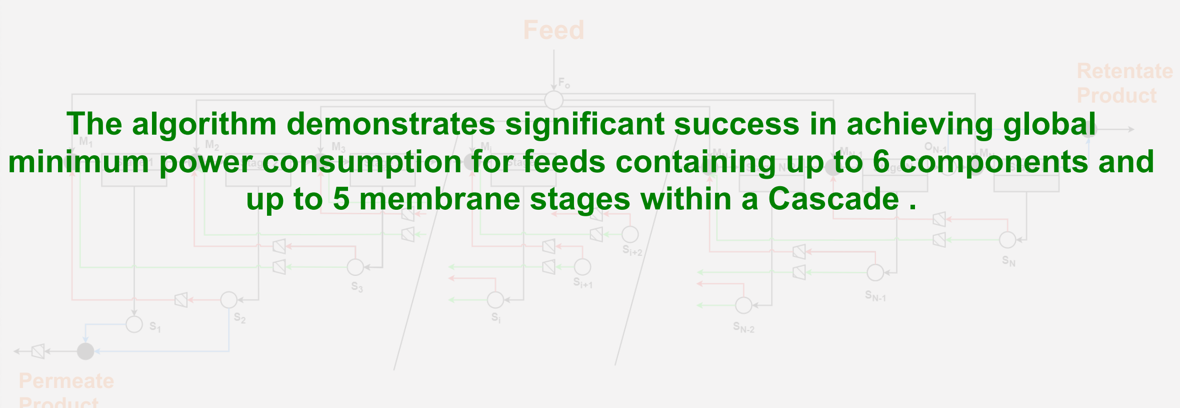
Leveraging superstructure optimization, our algorithm achieves global optimal configuration for multi-component Distillations by integrating Heat Pumps.



Global Optimization Of Multicomponent Membrane Cascade Power and The Overall Cost



Global Optimization Of Multicomponent Membrane Cascade Power and The Overall Cost

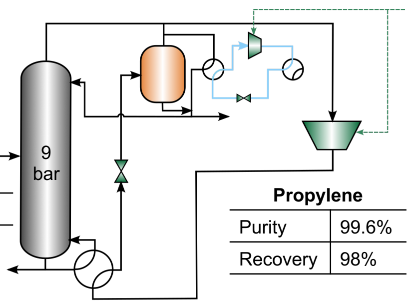


The algorithm demonstrates significant success in achieving global minimum power consumption for feeds containing up to 6 components and up to 5 membrane stages within a Cascade .

Heat Pumped Distillations Can Be Compared To Membrane separations

A Propylene-Propane Separation Case Study

Heat Pumped Distillation

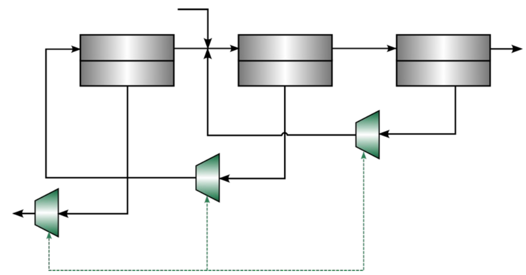


Comp	z_F
Propylene	0.7
Propane	0.3

Propylene	
Purity	99.6%
Recovery	98%

Electric Supply
$\dot{W}_{\text{comp}} = 1.2$ MW

Membrane Cascade



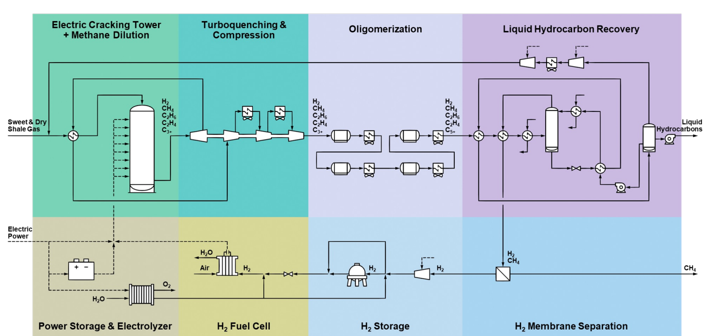
Permselectivity = 250

Electric Supply
$\dot{W}_{\text{comp}} = 2.4$ MW

CISTAR https://cistar.us/

In Summary

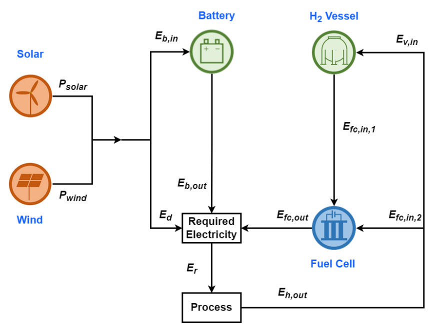
- **Created simplified plant flowsheets to produce alkenes and liquid products from shale gas.**



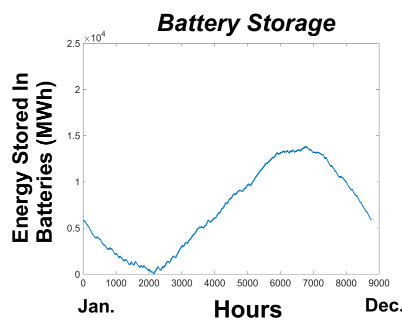
CISTAR https://cistar.us/

In Summary

- **Developed global optimization tools for renewable electricity-driven shale gas processing plants for decarbonization.**



Solar Power Only @ Bakken Field



CISTAR
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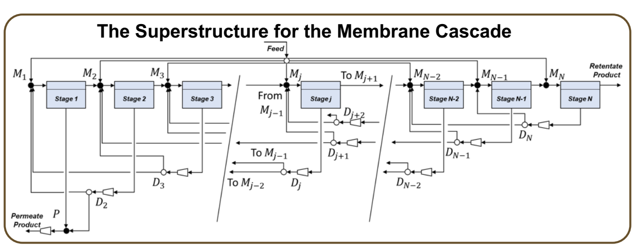
In Summary

- **Developed global optimization algorithm for binary and multicomponent membrane cascade power and the overall cost**



CISTAR
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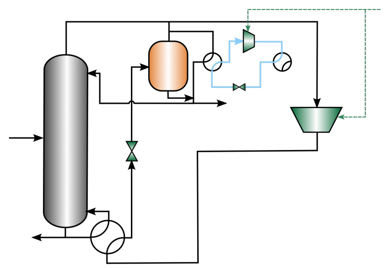
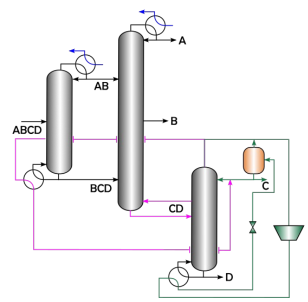
In Summary

- **Developing heat pumped distillation optimization methods for both binary and multicomponent distillations.**

Heat Pumped





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THANK YOU

QUESTIONS?

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