CO_2 Capture Systems and Opportunities for Process Intensification

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Timeline of Carbon Capture Research

1990 | **1995** | **2000** | **2005** | **2010** | **2015** | **2020**

1992
First International Conference on Carbon Dioxide Removal (ICCDR-1)

1993
DOE/MIT prioritize research needs for CO_2 capture and sequestration; first gen capture tech for PCC is aqueous amines

1997
NETL Carbon Capture Storage Program initiated with $1mil

2003
DOE/NETL initiate Regional Carbon Sequestration Partnership (RCSP)

2007
10 year anniversary of CCS program, which has grown to $100M

2009
NETL announces 12 large-scale capture projects; First National Carbon Capture Center (NCCC) opens led by DOE/NETL and Southern Company Services

2011
DOE/NETL publishes Carbon Dioxide Capture and Storage RD&D Roadmap

2012
$80-100/ton CO_2
Breakthrough CCS project at Air Products and Chemicals begins capturing CO_2 and sending to oilfield for EOR; Initial release of CCSI Toolset

2014
Sask Power's Boundary Dam commissioned

2016
$60/ton CO_2

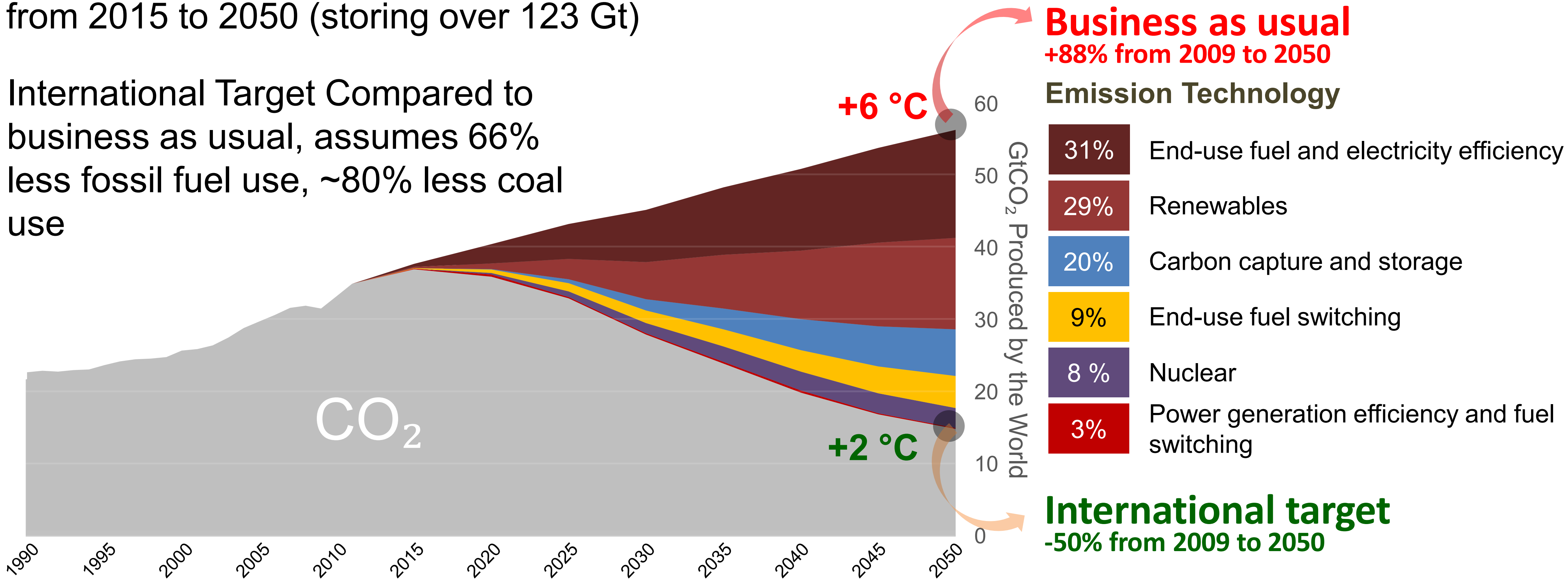
2017
Petra Nova carbon emissions reduction system begins operation

2020
$45/ton CO_2
Large scale pilot testing (10-25 Mwe) for 2nd gen tech

2025: 2nd gen tech target $40/ton CO_2
2030: Transformational tech target $30/ton CO_2

Need for CO_2 Capture

- CCS achieves 20% of cumulative reductions from 2015 to 2050 (storing over 123 Gt)
- International Target Compared to business as usual, assumes 66% less fossil fuel use, ~80% less coal use



- Limits to efficiency gains, fuel switching reductions and CCS only option for some industrial sectors
- Delaying or abandoning CCS would increase power sector compliance cost by 40+%

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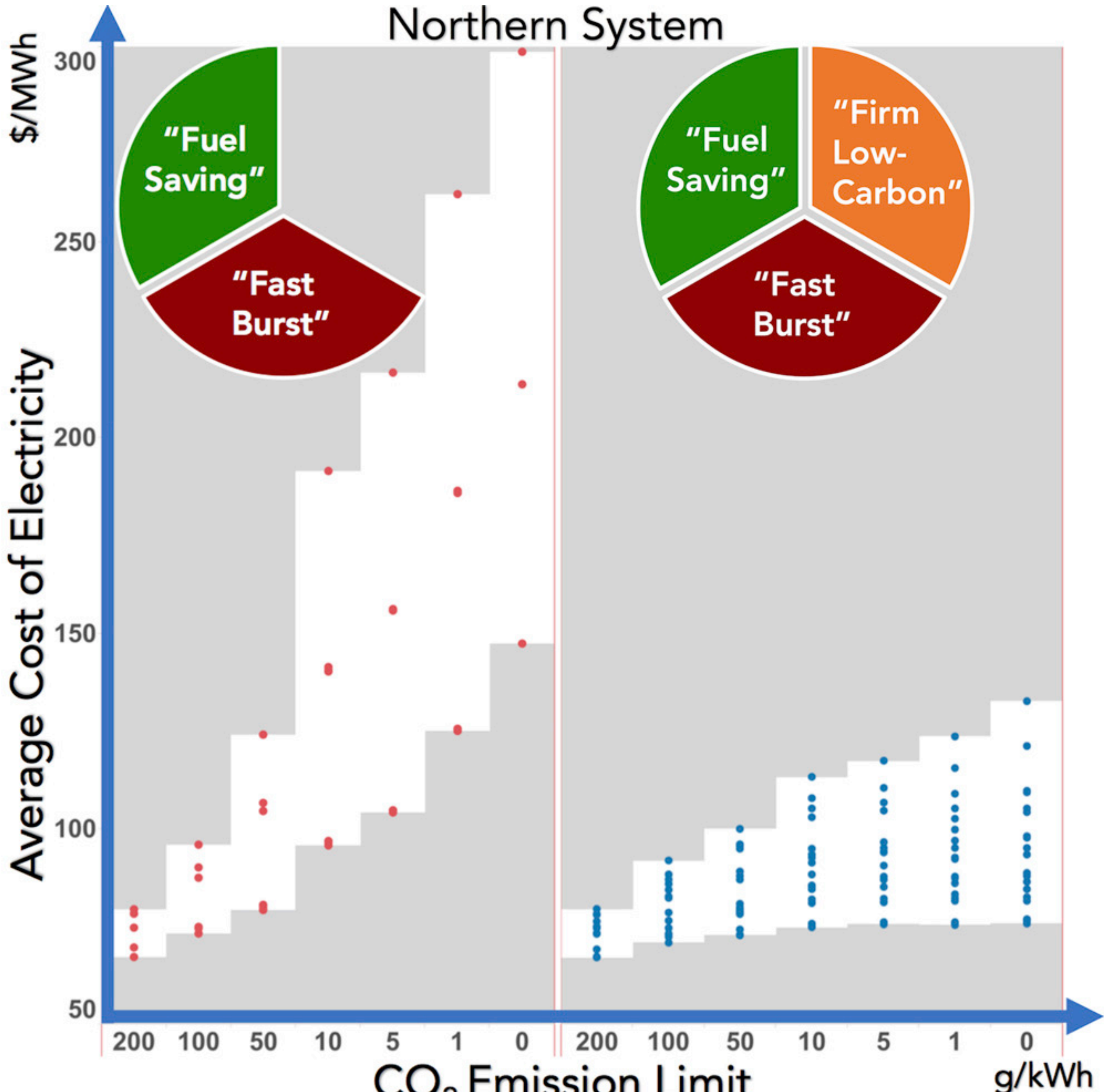
*Data based on International Energy Agency, Energy Technology Perspectives 2015 - www.iea.org/etp2015

Dispatchable Power with Capture Lowers Costs



- Solar, wind
- Storage, demand response
- Nuclear, CCS, geothermal

"Firm low-carbon" resources like CCS and nuclear lower the cost of deep decarbonization by 10-62%

Sepulveda, et al., Joule (2018)
https://doi.org/10.1016/j.joule.2018.08.006

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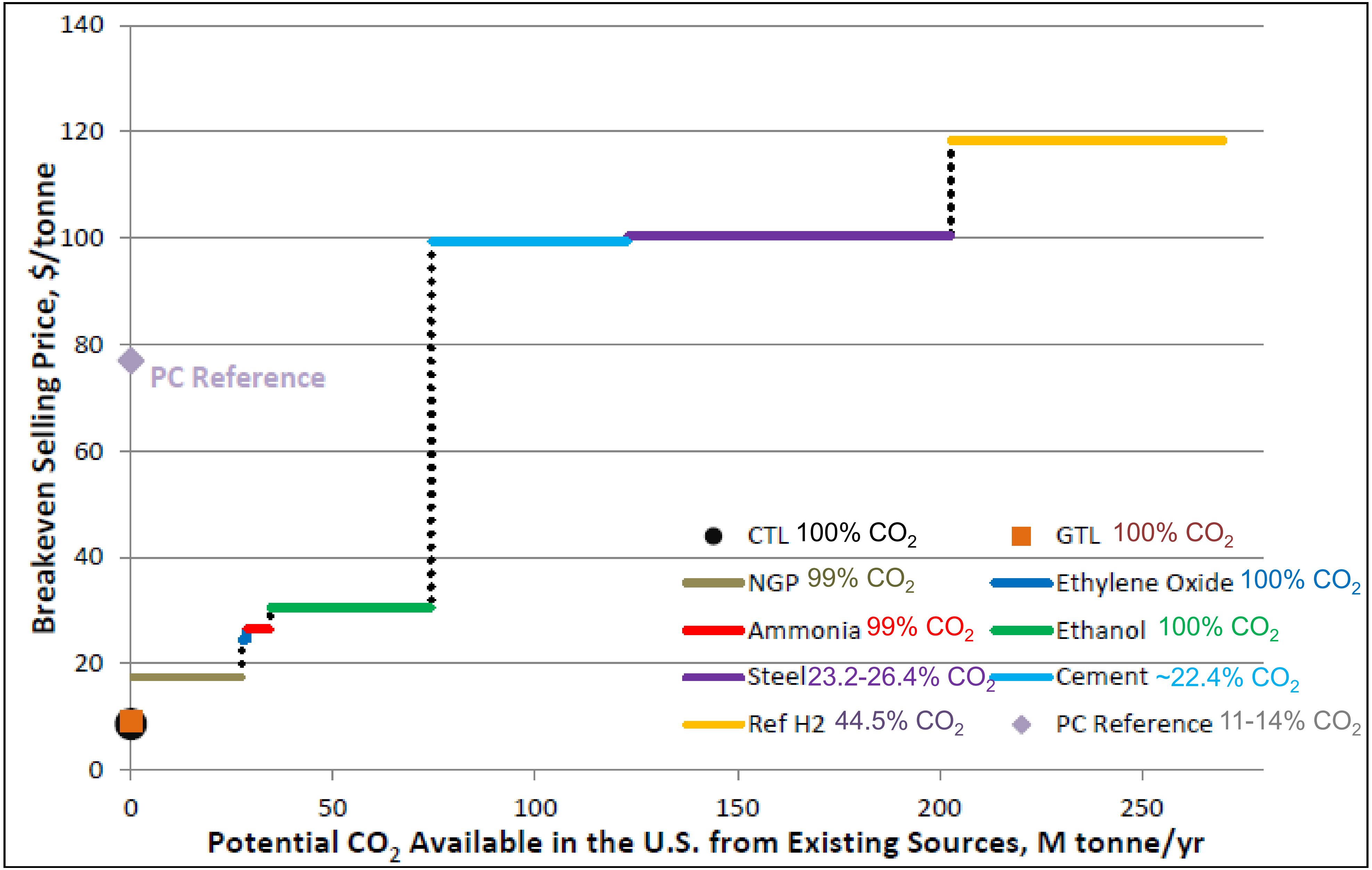

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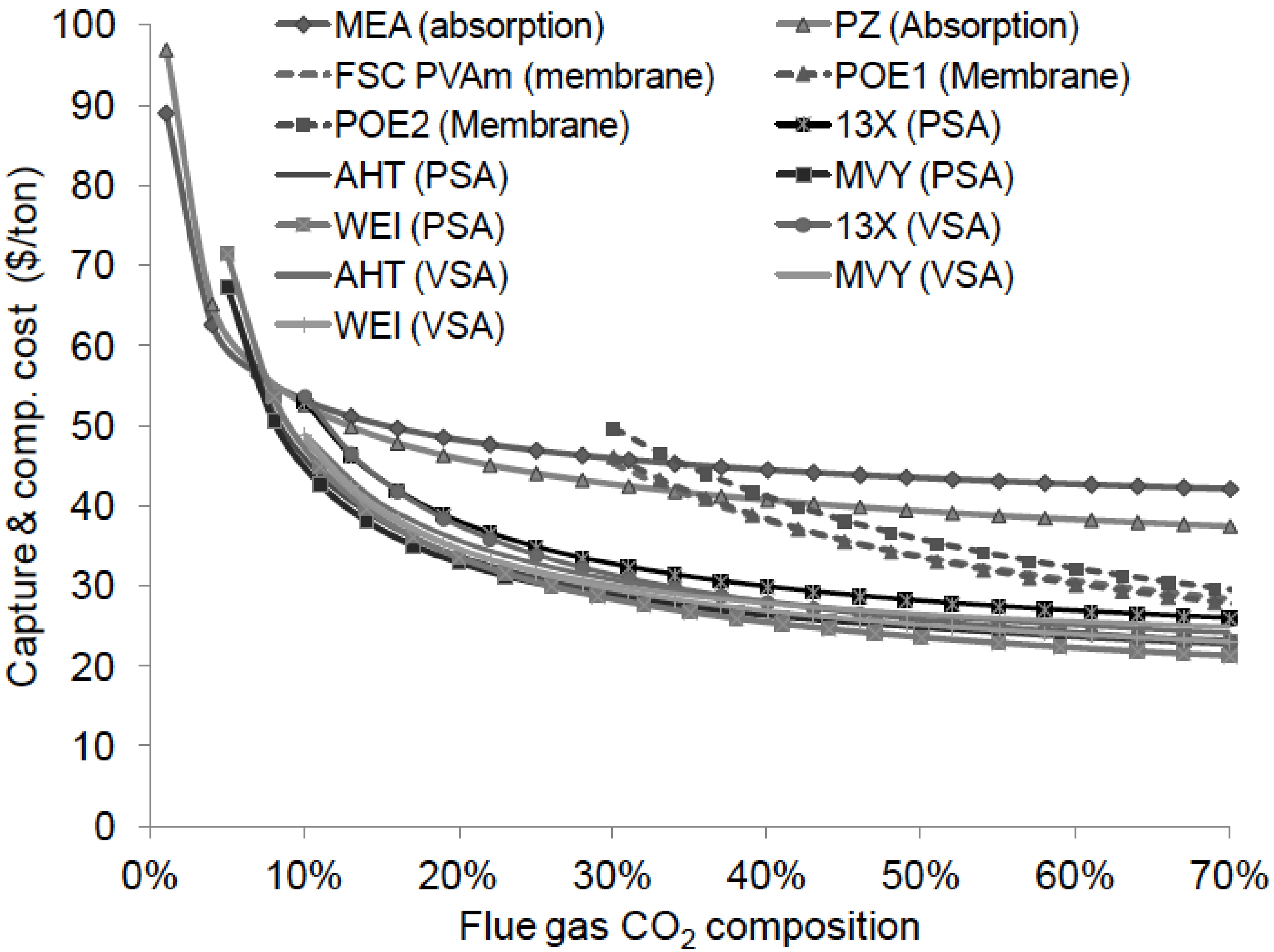
"Cost of Capturing CO_2 from Industrial Sources" January 2014

https://www.netl.doe.gov/research/energy-analysis/search-publications/vuedetails?id=1836

Cost Variability for Technology & CO_2 Concentration



Hasan, First, Boukouvala, Floudas. Proceedings of the 8th International Conference on Foundations of Computer-Aided Process Design – FOCAPD 2014, July 13-17, 2014.

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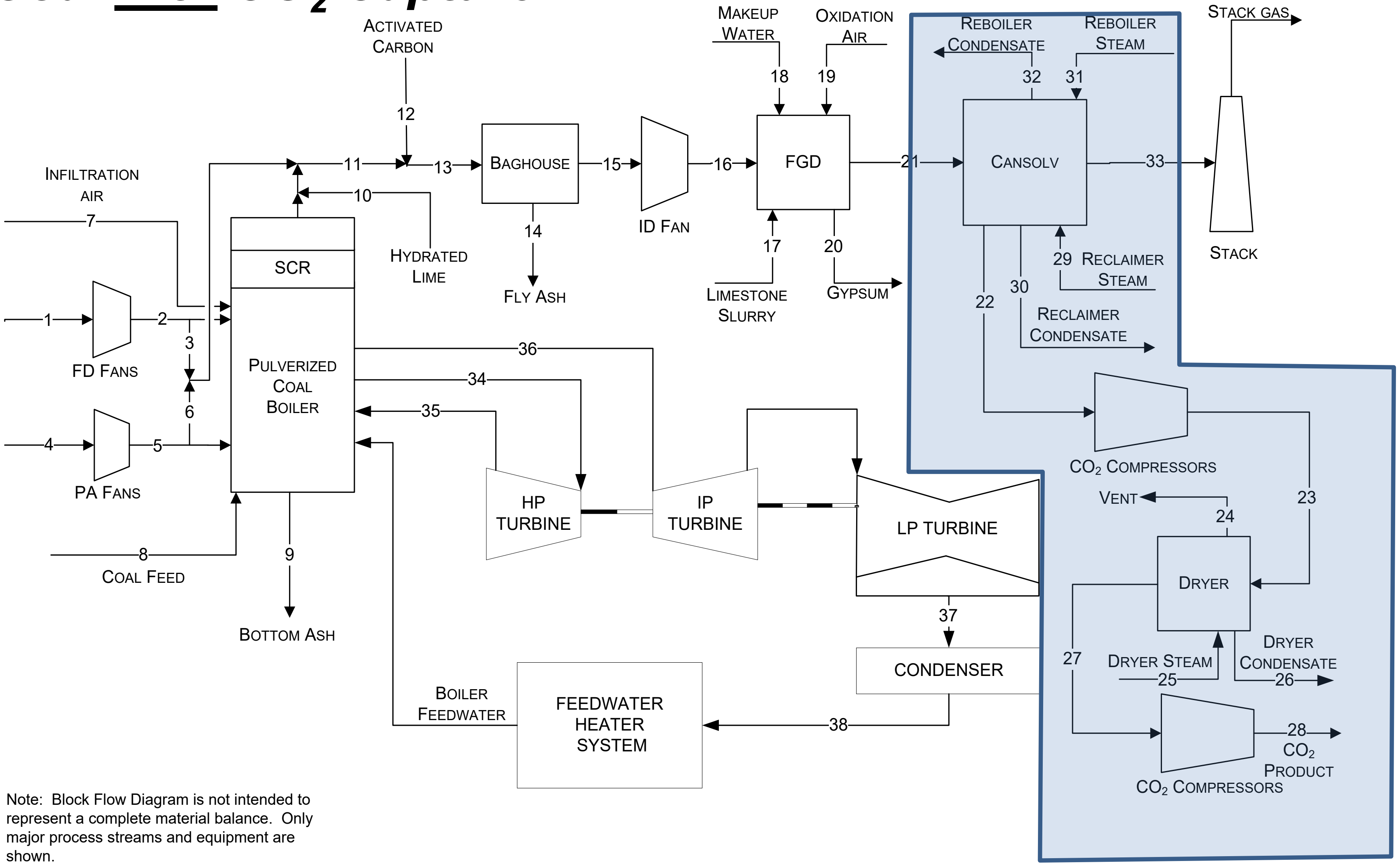
Supercritical Pulverized Coal Power Plant

Conventional Coal <u>with</u> CO_2 Capture



Note: Block Flow Diagram is not intended to represent a complete material balance. Only major process streams and equipment are shown.

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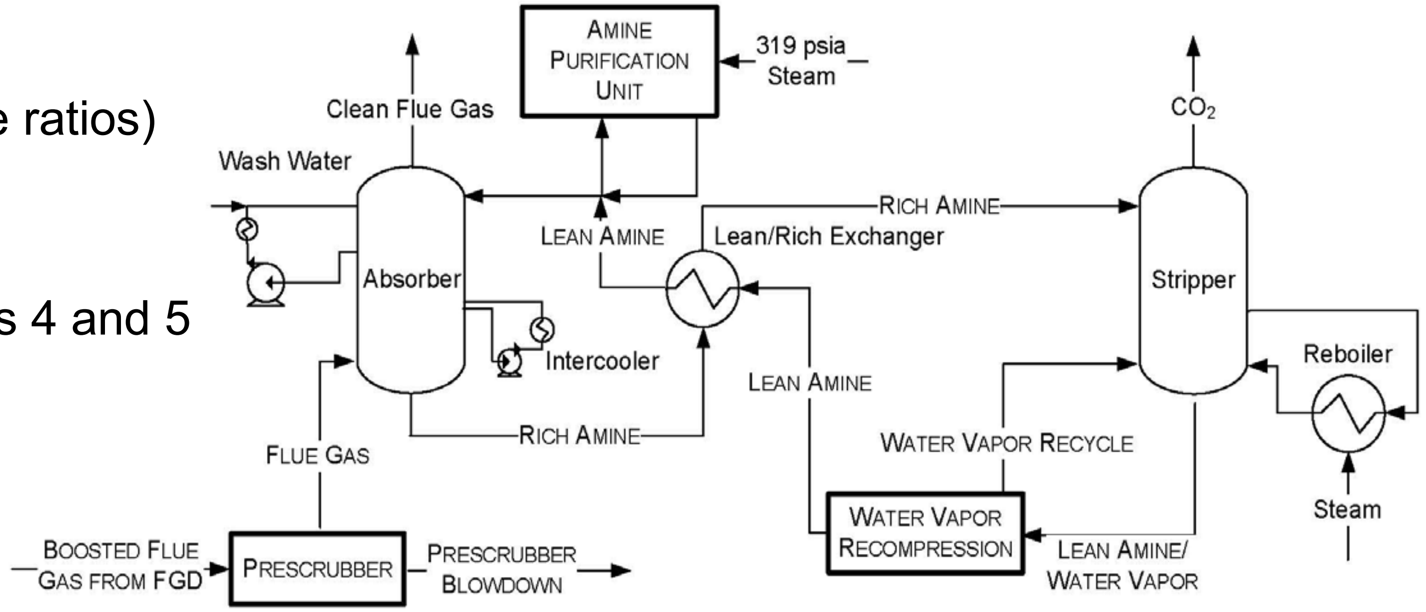
Supercritical Pulverized Coal Power Plant

- Pre-treatment
  - Lowers SO_x to ~ 1 ppmv from ~40 ppmv out of FGD
- Cansolv CO_2 Capture Process Details
  - 90 % CO_2 capture
  - Steam extraction from crossover pipe between IP and LP sections of steam turbine
  - Product CO_2 ~ 30 psia
- CO_2 Compression System
  - CO_2 compressed to 2,200 psig
  - 8 stages (2.23 to 1.48 stage pressure ratios)
  - Intercooling in each stage
    - Water knockout in first 3 stages
  - TEG dehydration unit between stages 4 and 5
    - 300 ppmw H_2O in CO_2 product



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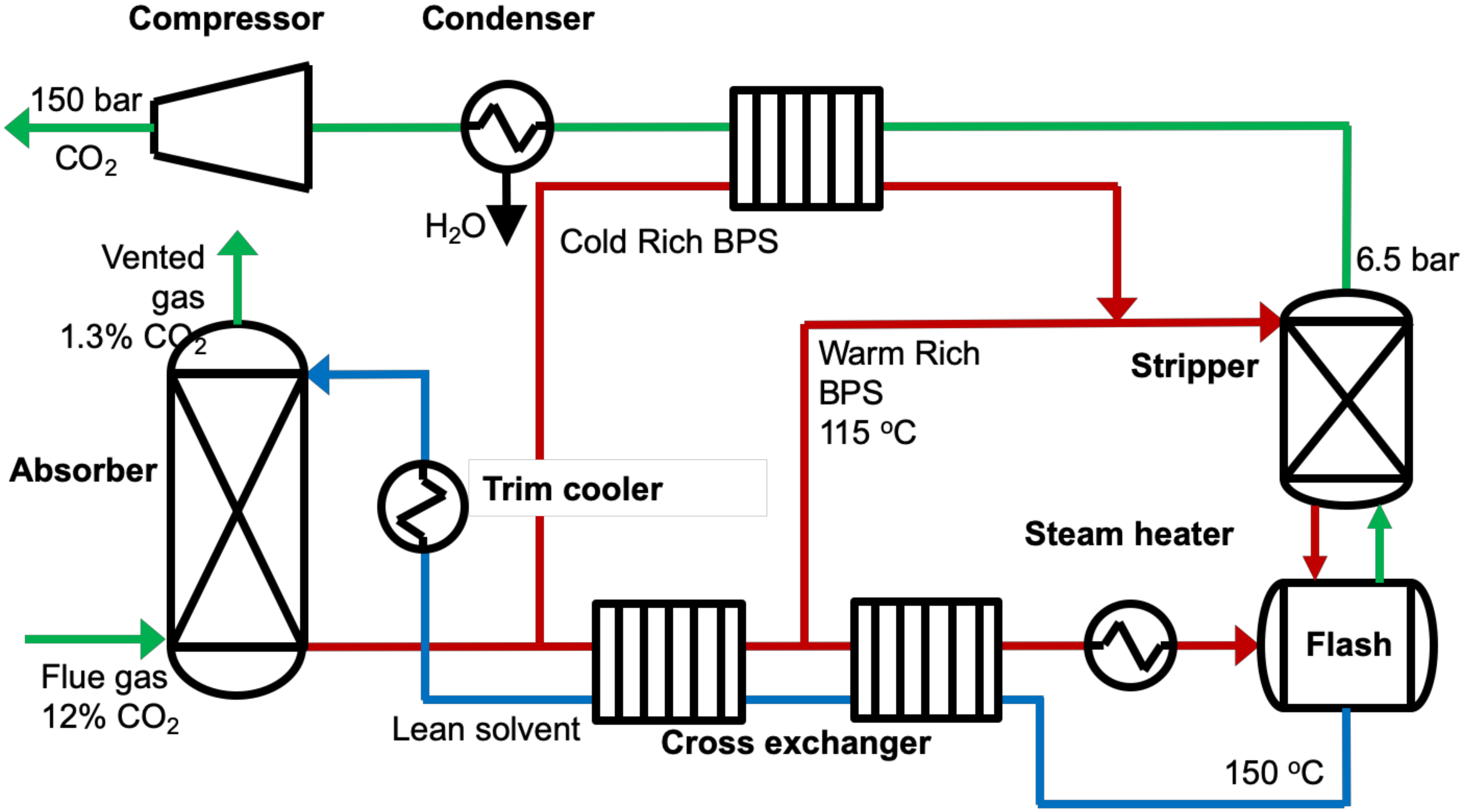
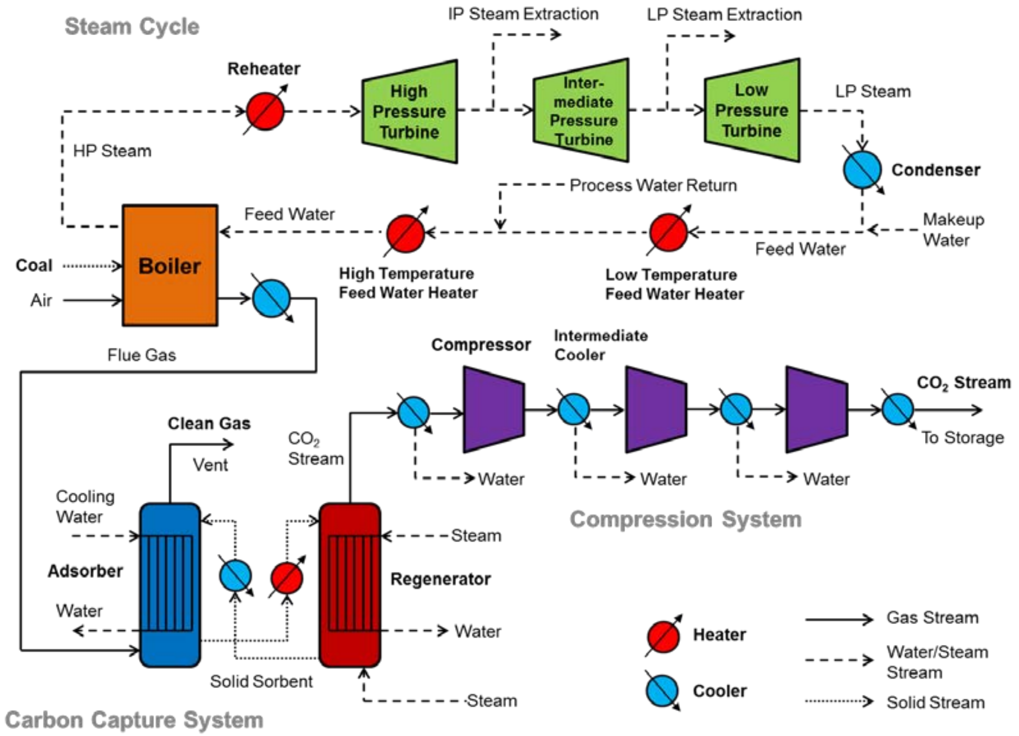
Advanced Stripper Alternative Process Configuration



Reference: Yu-Jeng Lin and Gary T. Rochelle / Energy Procedia 63 (2014) 1504 – 1513

Optimization & Heat Integration



Objective: Max. Net efficiency

Constraint: CO_2 removal ratio ≥ 90%

Decision Variables (17): Bed length, diameter, sorbent and steam feed rate

	w/o heat integration	Sequential	Simultaneous
Net power efficiency (%)	31.0	32.7	35.7
Net power output (MW_e)	479.7	505.4	552.4
Electricity consumption [b] (MW_e)	67.0	67.0	80.4

Base case w/o CCS: 650 MW_e, **42.1 %**

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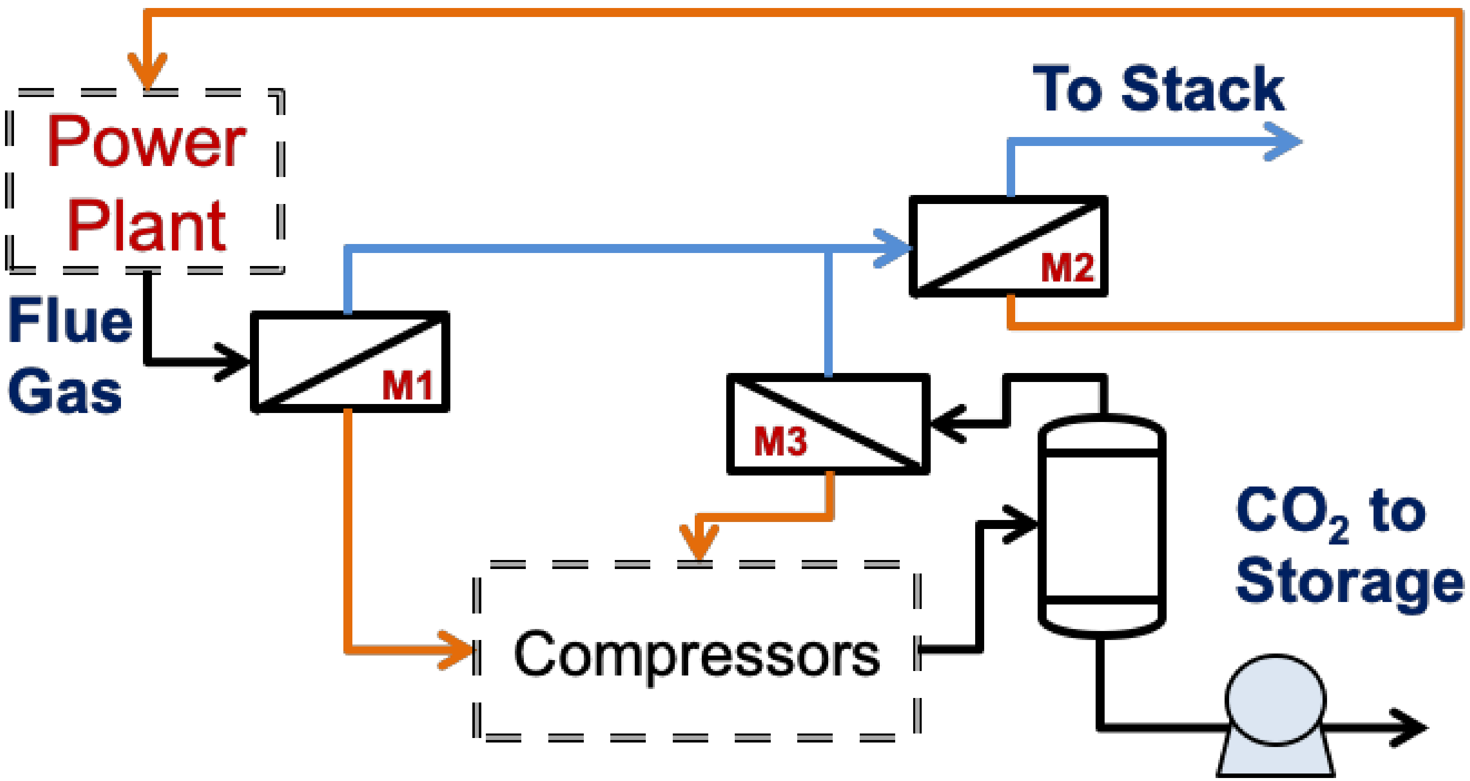
Chen, Y., J. C. Eslick, I. E. Grossmann and D. C. Miller (2015). "Simultaneous Process Optimization and Heat Integration Based on Rigorous Process Simulations." Computers & Chemical Engineering. doi:10.1016/j.compchemeng.2015.04.033

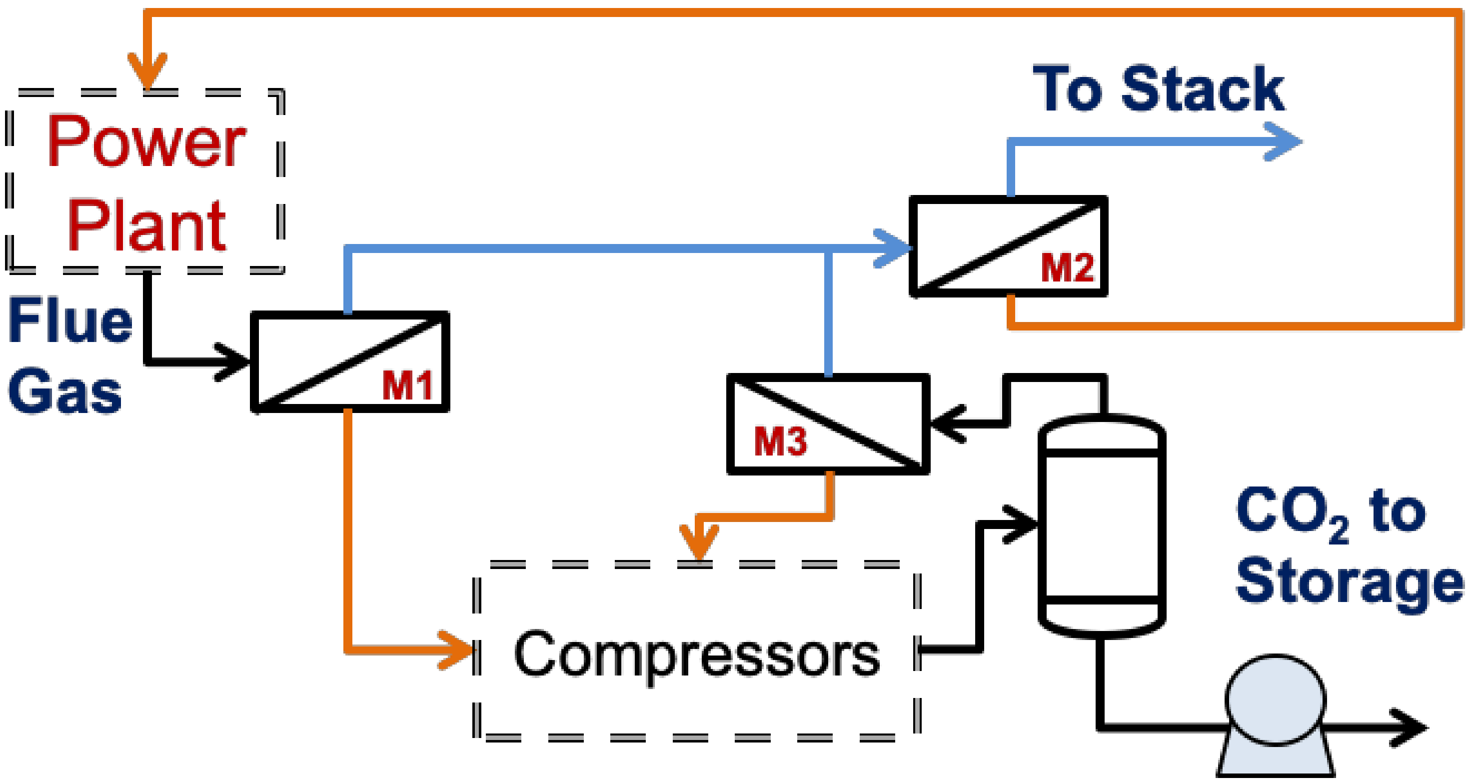
Simultaneous Optimization of Materials & Process

Membrane	Permeance (GPU)	Selectivity $\alpha_{CO2/N2}$	COE % Improvement	# Member Stages
Base	2500	28	Base	3



Simultaneous Optimization of Materials & Process

Membrane	Permeance (GPU)	Selectivity $\alpha_{CO2/N2}$	COE % Improvement	# Member Stages
Base	2500	28	Base	3
New	2600	74	**9.5%**	3



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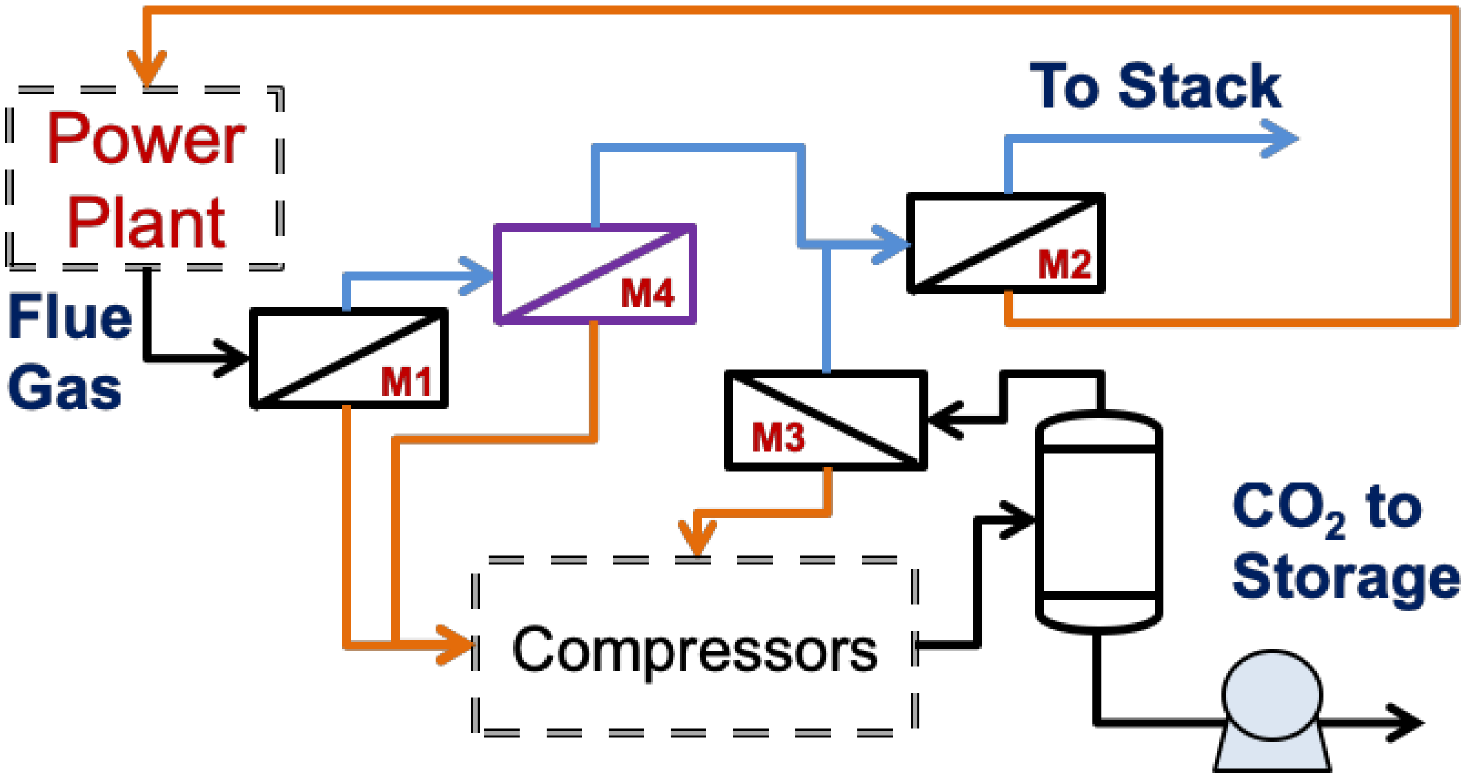
New	2600	74	**9.5%**	3
New	**2600**	**74**	**14%**	**4**



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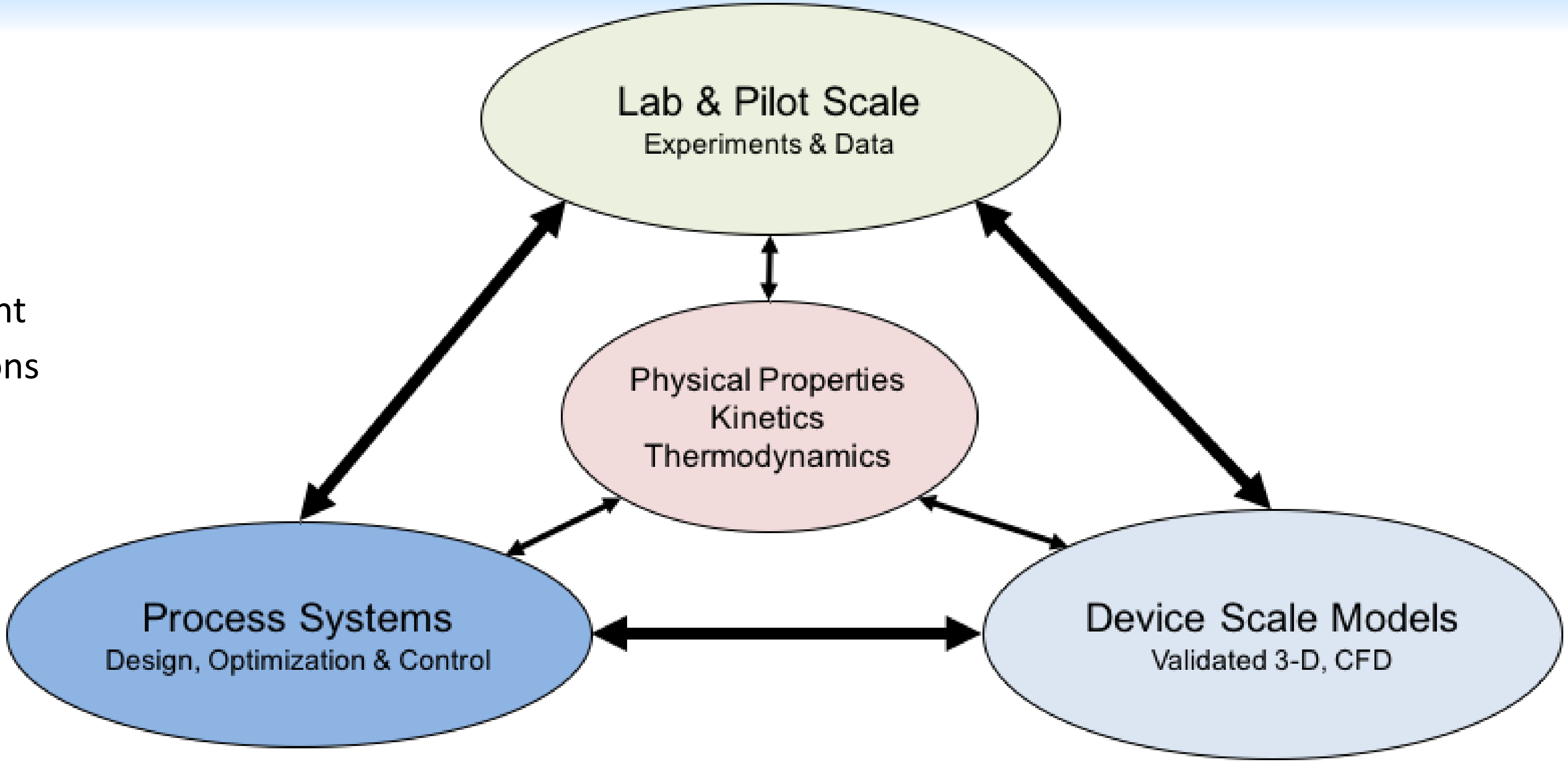
Carbon Capture Simulation Initiative

Maximizing the learning at each stage of technology development

- **Early stage R&D**
  - Screening concepts
  - Identify conditions to focus development
  - Prioritize data collection & test conditions
- **Pilot scale**
  - Ensure the right data is collected
  - Support scale-up design
- **Demo scale**
  - Design the right process
  - Support deployment with reduced risk



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West Virginia University
PRINCETON UNIVERSITY
BOSTON UNIVERSITY
THE UNIVERSITY OF TEXAS AT AUSTIN

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Carbon Capture Simulation for Industry Impact

Carbon Capture Pilot Plant Testing

Sequential Design of Experiments to Maximize Learning

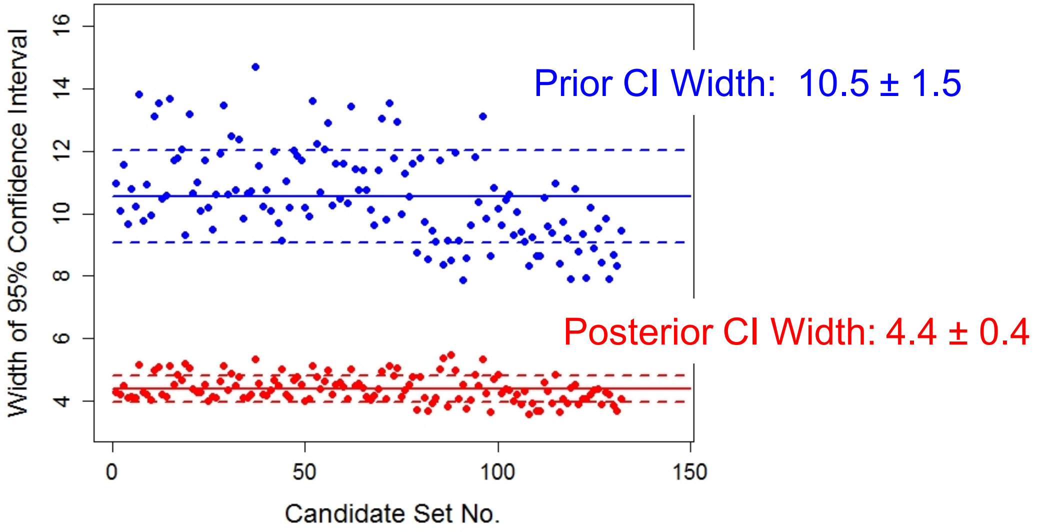
Technology Centre Mongstad – Summer 2018

www.tcmda.com

Model + Experiments + Statistics

Ensure right data is collected

Maximize value of data collected



Early Stage Systems Design & Optimization

DOCCS Transformational Carbon Capture Projects

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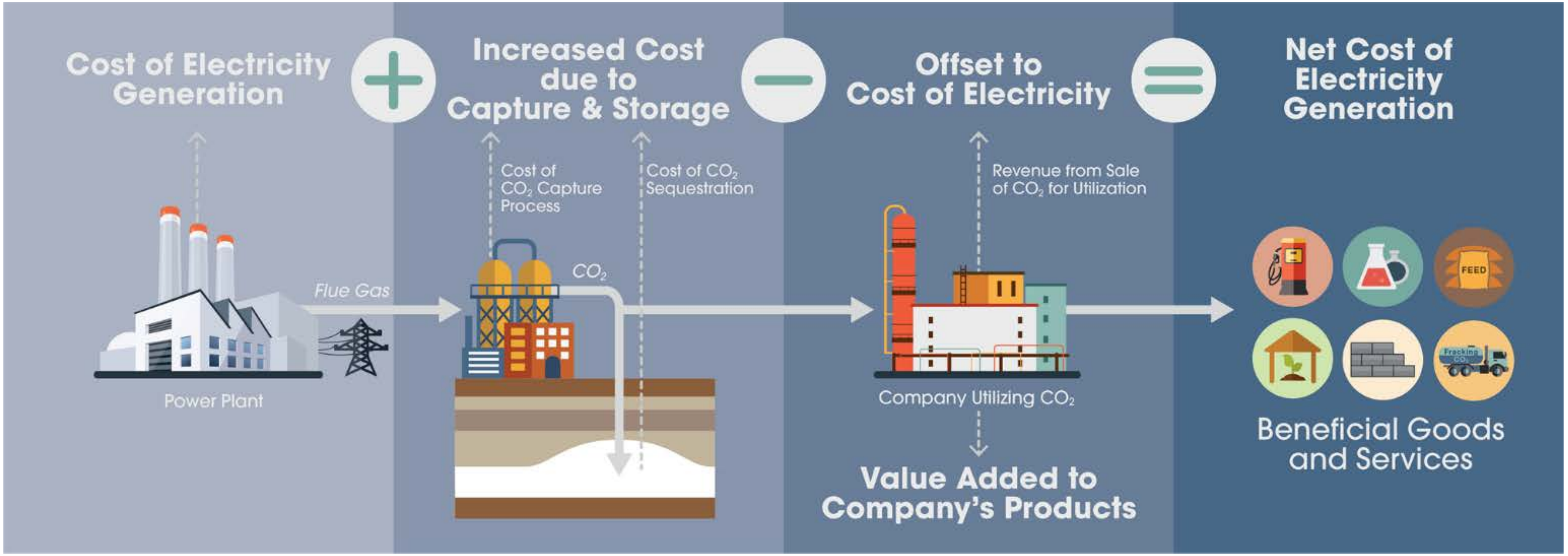
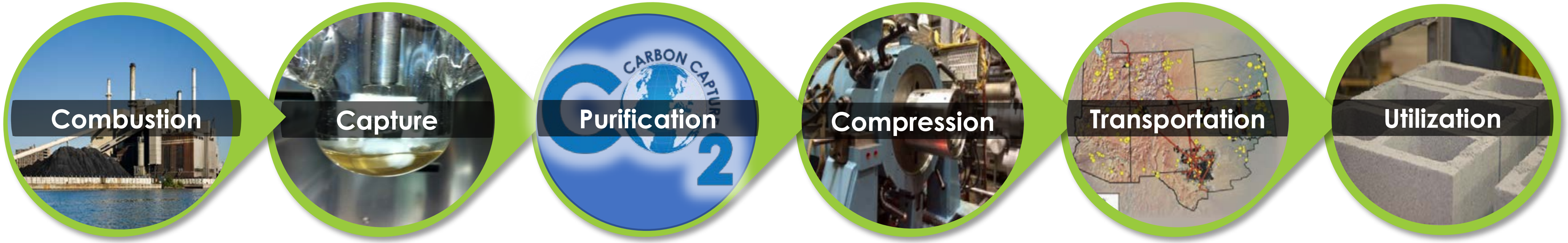
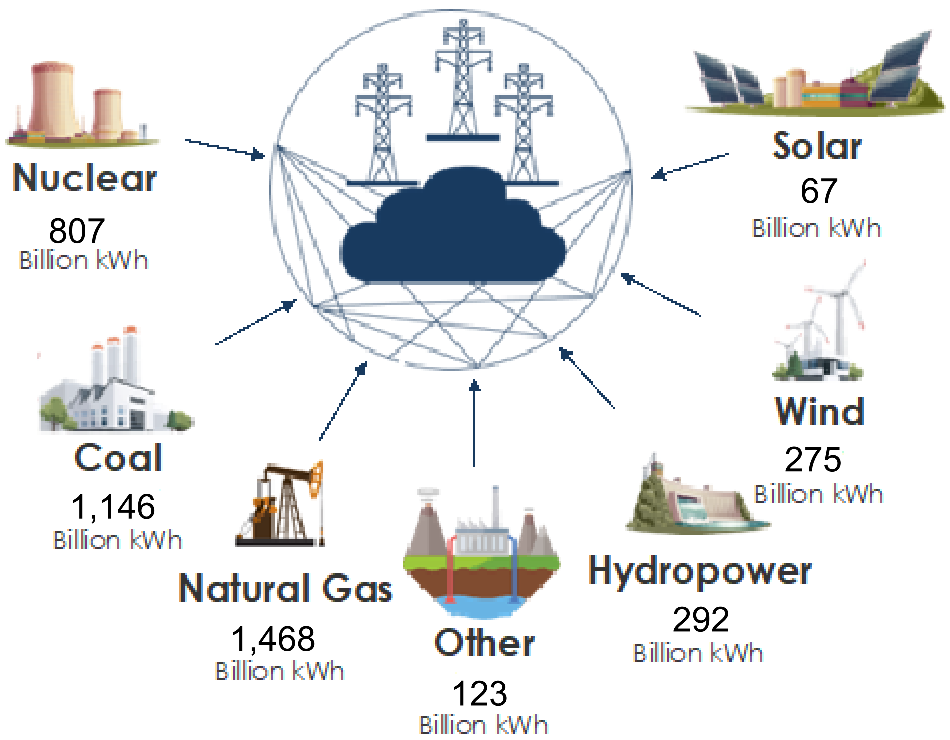
CO_2 Utilization Provides Revenue Stream





An Evolving Energy Ecosystem

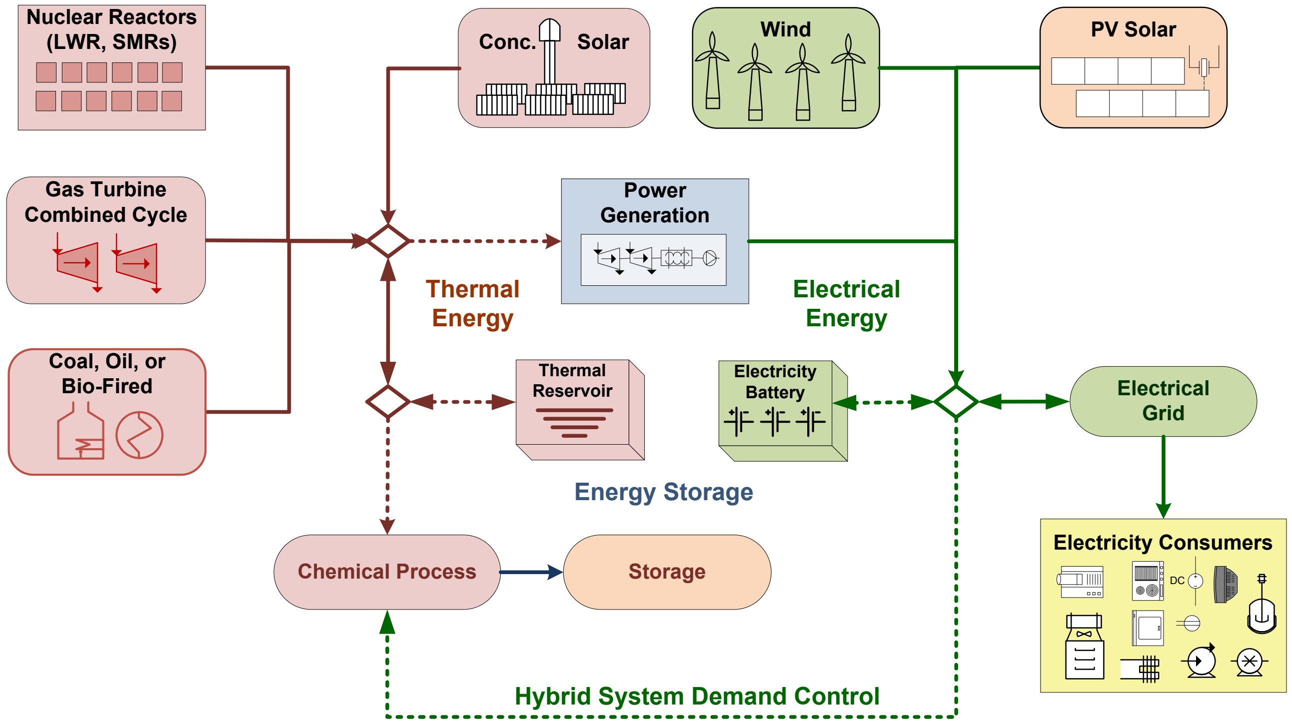
Coordinated Energy Systems



Total: 4,178 Billion kilowatt-hours (kWh)

Data source: EIA, 2018

Tightly Coupled Hybrid Energy Systems



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Process Intensification & Modularization

- **Intensification** smaller, cleaner, and more energy-efficient technology
  – Reactive distillation
  – Dividing wall columns
  – Rotating packed bed
  – Microreactors
- **Modular design**
  – *"Numbering up" instead of scaling up*
  – Reduced investment risk
  – Improved time to market
  – Increased flexibility
  – Improved safety
  – Reduced on-site construction

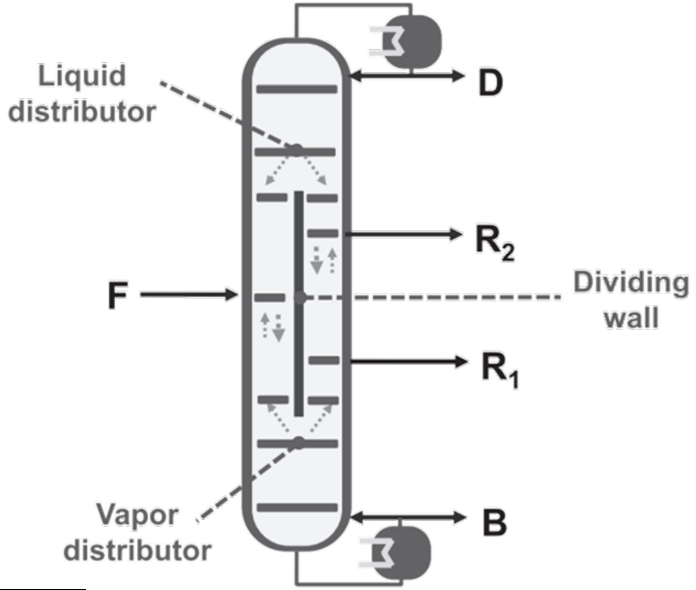
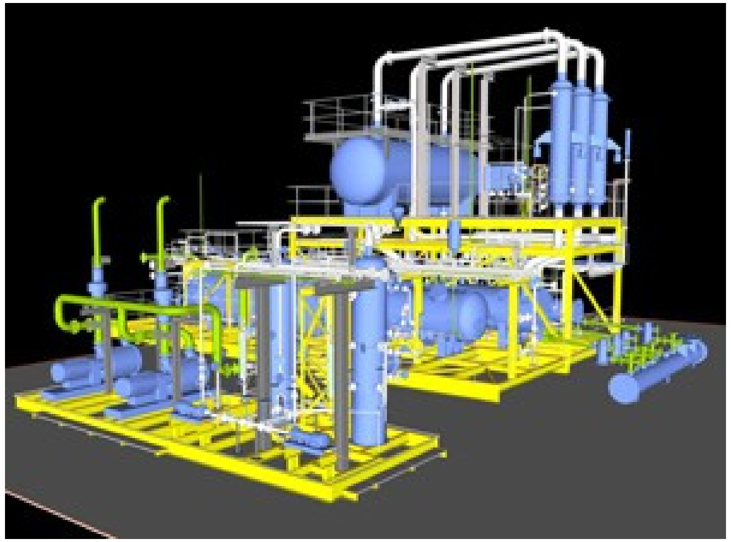
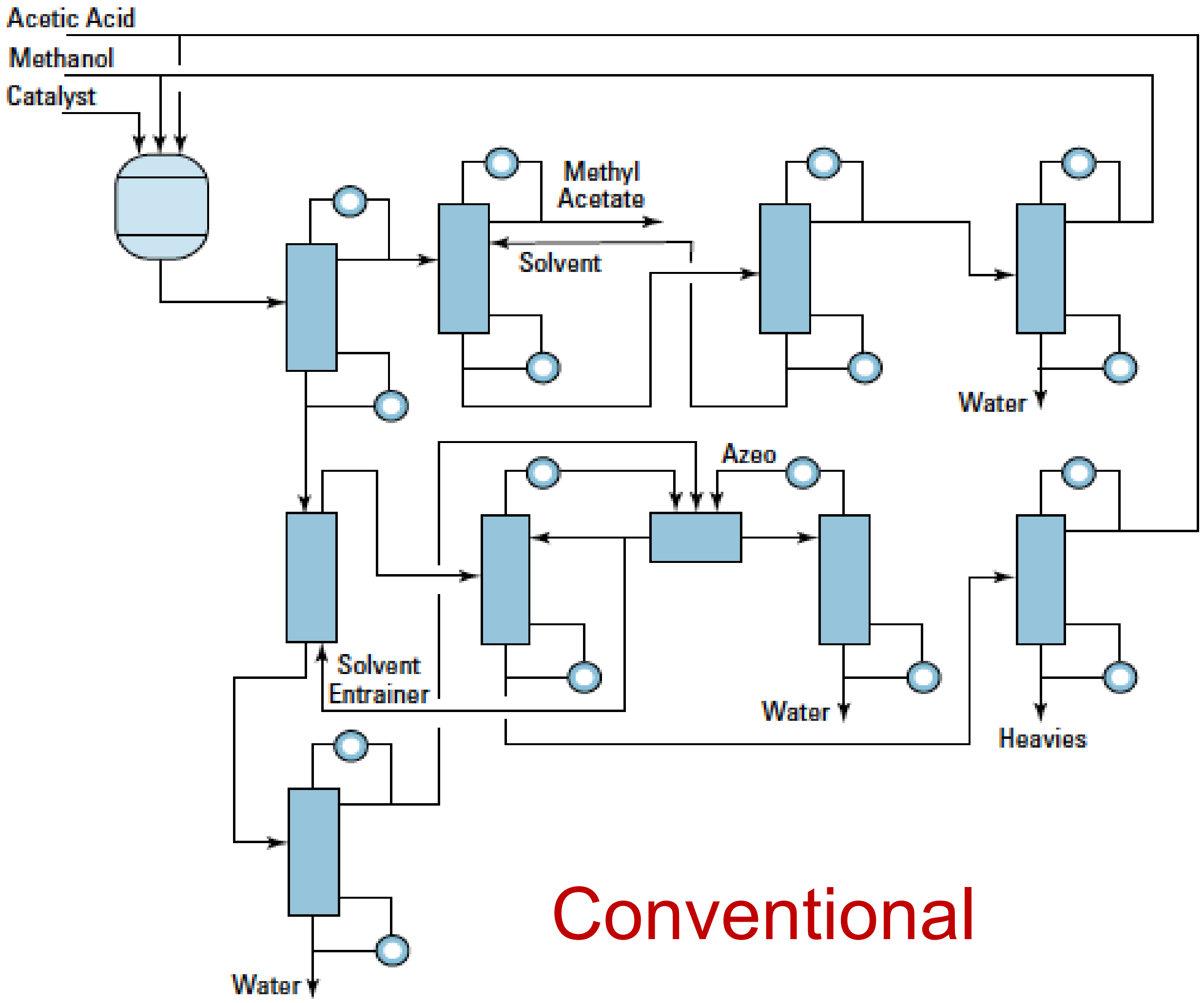


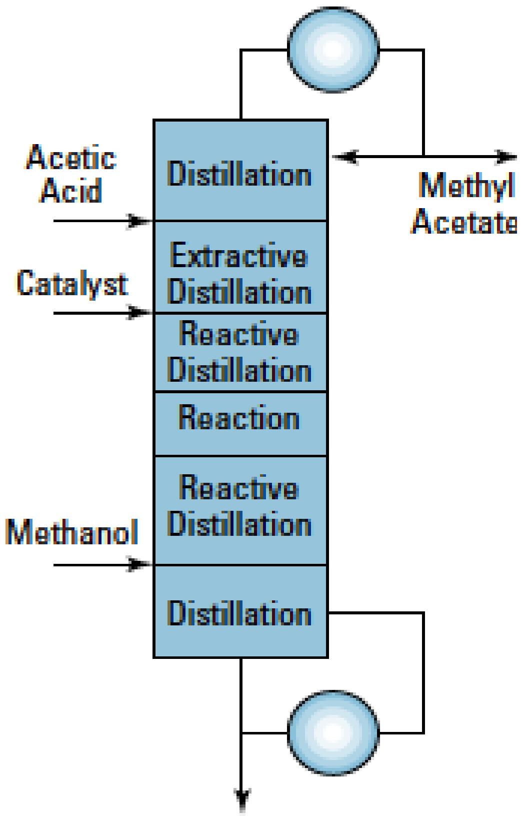
Figure from Rawlings et al., 2019



Process Intensification: Reactive Distillation



Conventional



Integrated: 90% savings

Stankiewicsz et al., "Process Intensification: Transforming Chemical Engineering", Chemical Engineering Progress, Jan 2000.
https://www.rvo.nl/sites/default/files/2013/10/Process%20Intensification%20Transforming%20Chemical%20Engineering.pdf

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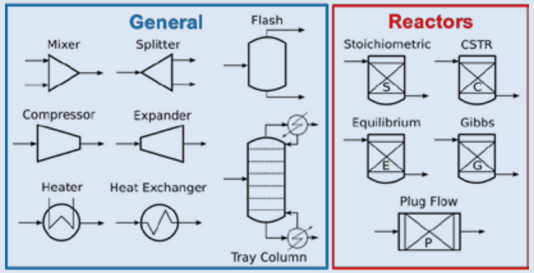
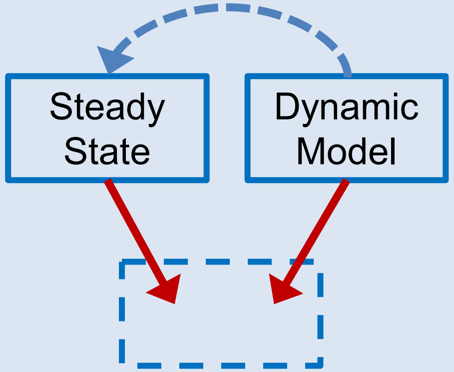
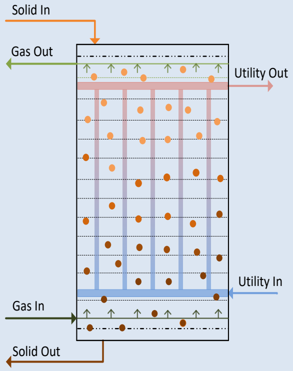
Advanced System Design & Optimization

Hierarchical Process Model Library





Model Customization

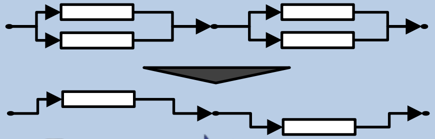


PYOMO

PYOMO DAE

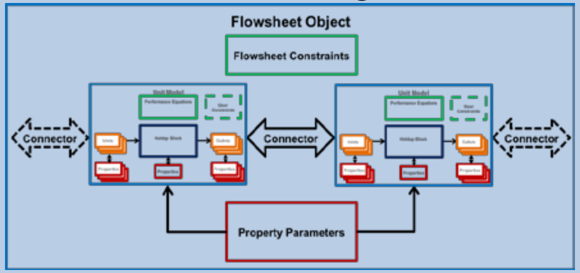
Algebraic Modeling Language

Conceptual Design via Superstructure

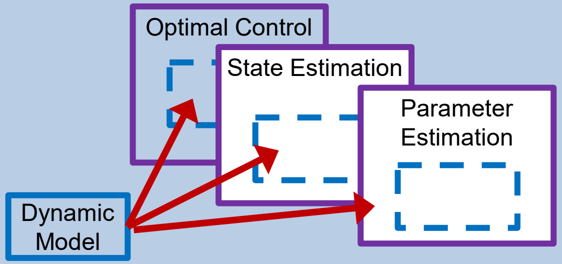


PYOMO GDP

Process Design & Optimization Process Integration



Dynamics & Control



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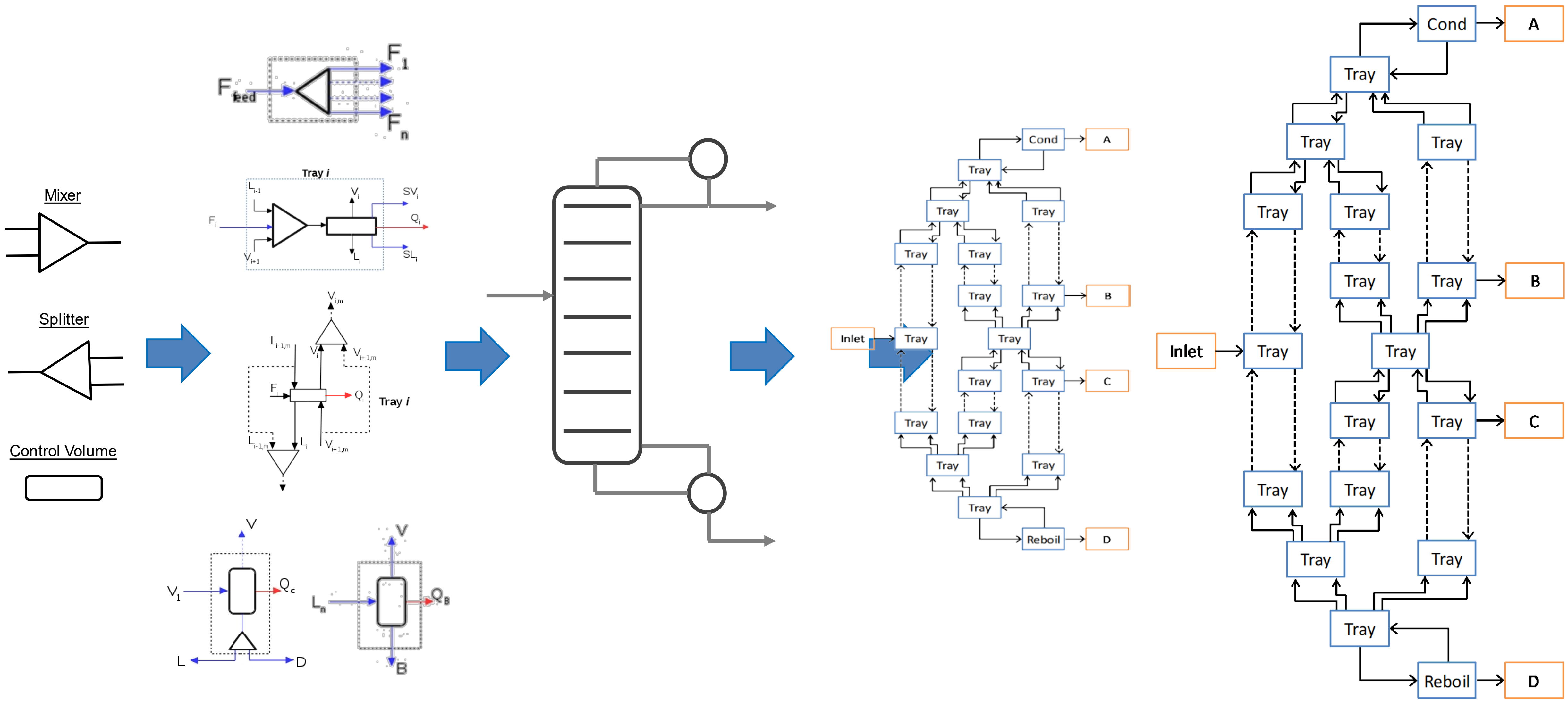
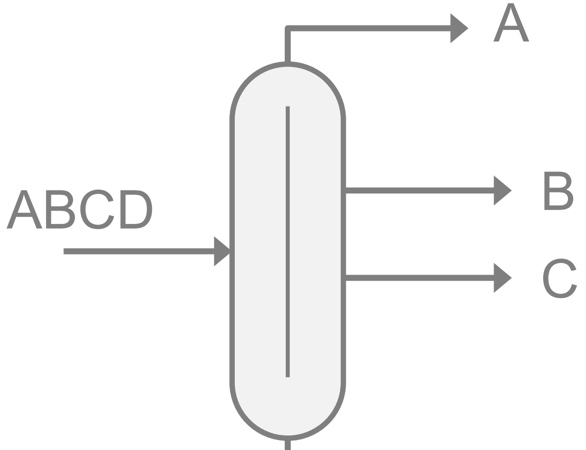
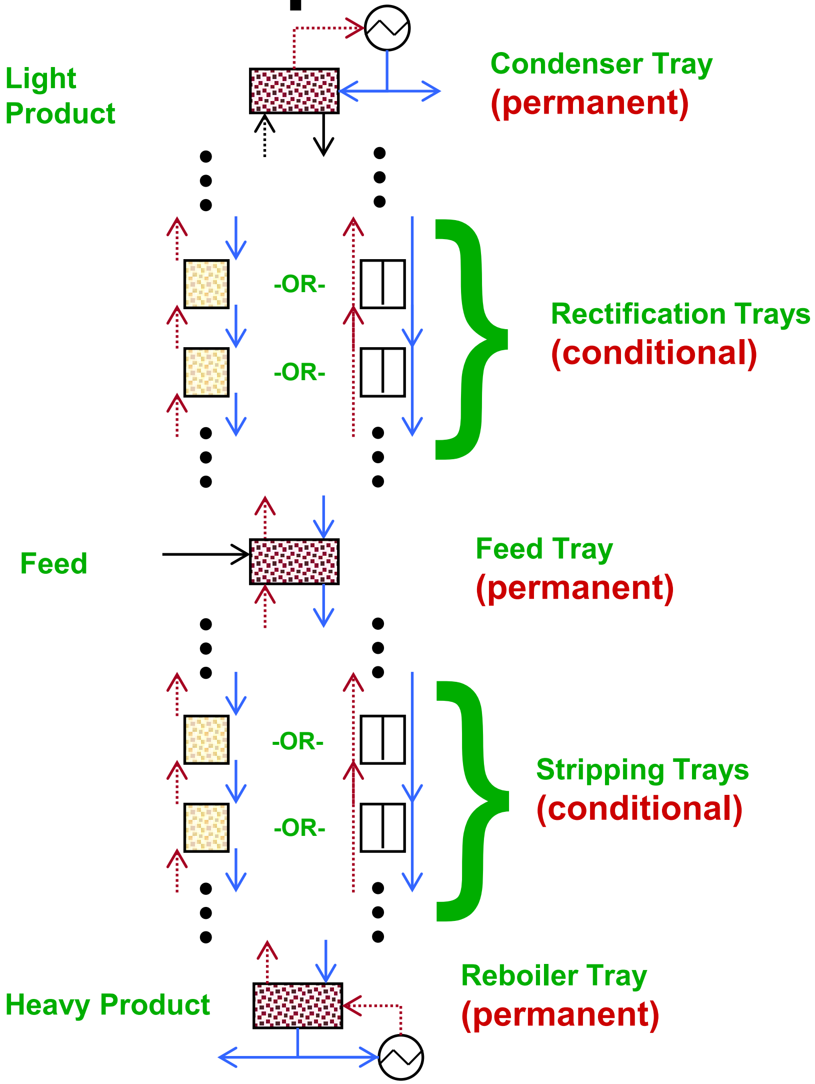
Basic blocks combine to model complex, intensified units



Kaibel Column Conceptual Design Example

- **Components:** Methanol, ethanol, n-propanol, n-butanol
  - 99% purity for each component
- **42 million combinations**
- **GDP model written using Pyomo.GDP**
  - 5715 constraints
    - 2124 nonlinear
  - 100 disjunctions
    - 3599 variables
      - 178 binary
      - 3421 continuous
- **Solved in 639 sec using GDPopt-LOA solver**
  - Logic-based outer approximation algorithm
  - **4 iterations**
- **Resulting design:**
  - **46 trays** (21% reduction vs. base case)
  - **Dividing wall between 12th and 26th tray**
  - **Feed at 18th tray**
  - **Side outlets at 13th and 22nd trays**



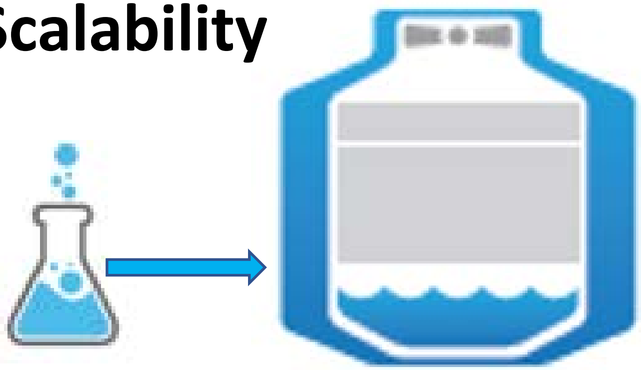


Optimal Design Kaibel Column reduces energy consumption by more than 40% compared to 2 columns

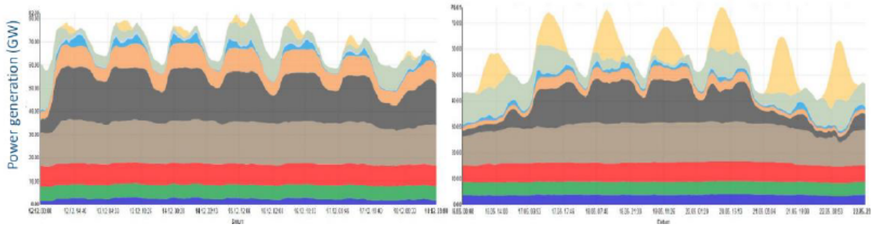
Challenges & Opportunities

Market Risk

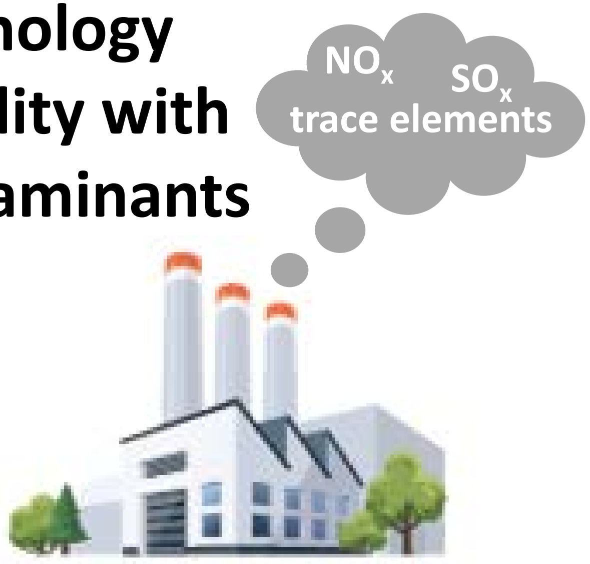
Scalability

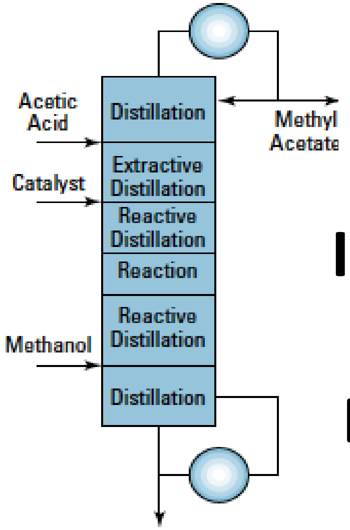


Variability of CO_2 streams



Technology Stability with Contaminants





Process Intensification System Development

Life Cycle Analysis

Conclusion

- Economics & Viability are f (system)
- Optimal system = f (materials, technology, concentration, operational approach)

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Carbon Capture Simulation for Industry Impact

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