Miniaturization of Processing Equipment:
Achieving Capital Efficiency with Modular Chemical Process Intensification

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ATAMI Advanced Technology and Manufacturing Institute

Oregon State University

RAPID Transforming Process Industries

TEXAS The University of Texas at Austin

CII Construction Industry Institute®

A fraction of the plant volume!

87% less CAPEX!

14% less OPEX !

1/5th the payback period!

Nearly twice the NPV!

HOW? Modular chemical process intensification (MCPI)

MCPI: the use of chemical process intensification to reduce the plant footprint, thereby enabling more efficient modular fabrication

Modularization

Moving work-hours to a beneficial fabrication site

Offsite Construction

Offsite Construction is helping to revolutionize the construction industry by introducing standardized, repeatable designs

Nuclear Power

Source: https://www.nextbigfuture.com/2018/04/nuscale-small-modular-nuclear-reactor-first-ever-to-complete-nrc-phase-1-review.html

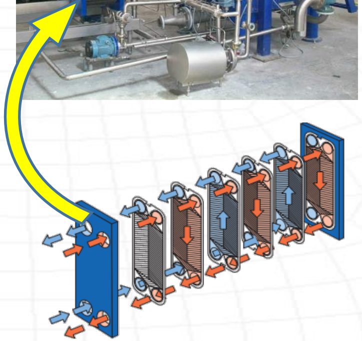
Buildings

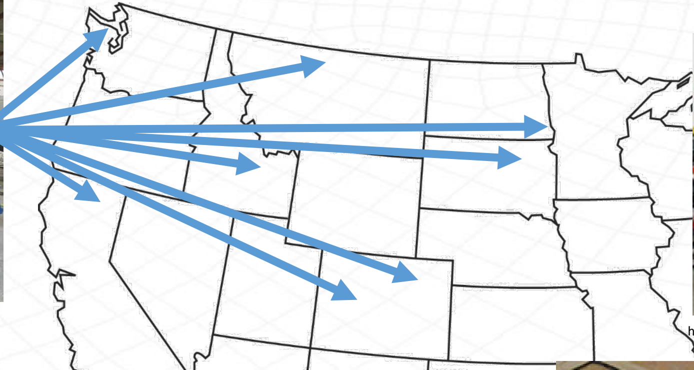
Source: https://www.ikopolymeric.com/offsite-construction-methods-and-their-benefits/

Offsite Construction

Chemical Process Industry

New approaches are emerging for building plants off-site at a centralized facility …





https://www.epicmodularprocess.com/design-build-process

http://www.zeton.com/site/chemicals/pictures.html

http://www.nitrogen-generators.com/wp-content/uploads/2014/02/HPN-no-background-203x300.png

http://www.koch-glitsch.com/siteimages/kmps.jpg

https://www.businesswire.com/news/home/20161018006554/en/Fluor-Completes-Module-Fabrication-Oil-Sands-Project

… and then transporting and installing modules on-site.

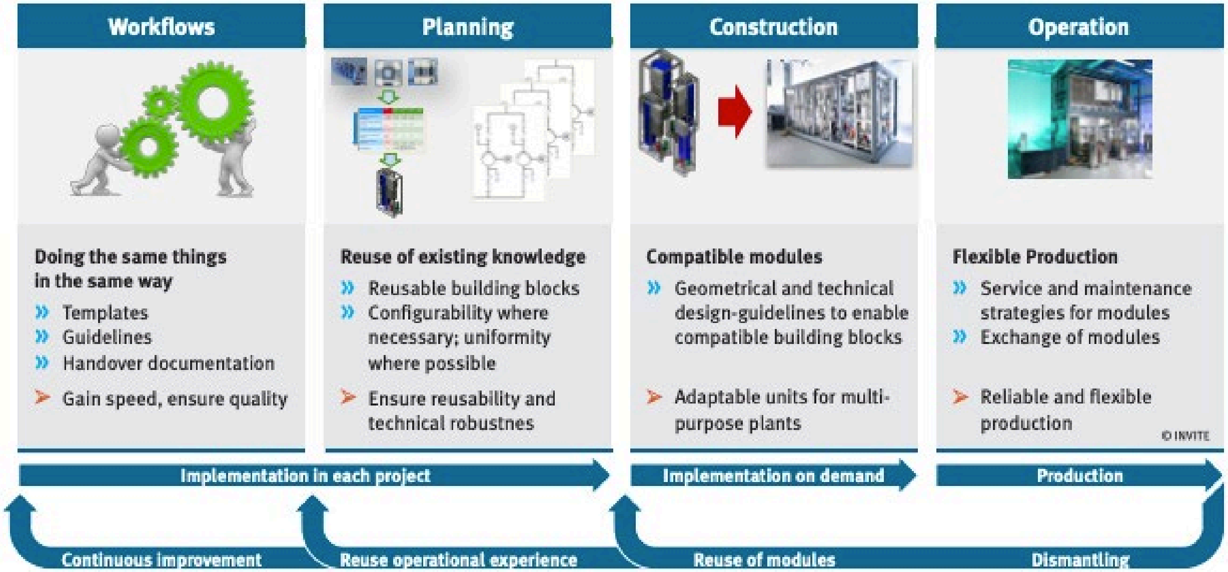
Module Size Depends on Market Needs

Motivation for Offsite Construction

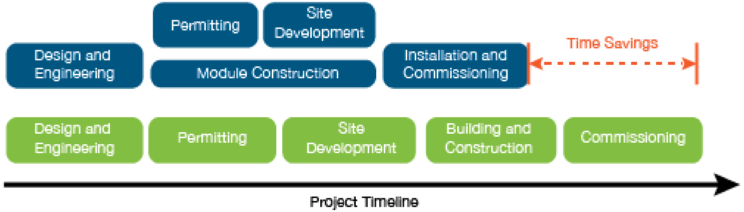
EPCs & Downstream Chemical

Module Manufacturing

- Improved worker productivity via factory assembly
- Ability to assemble in a controlled environment
- Ability to conduct preliminary testing off-site
- Ability to construct in parallel with securing site permits and preparing the site
- Shorter schedules
- Gets capital working faster

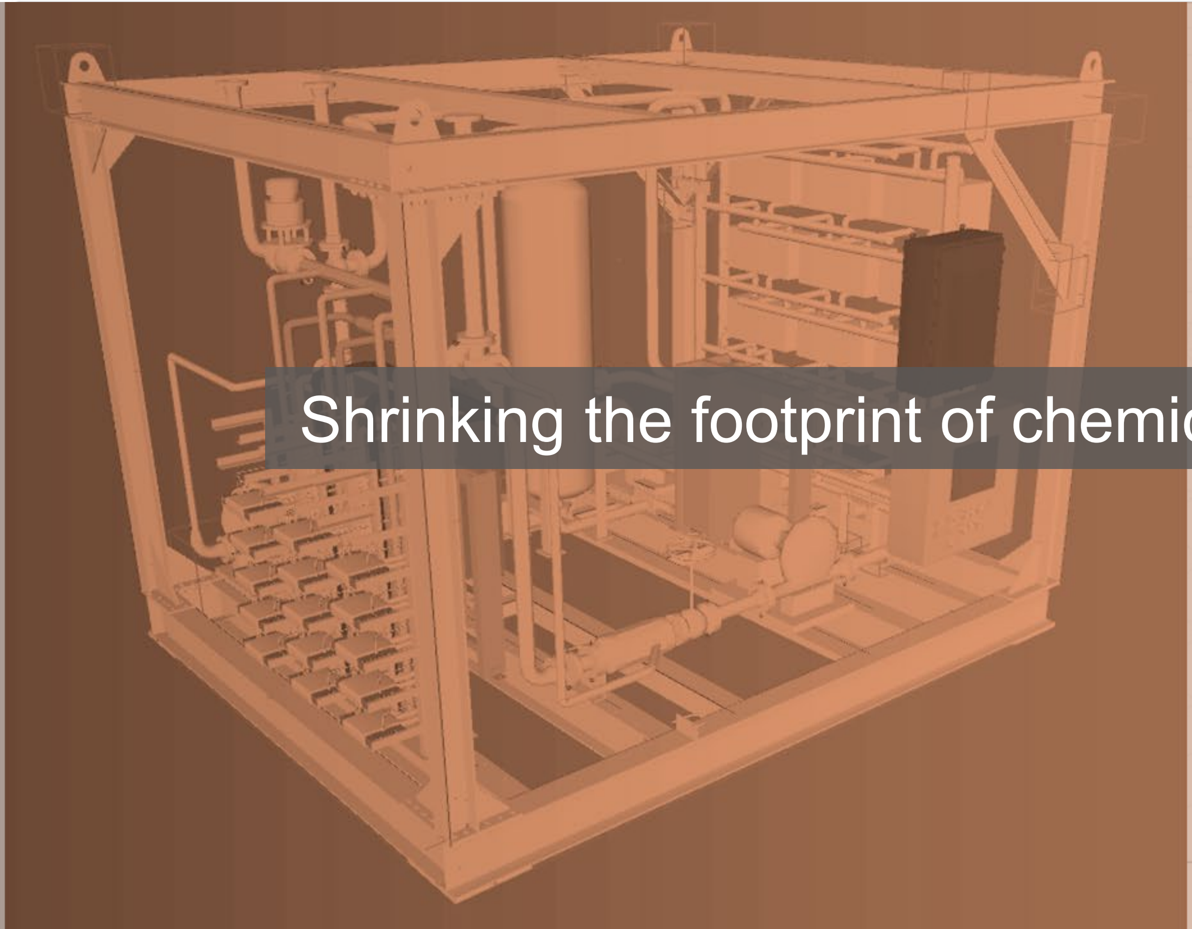


Modular Plants - DECHEMA. dechema.de/dechema_media/modularplants.pdf.



Baldea, M., et al. "Modularization in Chemical Processing." Chemical Engineering Progress 114.3 (2018): 46-54.

Chemical Process Intensification



Shrinking the footprint of chemical operations

Chemical Process Intensification

Any chemical engineering development that leads to a substantially smaller, cleaner, safer and more energy efficient [process] technology

Stankiewicz, A.I. and Moulijn, J.A. (2000). Process intensification: transforming chemical engineering. *Chemical Engineering Progress*, January, pp. 22-34.

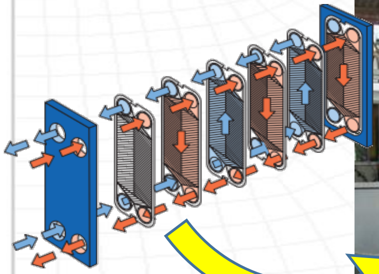
- Reduced capital investment
- Improved process safety
- Reduced energy use
- Lowered materials costs
- Increased process flexibility and inventory reduction
- Increased attention to quality
- Better environmental performance

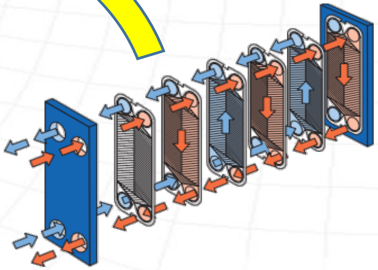
Keller, G.E., and Bryan, P.F. (2000). "Process engineering: moving in new directions." *Chemical Engineering Progress*, January, pp. 41-50.

Chemical Process Intensification

Solar Thermochemical Processing

Process Intensification enables distributed chemical processing.





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Pacific Northwest NATIONAL LABORATORY

Chemical Process Intensification

Solar Thermochemical Processing

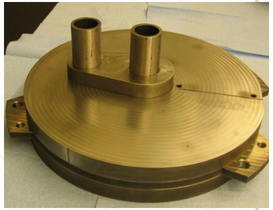
RAPID Transforming Process Industries

Process Intensification enables distributed chemical processing.

Microchannel HX

Conventional HX

Parameter	Units	µchannel HX		Commercial HX
HX mass	Kg	5	14X	70
HX volume	L	1.25	28X	35
Duty	Watts	3500		3500
Effectiveness	%	87		<80
Side 1, Air dP	in H2O	4.3		4.3
Side 2, Air dP	in H2O	3.1		3.1



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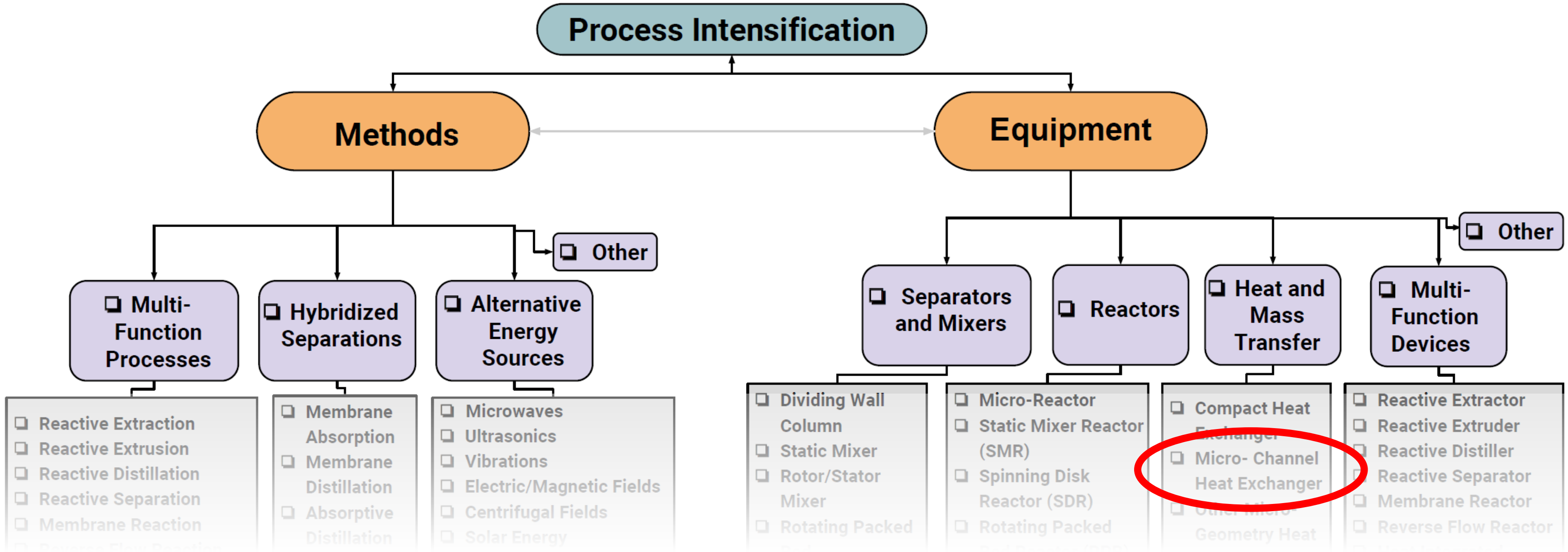
Chemical Process Intensification



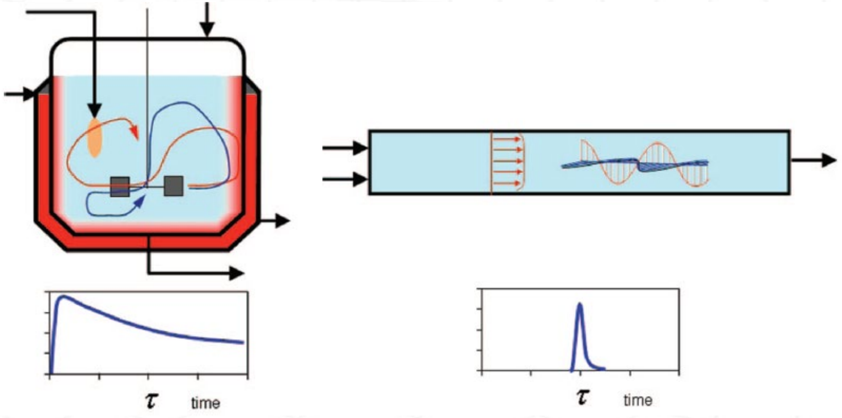
Guiding Principles of Process Intensification

1. Maximize effectiveness of intramolecular and intermolecular events.

2. Give each molecule the same processing experience.

3. Optimize driving forces at all scales and maximize the specific surface areas to which they apply.

4. Maximize synergistic effects from partial processes.



Tom Van Gerven and Andrzej Stankiewicz (2009). "Structure, energy, synergy, time – The fundamentals of process intensification." *Industrial & Engineering Chemistry Research,* 48(5): 2465-2474.

Symbiosis between Modularization and CPI

Mutually Beneficial Linkages

- Smaller process intensification equipment, leads to denser chemical plant layouts, which facilitates **modularization**

- Module **mobility** provides advantages:
  - geographically distributed customers/markets
  - energy sources/feedstocks
  - distribution challenges

- **Capacity flexibility** is possible with the “numbering-up” of modules

This is the idea behind Modular Chemical Process Intensification

Background of Case Studies

CASE STUDY 1	CASE STUDY 2	CASE STUDY 3
Specialty chemical driven by **manufacturer-operator** with the goal of reducing CAPEX	Commodity chemical driven by **developer-supplier** to address storage and distribution challenges	Commodity chemical driven by **developer-supplier** to take advantage of the availability of clean energy

Case Study 1

PERSPECTIVE	Manufacturer-operator
DISTRIBUTION DRIVER	Customer
CHEMICAL MARKET	Specialty chemical
PI INNOVATION	OTS Tubular RX Batch to Continuous
CLIENT MOTIVATION	Reduced CAPEX
PLANT SIZE REDUCTION	Vol = 250X
PHASE OF ASSESSMENT	1 year post-Pilot
NUMBERING-UP?	No numbering-up

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Specialty Chemical Production

Project Frame and Basis

	Mode	Cycle time (hours)	Process Tchnlgy	Heat transfer area (ft^2)	Heating time (hours)	Heat loss (kW)	Flushing material (gallons/ batch)	Nitrogen purge (SCF/ batch)	Cooling system
CSB	Batch	48	12,000 gal. stir tank reactor	628	10	17	1500	2800	water
MCPI	Continuous	N/A	Tubular reactor	39	N/A	1.2	N/A	N/A	air

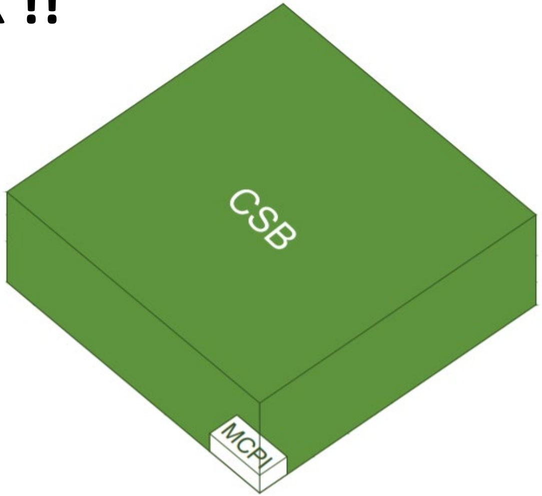
CASE STUDY 1

Specialty Chemical Production

(ISBL) CAPEX-Driver Differences

	Height	Footprint	Brownfield SIMOPS safety impact
CSB	30 ft	10,000 s.f	High
MCPI	6 ft	200 s.f.	Minimal

250X !!



Specialty Chemical Production

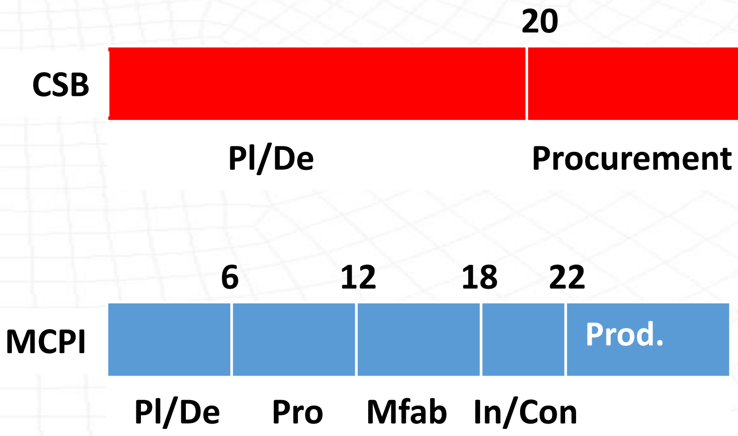
CAPEX

	Total Installed Cost	Engineering Cost
CSB	$3,500,000	$350,000
MCPI	$450,000	$55,000

Specialty Chemical Production

CASE STUDY 1

Time until Production (weeks)



70%

Shorter time to operations and revenue

Specialty Chemical Production

CASE STUDY 1

CAPEX, OPEX, NPV, and Payback Period

CAPEX (USD)	NPV	PAYBACK PERIOD (MONTHS)
MCPI is 87% lower	**MCPI is 1.9 times higher**	**MCPI is 80% shorter** CSB: 12.3 MCPI: 2.5

OPEX (USD)	O&M FTE	COST OF POWER & UTILITIES
MCPI is 14% lower	**MCPI is 91% lower** CSB: 9 MCPI: 0.8	**MCPI is 40% lower** CSB: $40 K MCPI: $24 K

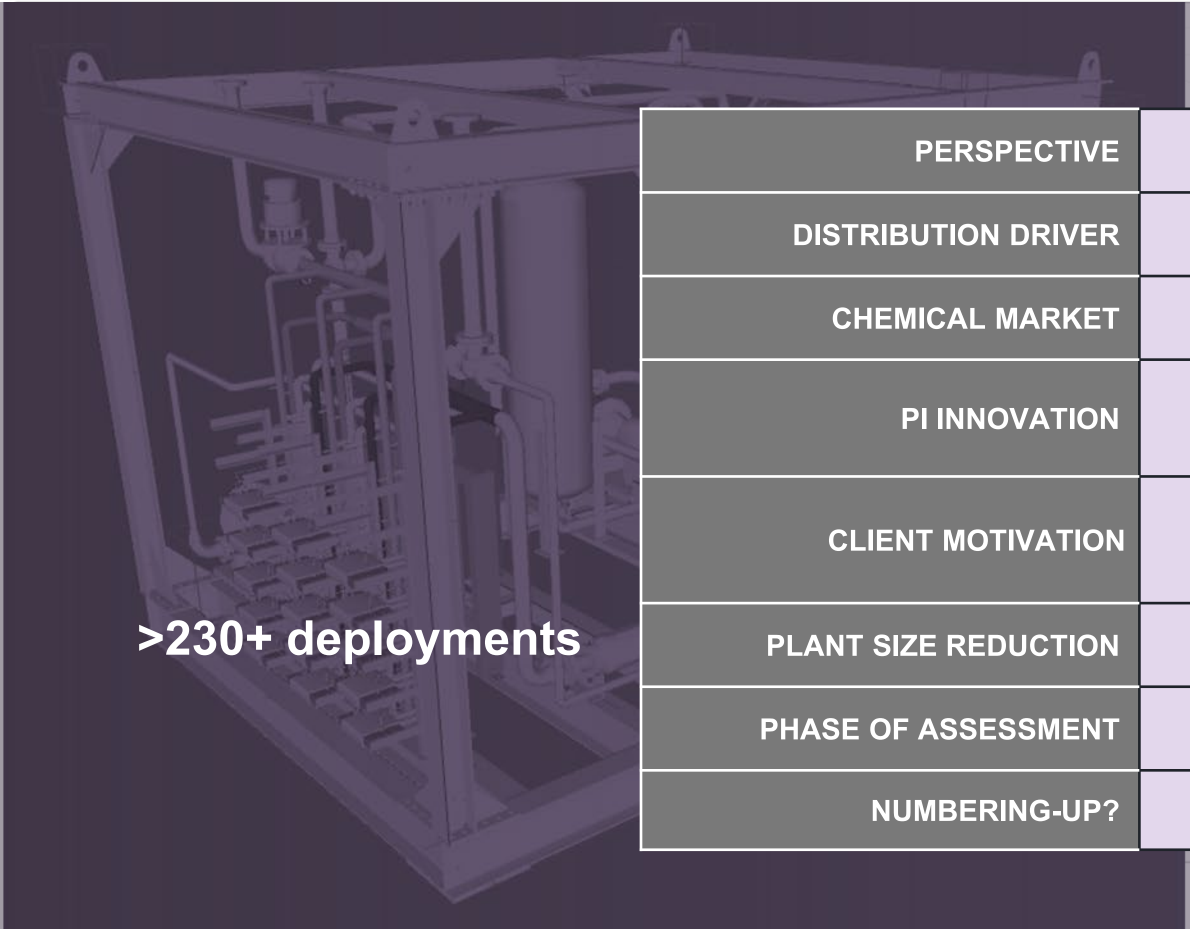
Specialty Chemical Production

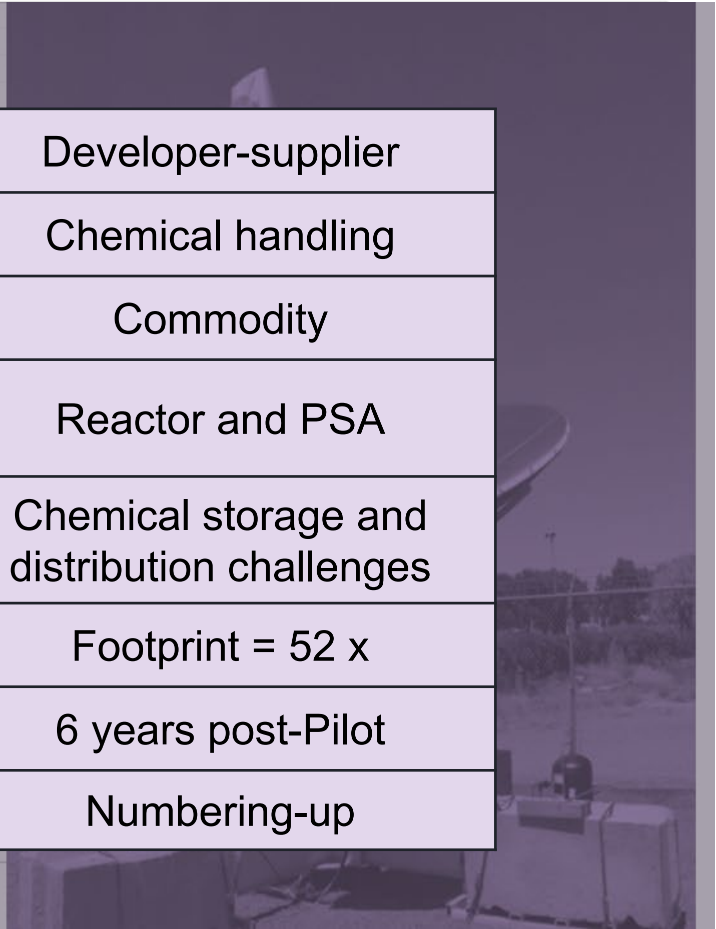
Top Drivers of Superior MCPI Capital Efficiency

55 Drivers from the Literature / Top 6 Drivers

- PI **equipment** is **smaller, cheaper, and available off-the-shelf**
- **Lower weight** of MCPI means **simpler and lower-cost foundations, support structure**
- **Reduced** module installation time and effort (**SIMOPS**)
- **Earlier recovery of investment** from early production and sales
- Unit **productivity rate improvements** for module fabrication
- **Pre-shipment testing** of modules enhances **performance assurance**

Case Study 2





>230+ deployments

PERSPECTIVE	Developer-supplier
DISTRIBUTION DRIVER	Chemical handling
CHEMICAL MARKET	Commodity
PI INNOVATION	Reactor and PSA
CLIENT MOTIVATION	Chemical storage and distribution challenges
PLANT SIZE REDUCTION	Footprint = 52 x
PHASE OF ASSESSMENT	6 years post-Pilot
NUMBERING-UP?	Numbering-up

Distributed Commodity Production

CASE STUDY 2

OPEX Features and Other Assumptions

Conventional Stick-Built (CSB)

52X reduction in plant area

MCPI

Plant Area for 300 normal meters cubed per hour Capacity

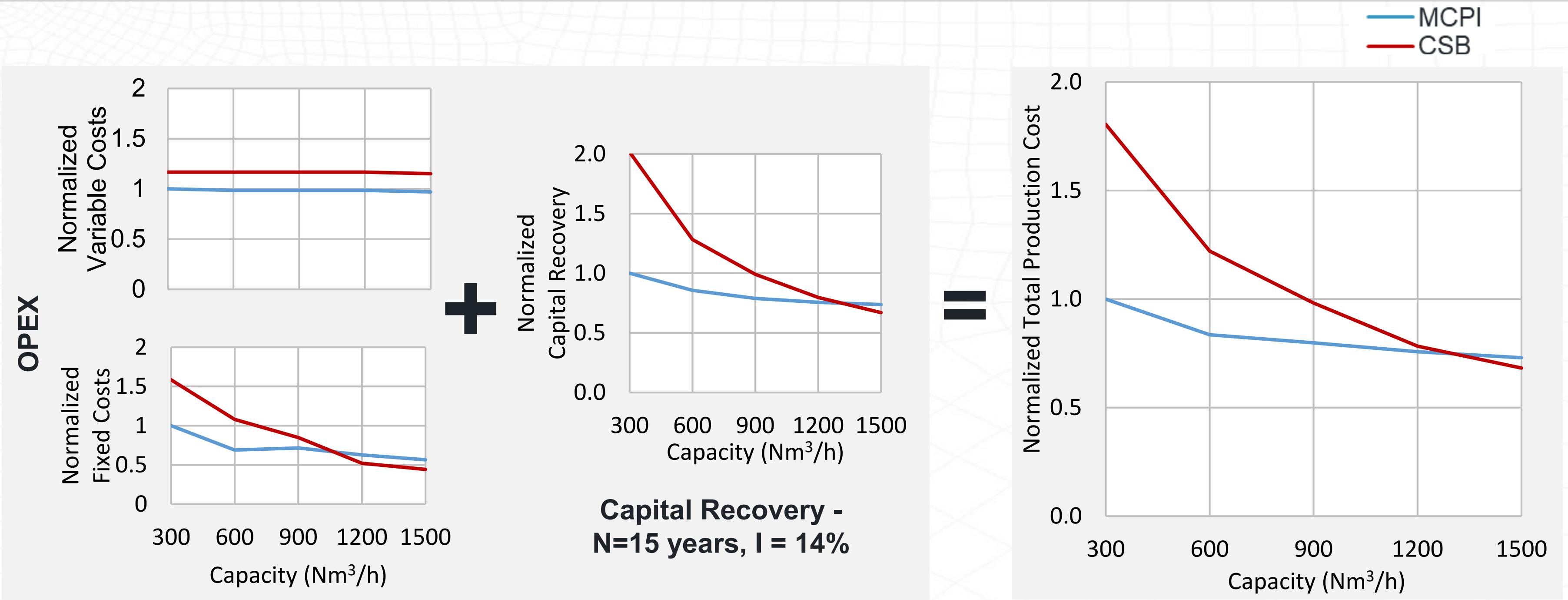
*MCPI plant is one module

	Process Technology	Footprint	Brownfield SIMOPS impact	Operations Staff	Scale-up Rate
CSB	Conventional reactor and PSA	24,000 ft^2	High	Scales with plant size	Full capacity in 3 years
MCPI	Catalytic reactor and Intensified PSA	460 ft^2	Minimal	1 FTE (1-2 skids) 2 FTE (3-5 skids)	Double capacity beyond year 2

Distributed Commodity Production

CASE STUDY 2

Total Production Cost: MCPI vs. CSB



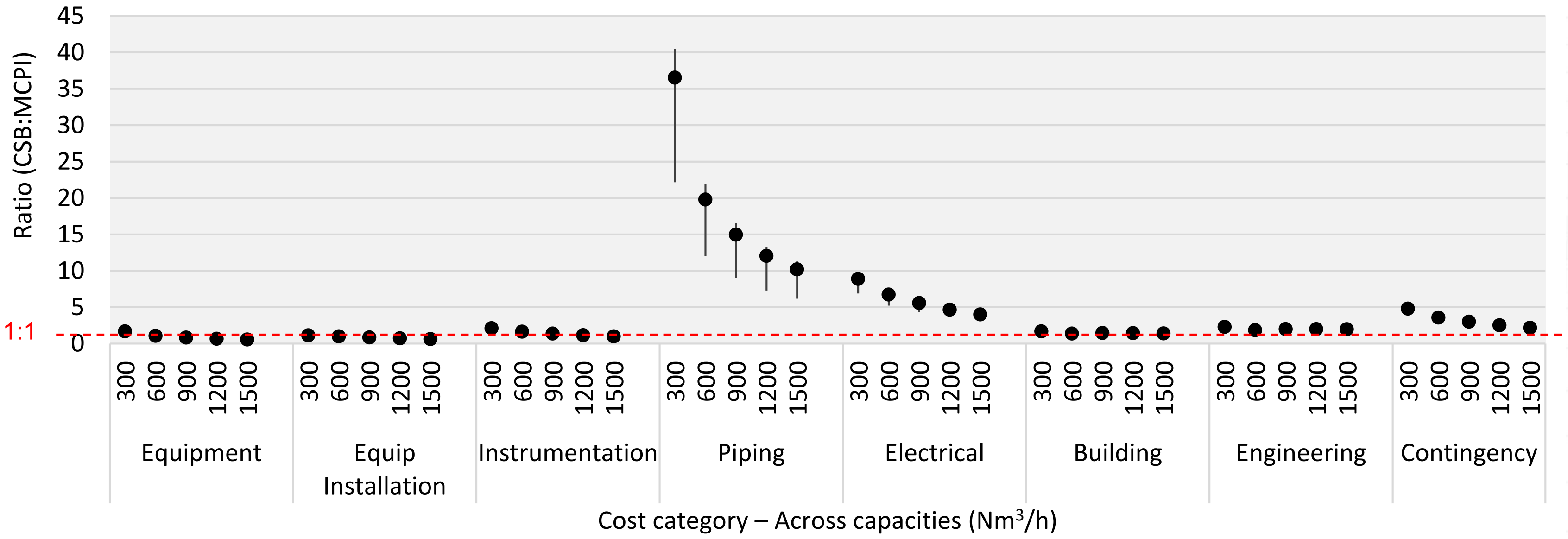
At the baseline capacity of 300 normal meters cubed per hour:

- 30-40% reduction in OPEX (better labor utilization, conversion + energy efficiency)
- 50% reduction in CAPEX
- Overall 42% reduction in production cost

Distributed Commodity Production

CASE STUDY 2

CAPEX Comparison (CSB : MCPI)



- **Interconnection systems (piping and electrical)** are the primary drivers for reduced MCPI CAPEX
- **Equipment costs** for CSB become lower than those for MCPI above a 2-train capacity; **instrumentation** at a 5 trains
- Other costs (engineering, buildings, and contingency) are lower for MCPI relative to CSB

Distributed Commodity Production

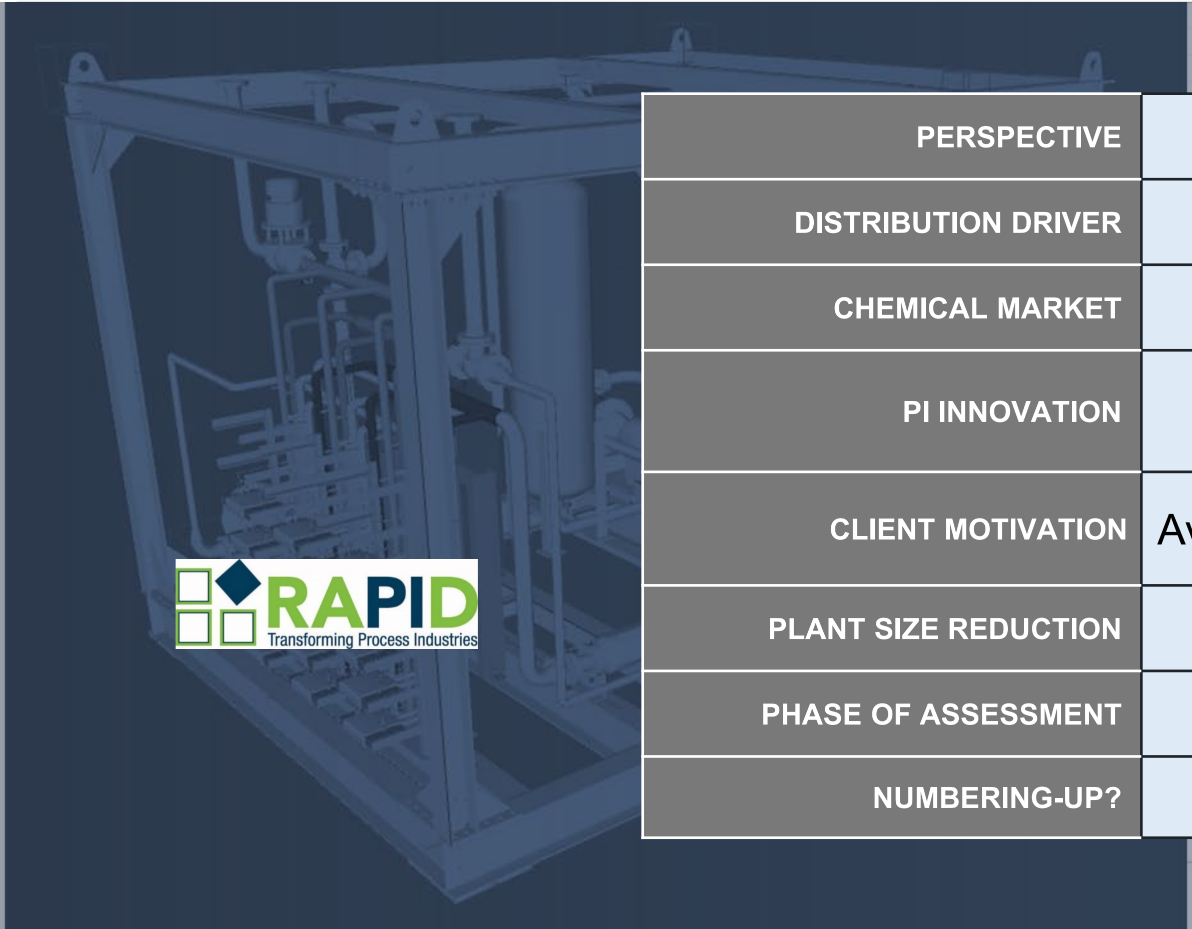
CASE STUDY 2

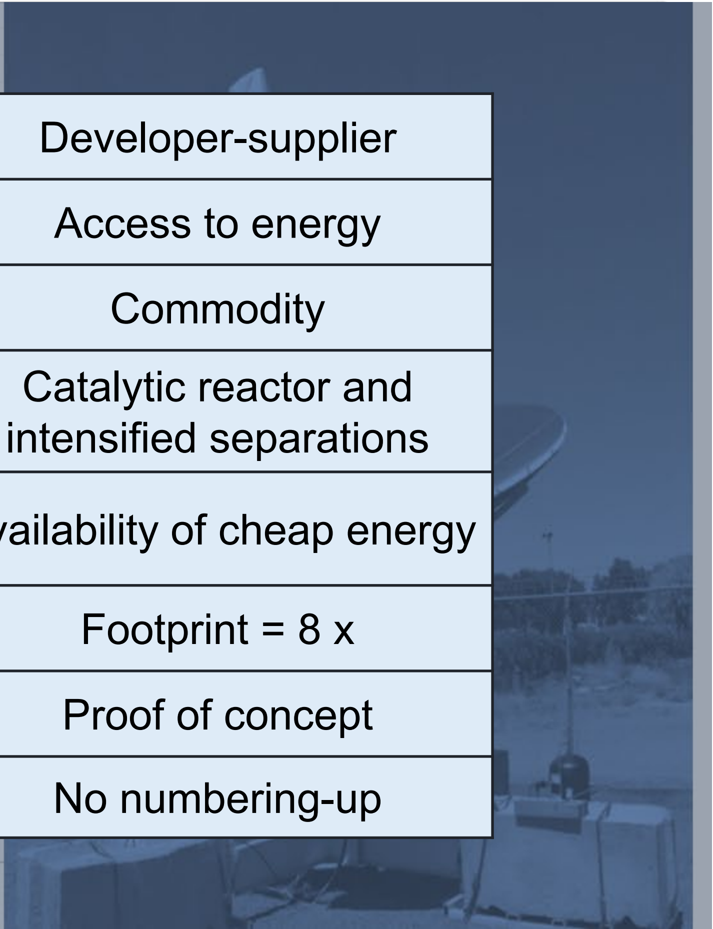
Top Drivers of Superior MCPI Capital Efficiency

55 Drivers from the Literature / Top 6 Drivers

- PI equipment requires fewer interconnecting systems
- Reduced construction footprint, less land, less infrastructure, etc.
- Reduced CapEx due to reduced number of components
- Reduced equipment assembly/installation time and labor effort
- Design effort reduction from DOBM for second, third, fourth, etc. modules
- Module fabricator learning curve benefits from standardization (DOBM)

Case Study 3





PERSPECTIVE	Developer-supplier
DISTRIBUTION DRIVER	Access to energy
CHEMICAL MARKET	Commodity
PI INNOVATION	Catalytic reactor and intensified separations
CLIENT MOTIVATION	Availability of cheap energy
PLANT SIZE REDUCTION	Footprint = 8 x
PHASE OF ASSESSMENT	Proof of concept
NUMBERING-UP?	No numbering-up

Leveraging Cheap Distributed Energy

CASE STUDY 3

Comparison: PI / Process / OPEX Features

Plant Area for 146k MTPY Capacity

*MCPI plant has 5 modules

Conventional Stick-Built (CSB)

8X reduction in plant area

MCPI*

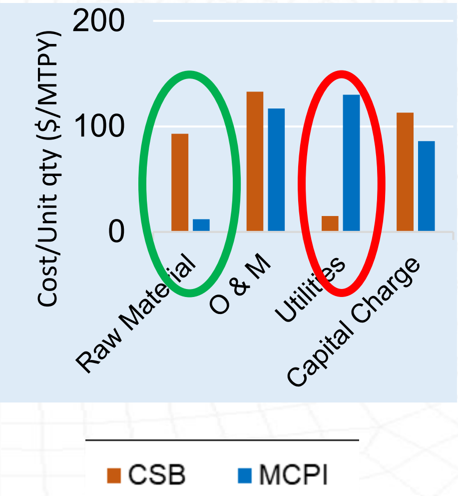
	Process Technology	Footprint	Brownfield SIMOPS impact	Operations Staff	Learning Curve	Scale-up Rate
CSB	Conventional reactor and separations	141k sq. ft.	High	Scales with plant size	N/A	Full capacity in 3 years
MCPI	Catalytic reactor and intensified separations	18k sq. ft.	Minimal	8 FTE (any # of trains)	80%	Double capacity beyond year 2

Net Present Value Analysis

Plant life = 25 yrs @ 10% discount rate

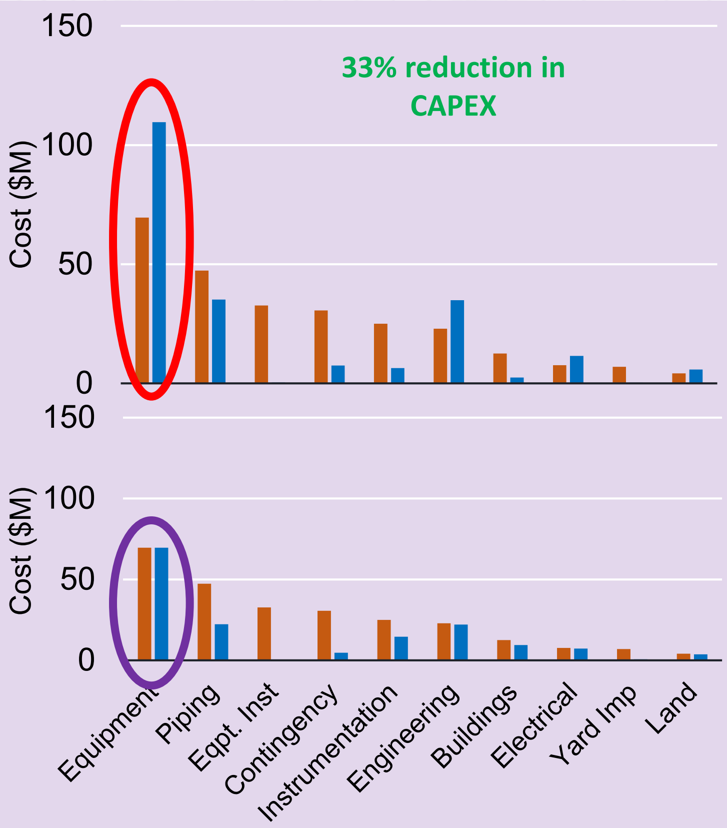
CASE STUDY 3

OPEX Cost Breakdown

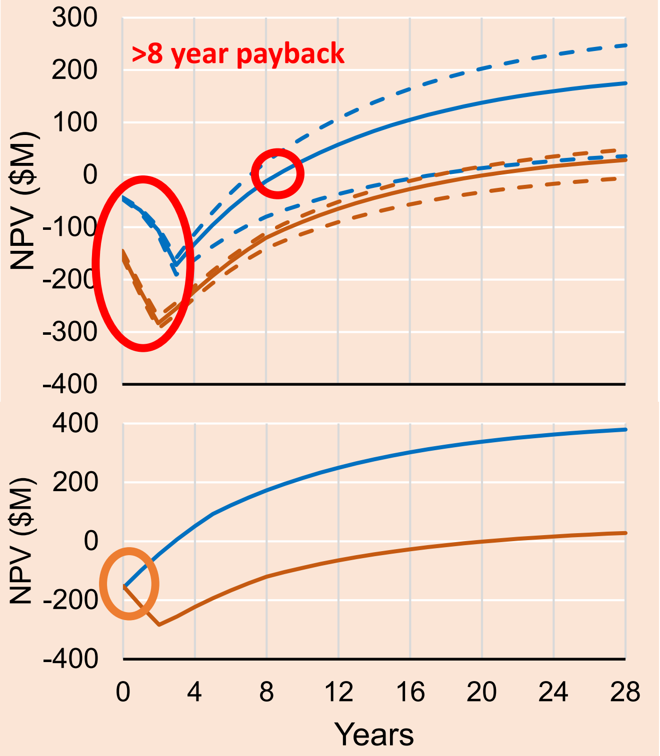


- Utility costs > feedstock gains even with lower utility rates
- Manage cost of innovative PI equipment
- Faster time-to-market

CAPEX Cost Breakdown



NPV Risk Profile



Decrease payback period from >8 years to 2.5 years

Leveraging Cheap Distributed Energy

CASE STUDY 3

Top Drivers of Superior MCPI Capital Efficiency

55 Drivers from the Literature / Top 4 Drivers

- Reduced time of fabrication of equipment (parallel fabrication, reduced size, piping, etc.)
- Faster-time to market for new investments; earlier product sales due to shorter processing times
- Economic benefits from earlier completion; Earlier recovery of investment from early production and sales
- Increased efforts for engineering of new technologies

- Higher capital expenditures for new advanced equipment
- Significantly higher energy demand

KEY TAKE-AWAYS

MCPI is NOT a “one-size fits all” solution

Sometimes CPI technology does not exist “off-the-shelf”

The development of specialized CPI technology <u>must</u> be managed

Key drivers were NOT identified as top drivers by the case study partner

Case Study 4

Solar Thermochemical Processing

RAPID Transforming Process Industries

Sourcing of specialty microchannel components was difficult.

Microchannel HX

Conventional HX

Parameter	Units	µchannel HX		Commercial HX
HX mass	Kg	5	14X	70
HX volume	L	1.25	28X	35
Duty	Watts	3500		3500
Effectiveness	%	87		<80
Side 1, Air dP	in H2O	4.3		4.3
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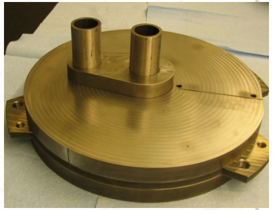
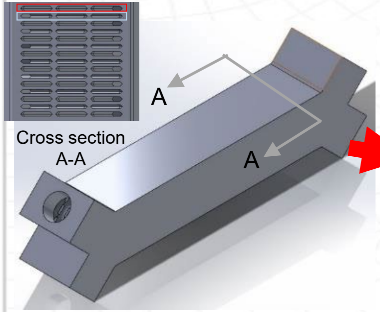
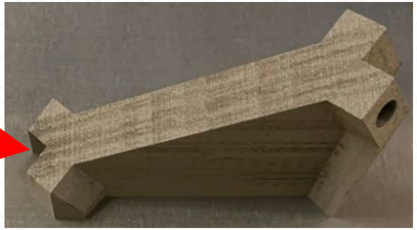


High Temperature Recuperators

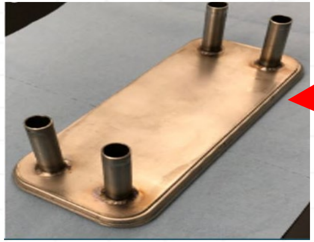
Across Breadth of Production Volumes

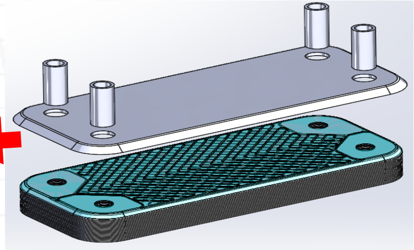
LPBF Inconel 625 HTR



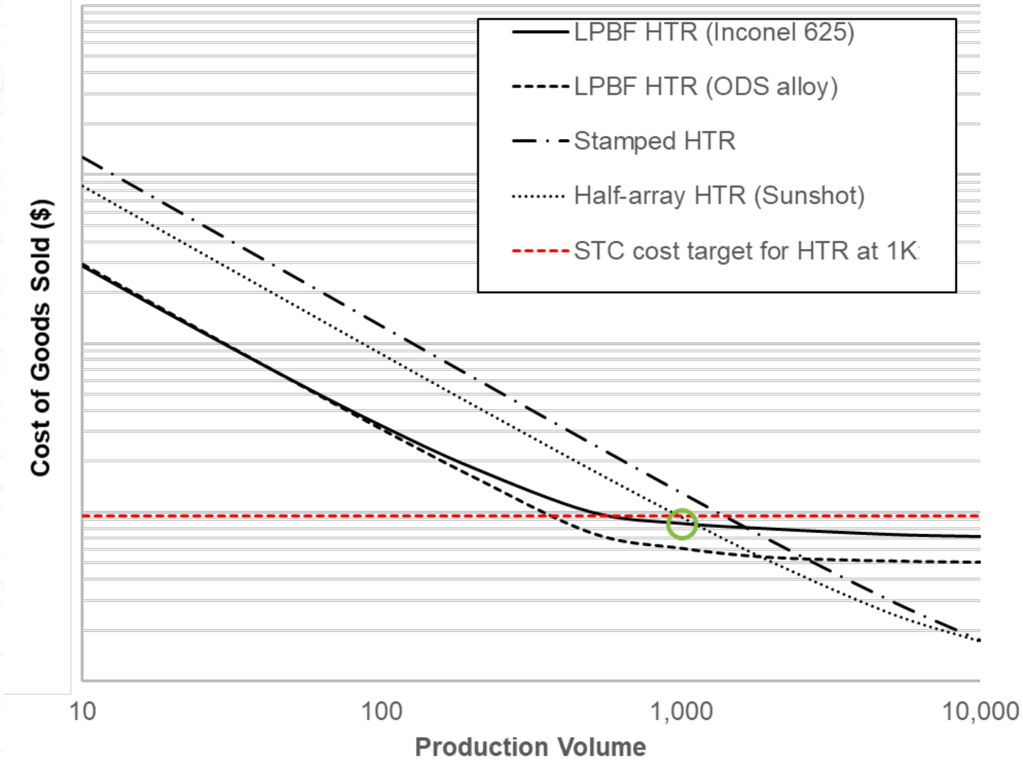


LPBF ODS 316L SS HTR



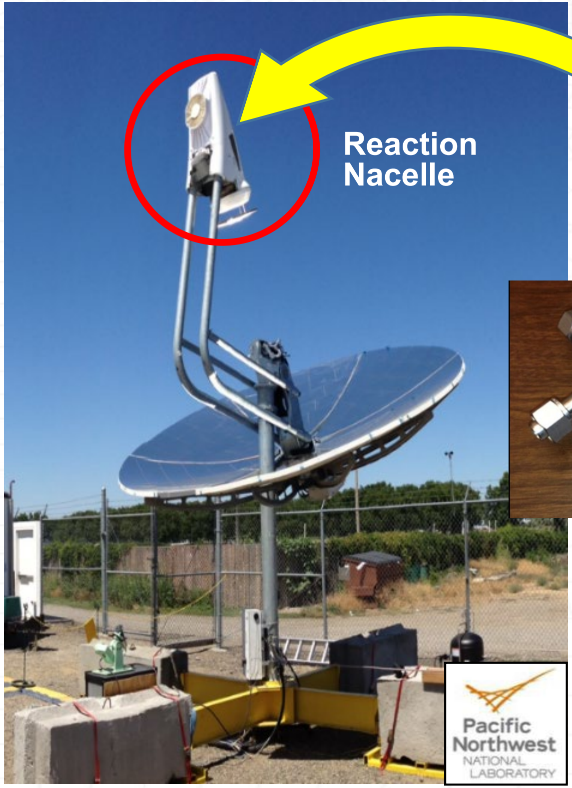


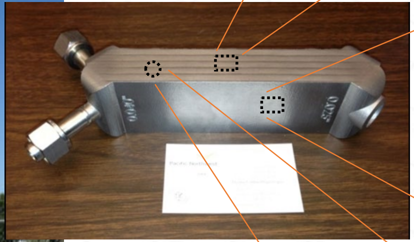
Stamped-brazed Inconel 625 HTR

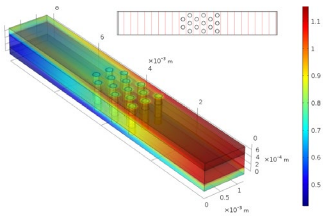


Polymetal Additive Manufacturing

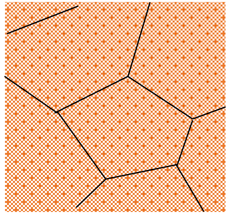
Solar Thermochemical Processing



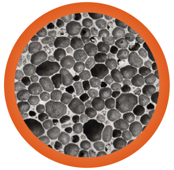




Thermally-enhanced pins to direct heat transfer vertically, minimizing axial heat transfer within compact HXs



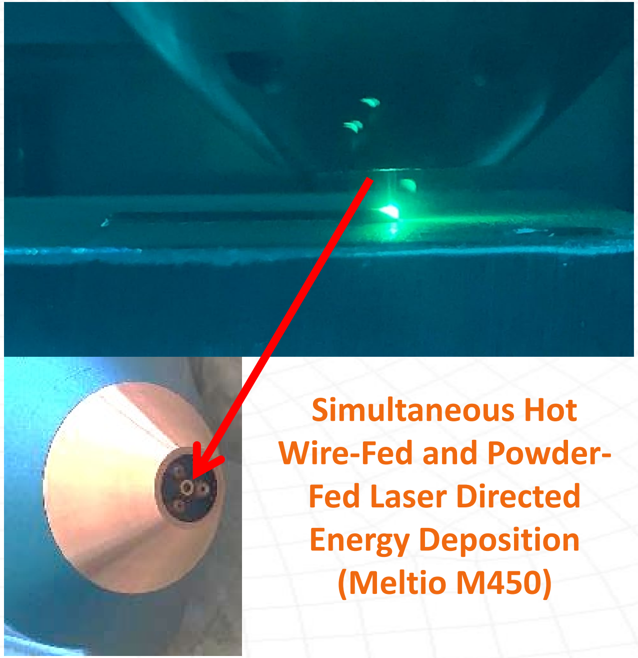
Metal matrix composites enables further lightweighting of the HXs with higher strength and better thermal stability at equivalent density



Integrated catalyst scaffold for reducing the costs of producing catalytic chemical reactors

Polymetal Additive Manufacturing

Inc625/GRC42 Transitional Alloy (Paul et al. 2021)



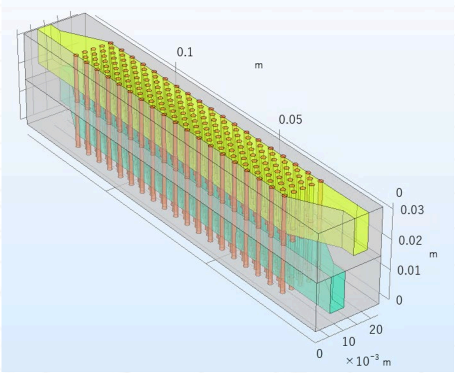
Simultaneous Hot Wire-Fed and Powder-Fed Laser Directed Energy Deposition (Meltio M450)

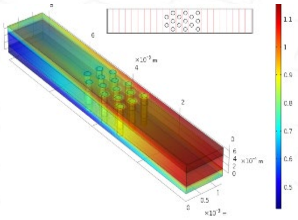
Materials

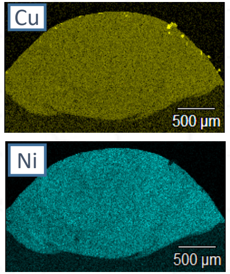
Inconel 625 (70 wt%)

+

GRCop 42 (30 wt%)







Programmable Machine Tool + Primary Alloys = 13X ↑ in Thermal Conductivity

(20X size reduction)

Case Study Key Learnings

1. CPI technology significantly **reduces plant size**, which reduces construction scope, enables modularization, reduces CAPEX, reduces time-to-market and accelerates capital recovery

2. **Operating expenditures** are reduced in MCPI plants due to the need for less operating staff due to the conversion of the chemical process from batch to continuous or from a reduced number of operating steps

3. Opportunities exist to convert specialty chemical operations from **batch-to-continuous** chemical processing reducing CAPEX and time-to-market

4. CPI technology significantly reduces the cost of **interconnecting systems**

5. When developing specialty CPI technology, the cost of **process intensification equipment** is an important driver that **must be managed**

Recap / Closure

MCPI challenges old plant design paradigms and offers new opportunities

Substantial benefits may be realized, if managed

A visionary champion is critical to advance MCPI within large organizations

Pursue MCPI through the AIChE RAPID Institute: https://www.aiche.org/rapid

Modular Chemical Process Intensification "Boot Camp"

RAPID
Transforming Process Industries

www.aiche.org/ch375

Oregon State University

When: June 21-24, 2022

Where: Corvallis, OR at OSU ATAMI

- Advanced Technology and Manufacturing Institute (ATAMI) is a 80,000 sq ft R&D and university commercialization facility and past home to the RAPID Modular Manufacturing Focus Area.
- Advanced manufacturing technologies available through ATAMI include laser powder bed fusion, laser directed energy deposition, binder jetting and polymetal additive manufacturing among others.

What:

- Use characteristic time-scale analysis to identify and design PI components for an MCPI application.
- Cost/performance trade-offs in developing innovative PI component designs.
- Engage additive manufacturing/3D printing equipment used to build PI components.
- Consider the deployment of MCPI plants through Engineering, Procurement and Construction firms.
- Consider the business rationale for designing and scaling up an MCPI plant.

Who Should Attend:

- Professional engineers interested in advancing MCPI within their organizations
- Open to anyone including RAPID members

Instructors:

- Professor Brian Paul is a manufacturing engineering professor with over 20 years experience helping small companies take process intensification technology to market
- Professor Goran Jovanovic is a chemical engineering professor with over 20 years of experience developing atto/nano/microtechnologies for industrial-scale chemical engineering applications

THANK YOU!

QUESTIONS?

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