U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Advanced Manufacturing, Clean Energy Technologies and Process Intensification

September 29, 2014

NSF Process Intensification Meeting

VA Tech Executive Center, Arlington, VA

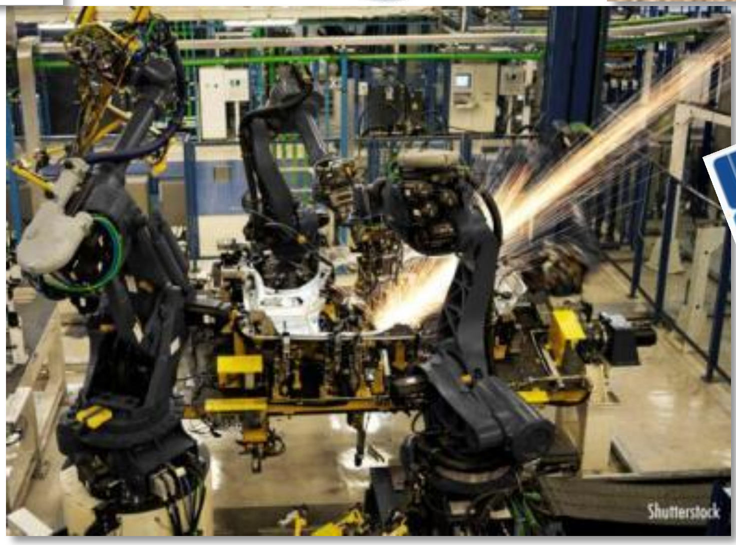
Mark Johnson

Director

Advanced Manufacturing Office

www.manufacturing.energy.gov

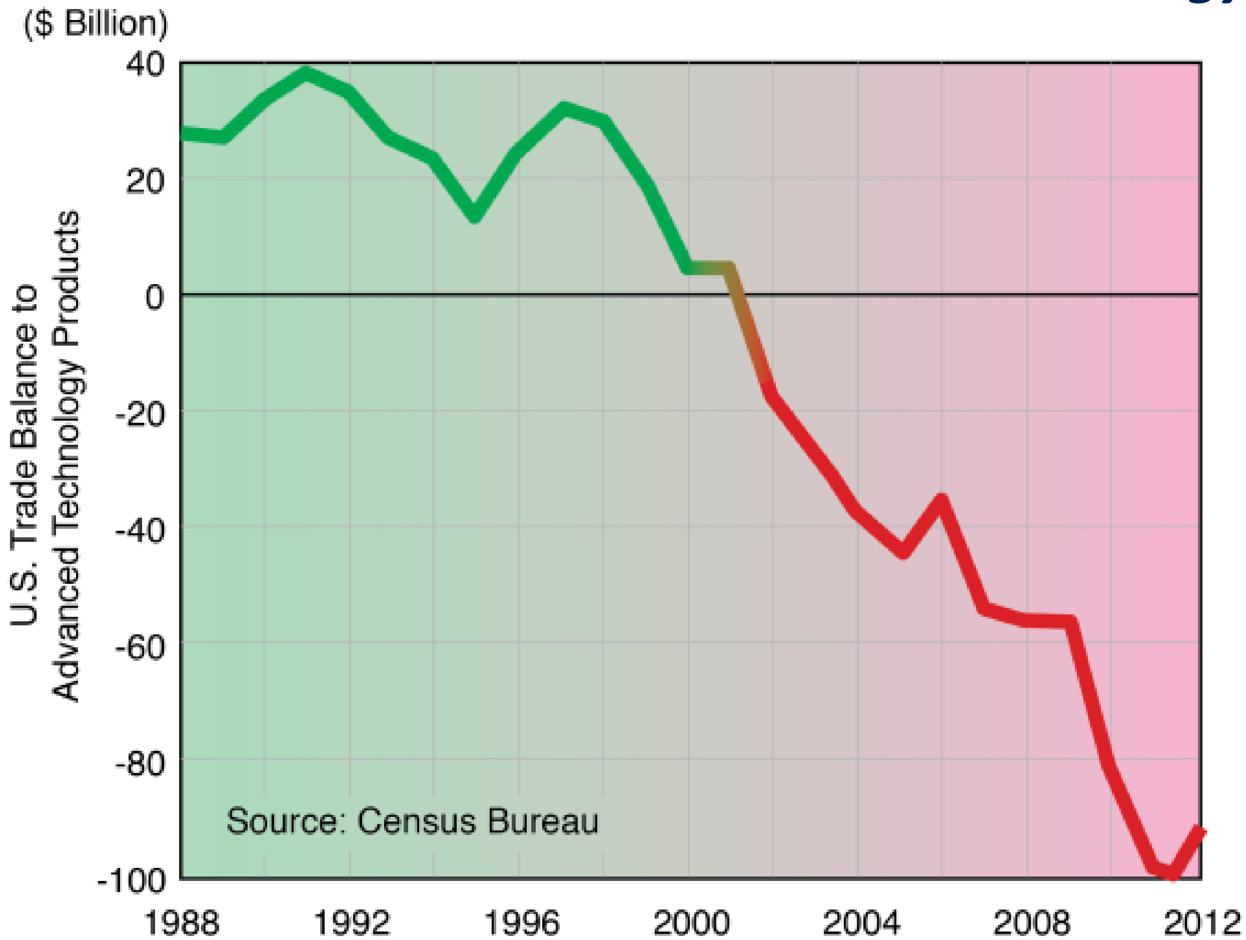
Status Quo: Products invented here, and made elsewhere



Significance of U.S. Manufacturing

11% of U.S. GDP, **12** million U.S. jobs, **60%** of U.S. Exports

U.S. Trade Balance of *Advanced Technology*



Swung to historic deficit, lost 1/3rd of workforce

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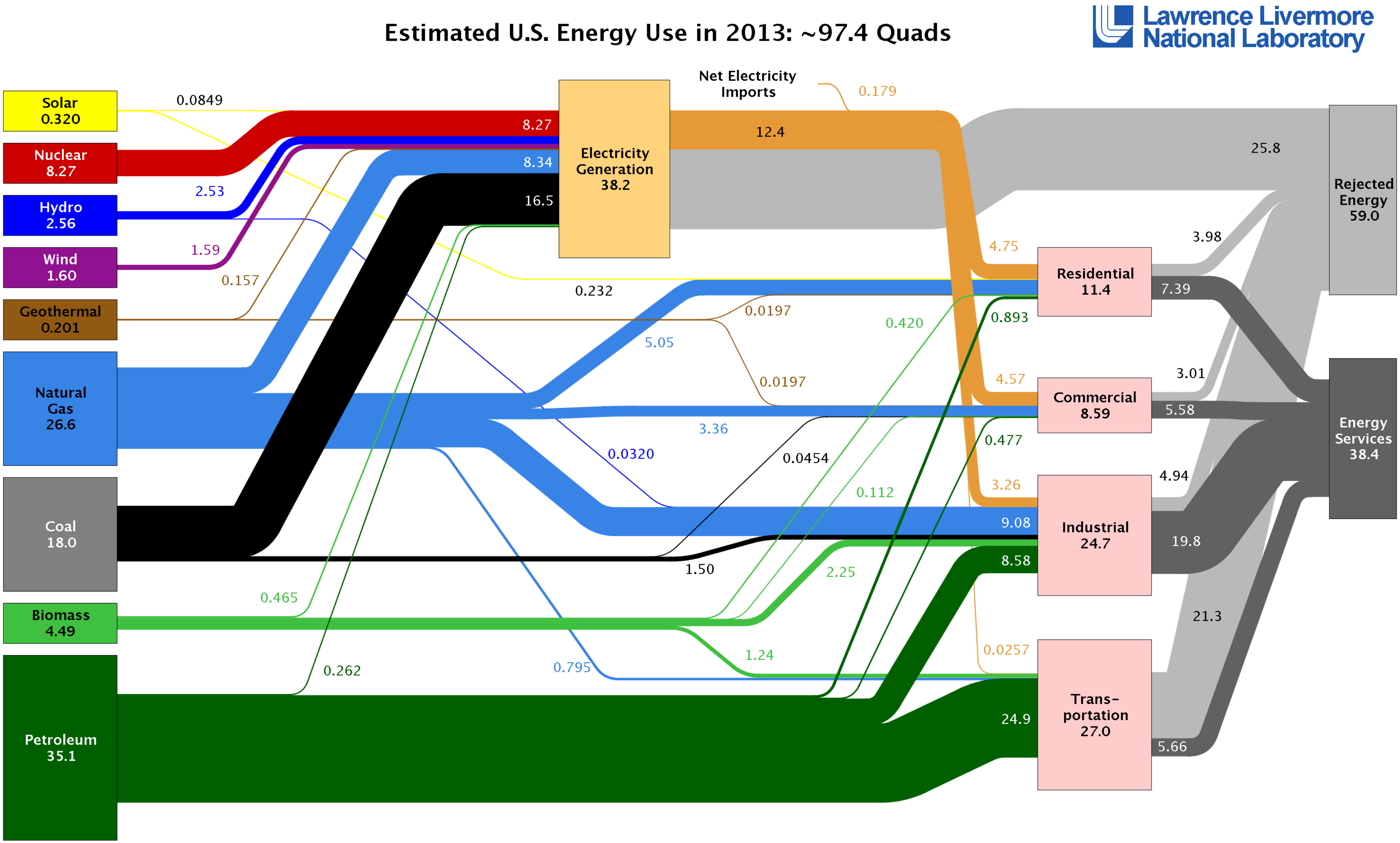
Clean Energy: Nexus of Opportunities

- Energy self-reliance
- Stable, diverse energy supply

- Competitiveness in clean energy
- Domestic jobs

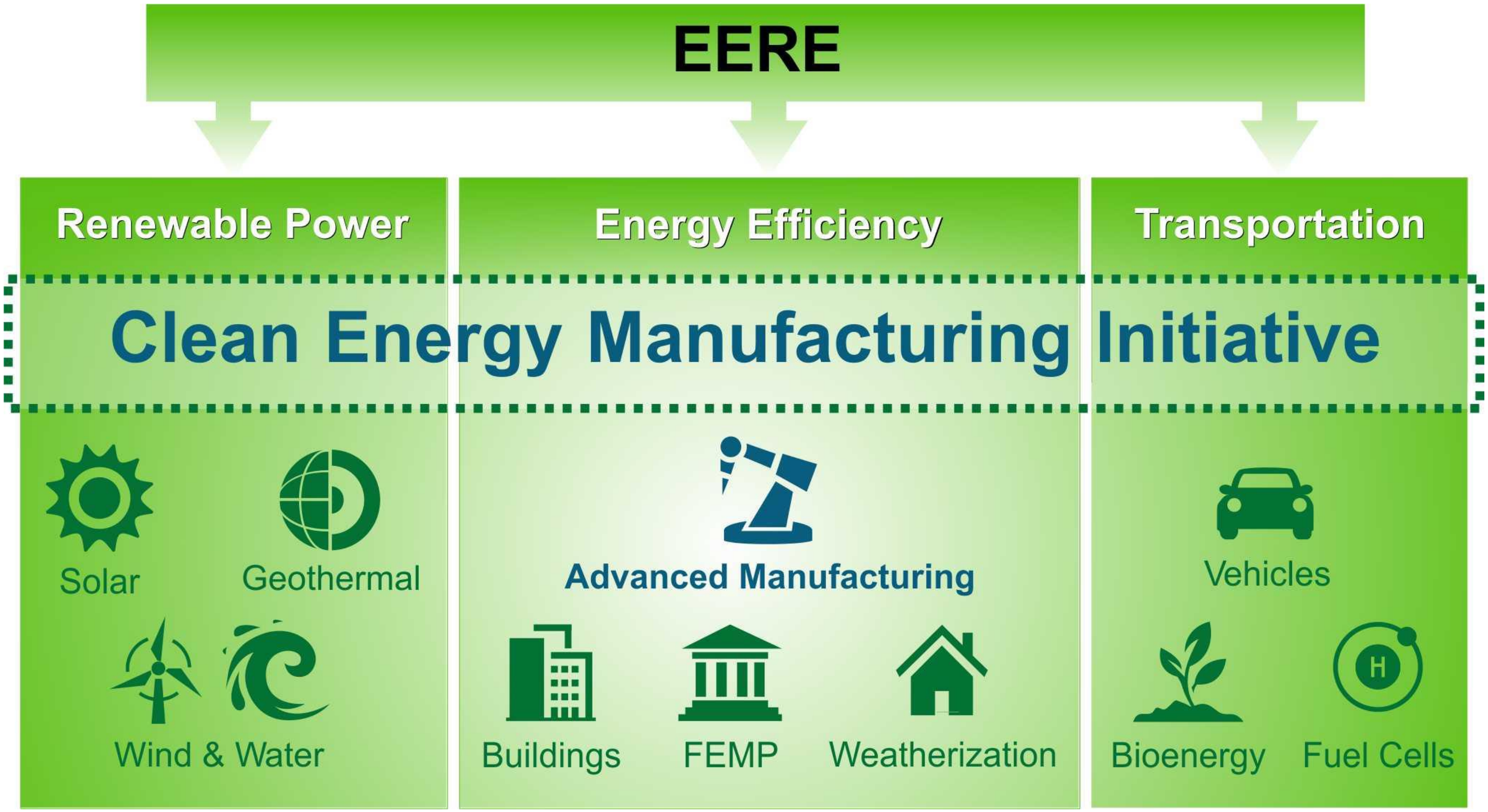
- Clean air
- Climate change
- Health

Energy Efficiency & Manufacturing Technology



Source: LLNL 2014. Data is based on DOE/EIA-0035(2014-03), March, 2014. If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant "heat rate." The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 65% for the residential and commercial sectors 80% for the industrial sector, and 21% for the transportation sector. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

Clean Energy Manufacturing Initiative – DOE



Collaboration toward:

- Common goal to collectively ***increase U.S. manufacturing competitiveness***

Coordination for:

- Comprehensive Strategy
- Collaborative Ideas

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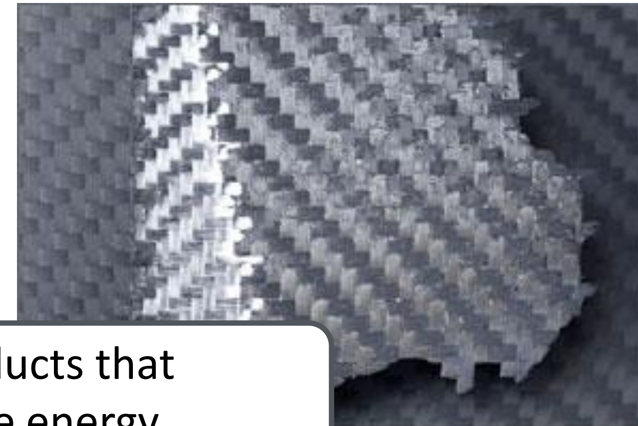
Clean Energy Manufacturing Initiative: Objectives

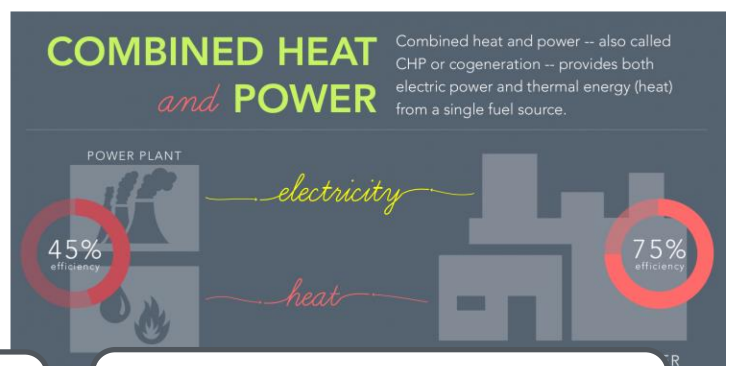
1. **Increase U.S. competitiveness in the production of clean energy products**



Products that generate clean energy

Products that save energy

2. **Increase U.S. manufacturing competitiveness across the board by leveraging energy productivity and low-cost domestic fuels and feedstocks**



Advanced Manufacturing Technologies

Combined Heat & Power

Industrial Energy Efficiency

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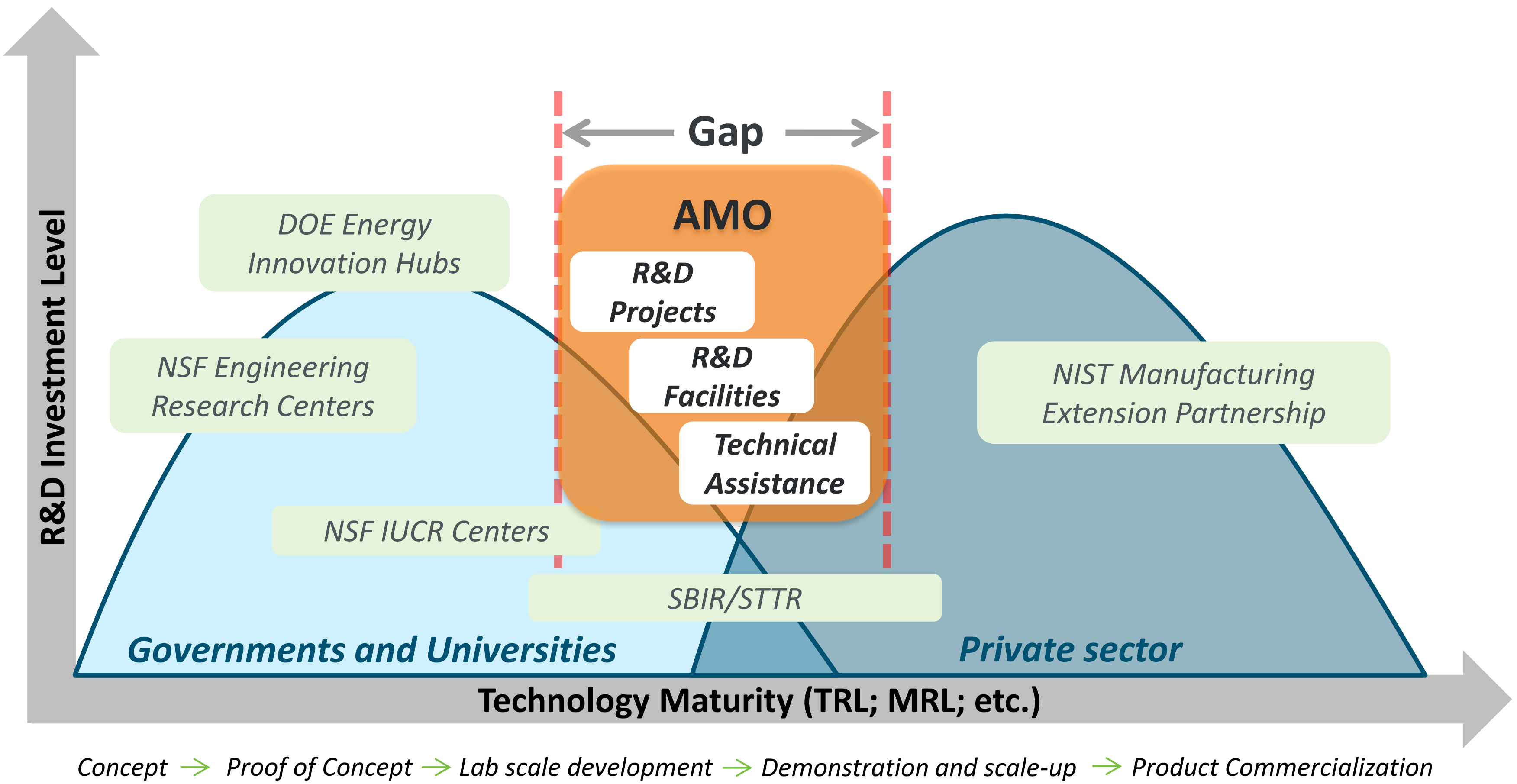
Bridging the Gap to Manufacturing

AMO: Advanced Manufacturing Office



Manufacturing Sector Whitespace

Embedded Energy Intense Manufacturing

Traditional Industry Sector Focus Areas

- Metals
- Glass & Ceramics
- Forest & Biomass
- Petrochemicals
- Extraction
- Concrete

Energy Use-Impactful Manufacturing

- Transportation
- Efficient Systems
- Power Generation
- Energy Delivery

Cross-Cutting Impact Opportunities

Broad Topical Areas

- **Platform Materials and Technologies for Energy Applications**
  - Advanced Materials Manufacturing (Mat'l Genome, Nanomaterials, etc.)
  - Critical Materials
  - Advanced Composites & Lightweight Materials
  - 3D Printing / Additive Manufacturing
  - 2D Manufacturing / Roll-to-Roll Processes
  - Wide Bandgap Power Electronics
  - Next Generation Electric Machines
- **Efficiency in Manufacturing Processes (Energy, CO_2)**
  - Advanced Sensors, Controls, Modeling and Platforms (ie. Smart Manf.)
  - Advanced Chemical Process Intensification
  - Grid Integration of Manufacturing (CHP and DR)
  - Sustainable Manufacturing (Water, New Fuels & Energy)
- **Emergent Topics in Manufacturing**

1. Technical Assistance
2. R & D Projects
3. Manufacturing R & D Facilities
4. Process Intensification

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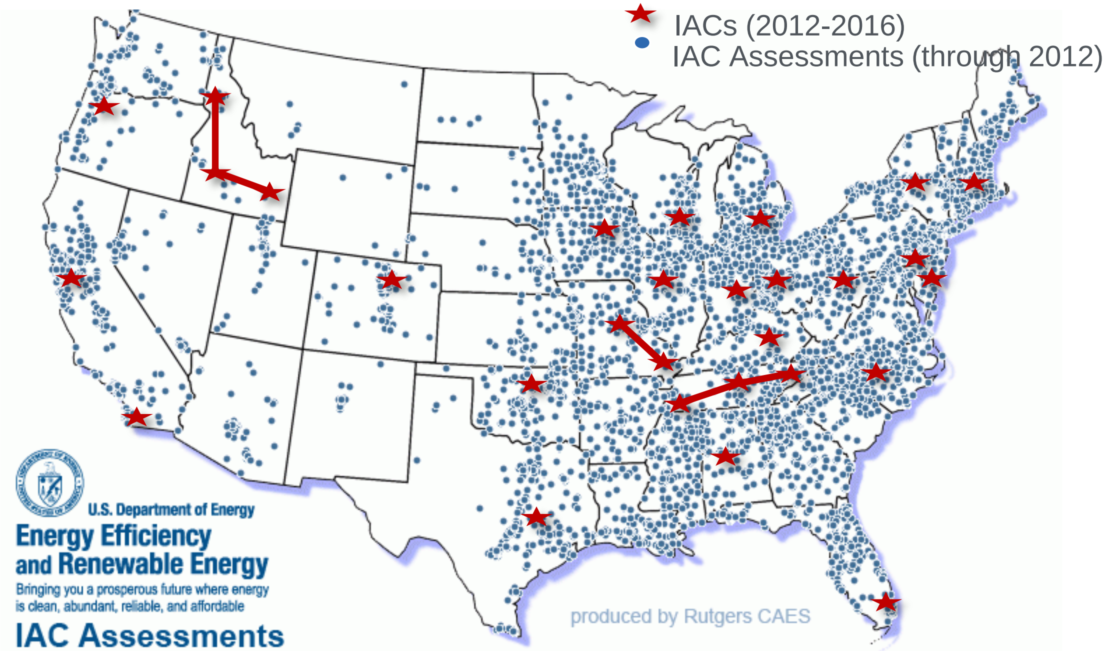
Better Plants Program

- Voluntary pledge to reduce energy intensity by 25% over ten years over all facilities
- Over 120 Program Partners, over 1,750 plants, ~8% of the total U.S. manufacturing energy footprint
- Partners implement cost-effective energy efficiency improvements that:
  - Save money
  - Create jobs
  - Promote energy security
  - Strengthen U.S. manufacturing competitiveness
- **Through the Better Plants Program, companies receive national recognition and technical support from DOE**

Industrial Assessment Centers (IACs)

- IAC Program: Targets Energy Savings in Small-Medium Size Firms
- Average IAC client will save more than $46,000 in energy and process improvements (nearly 4X return in 18 months)
- Secondary benefit: Training next generation of Energy Leaders



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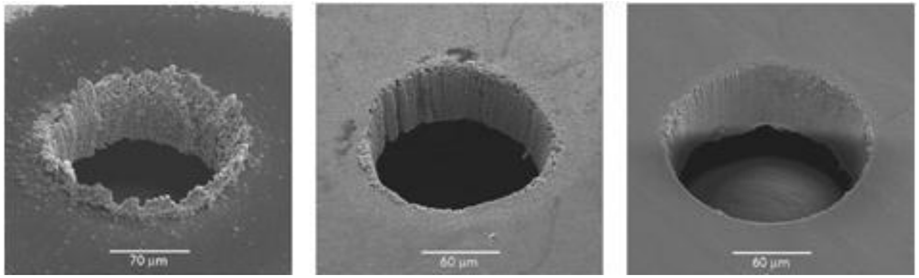
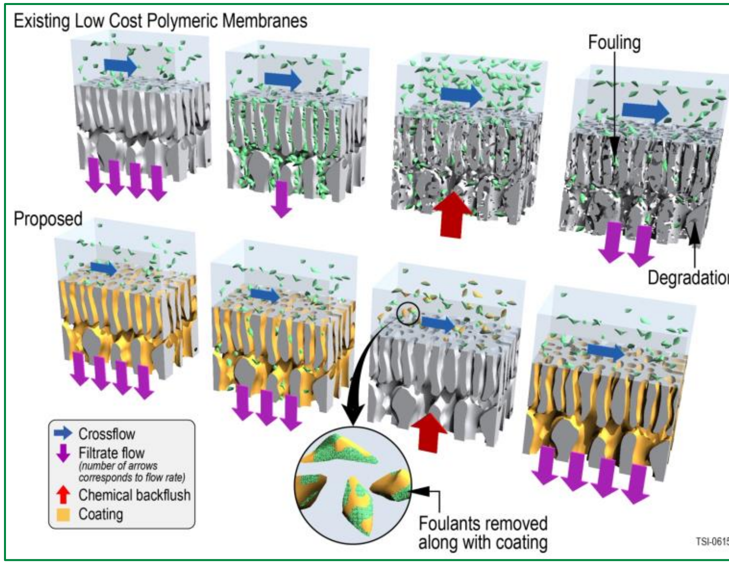
1. Technical Assistance
2. **R & D Projects**
3. Manufacturing R & D Facilities
4. Process Intensification

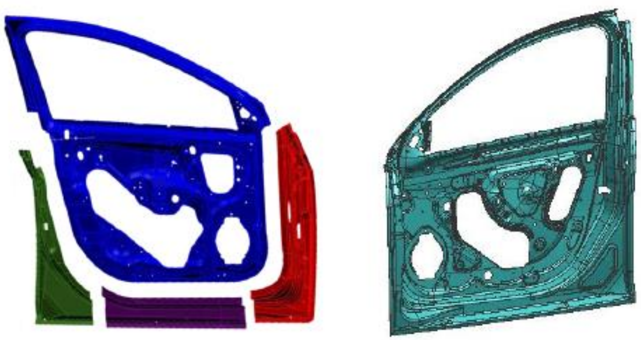
R&D Projects – Manufacturing Processes



Ultrafast, femtosecond pulse lasers (right) will eliminate machining defects in fuel injectors.
Image courtesy of Raydiance.



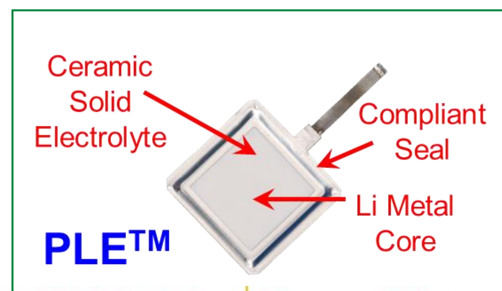
Protective coating materials for high-performance membranes, for pulp and paper industry.
Image courtesy of Teledyne



Energy-efficient large thin-walled magnesium die casting, for 60% lighter car doors.

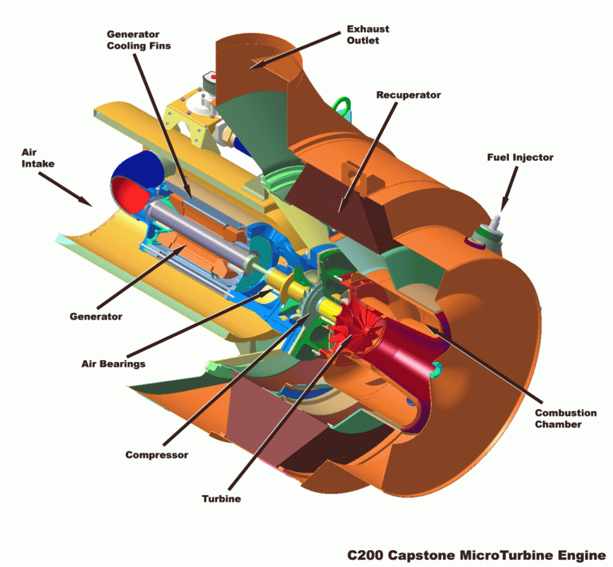
Graphic image provided by General Motors.

A water-stable protected lithium electrode.
Courtesy of PolyPlus



R&D Projects: Combined Heat and Power (CHP) (Process Intensification of Electric Power)

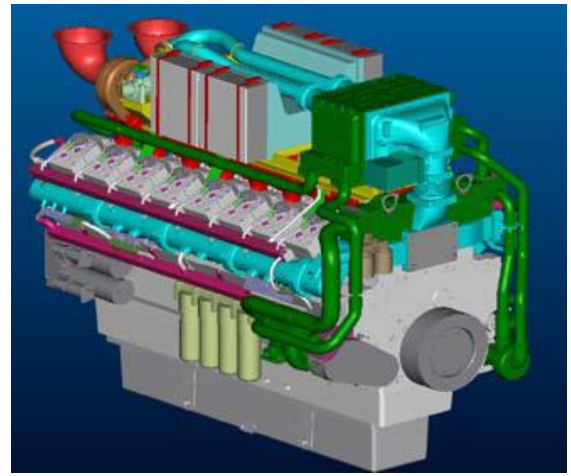
Advanced MicroTurbine System (AMTS) R&D Program



C200 MicroTurbine Engine

Capstone photos source: capstoneturbines.com

Advanced Reciprocating Engine Systems (ARES) R&D Program



QSK60G engine

1. Technical Assistance
2. R & D Projects
3. **Manufacturing R & D Facilities**
4. Process Intensification

Shared R&D Facilities

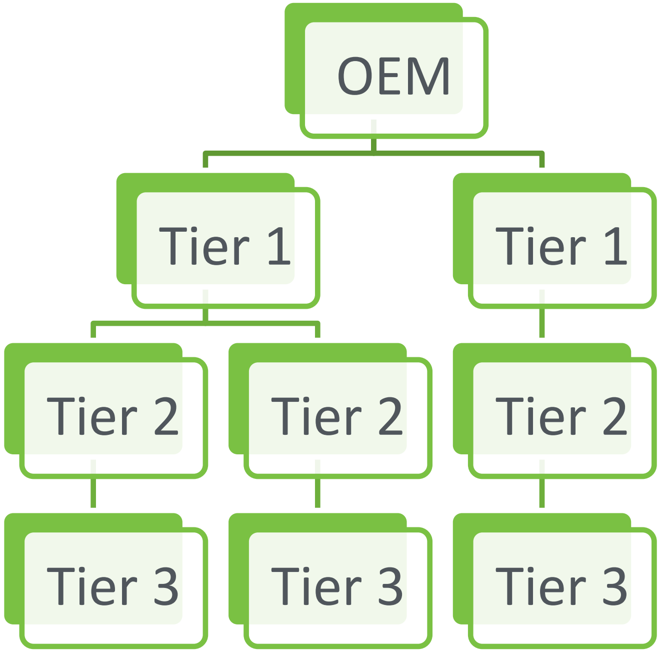
- Address market disaggregation to rebuild the industrial commons

Then

Ford River Rouge Complex, 1920s

Photo: Library of Congress, Prints & Photographs Division, Detroit Publishing Company Collection, det 4a25915.

Now



- **How do we get innovation into manufacturing today?**

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AMO-supported R&D Facilities

1. **Manufacturing Demonstration Facility** at Oak Ridge National Lab
2. **America Makes**, The National Additive Manufacturing Innovation Institute
3. **Critical Materials Institute**: *A DOE Energy Innovation Hub* at Ames National Lab
4. **Next Generation Power Electronics Manufacturing Innovation Institute**
5. **Composites Materials and Structures Manufacturing Innovation Institute** (future – active solicitation)

DOE Assistant Secretary David Danielson during ribbon cutting ceremony of the Carbon Fiber Technology Facility at Oak Ridge National Laboratory. Carbon fiber has the potential to improve the fuel efficiency of vehicles.

Photo courtesy of Jason Richards, Oak Ridge National Laboratory.

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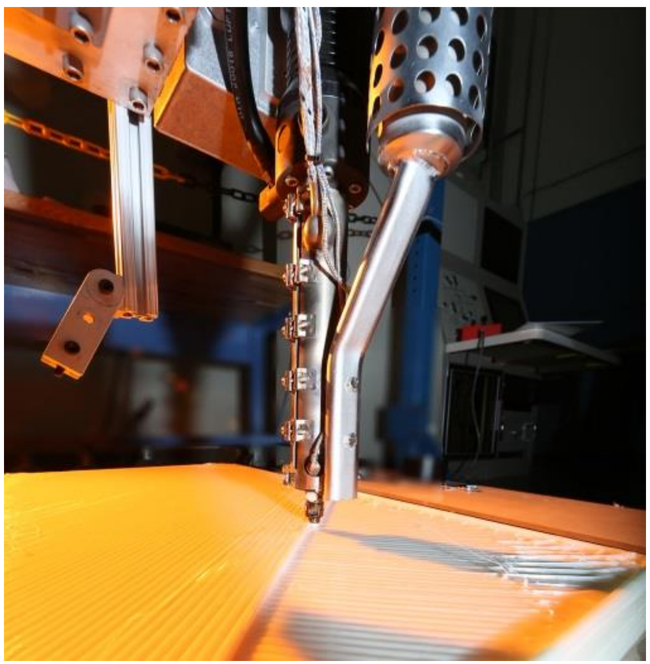
Manufacturing Demonstration Facility at Oak Ridge National Lab

Supercomputing Capabilities

Spallation Neutron Source



Additive Manufacturing

Arcam electron beam processing AM equipment

POM laser processing AM equipment

Program goal is to accelerate the manufacturing capability of a multitude of AM technologies utilizing various materials from metals to polymers to composites.

America Makes

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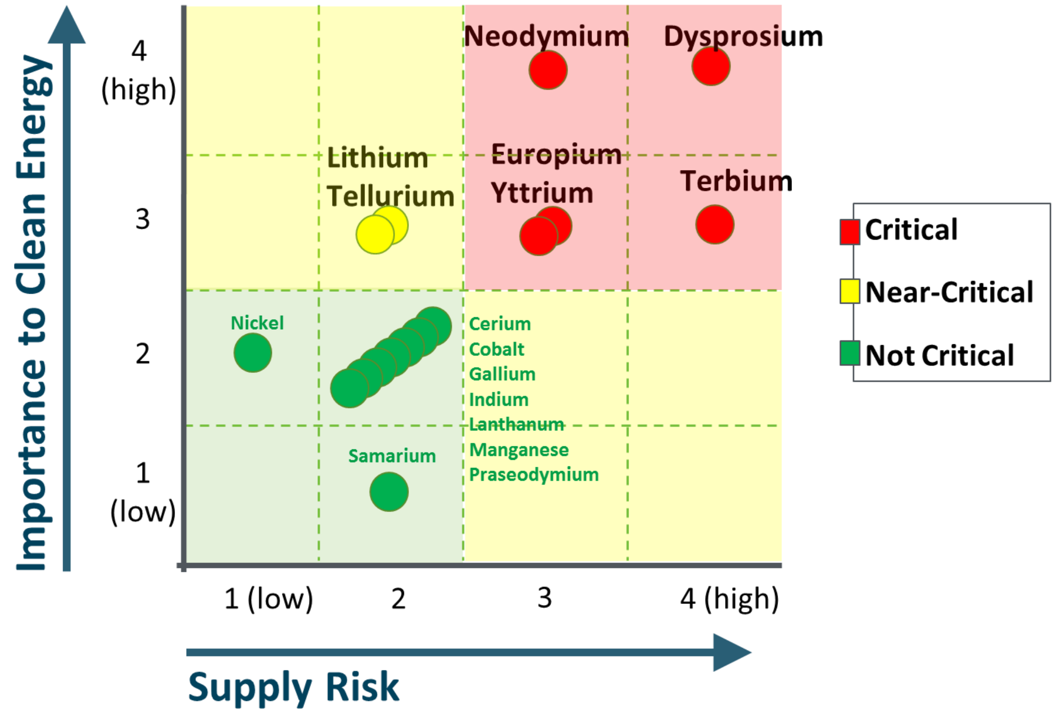
Accelerating Energy Innovations

Critical Materials Institute

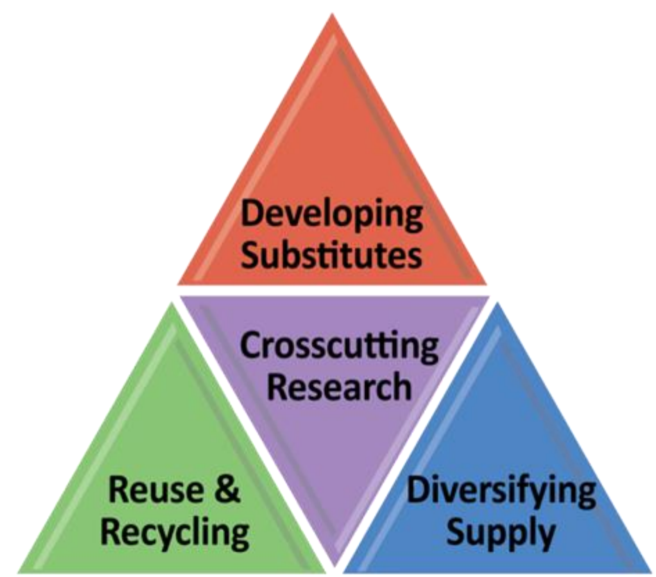
A DOE Energy Innovation Hub

- Consortium of 7 companies, 6 universities, and 4 national laboratories
- Led by Ames National Laboratory

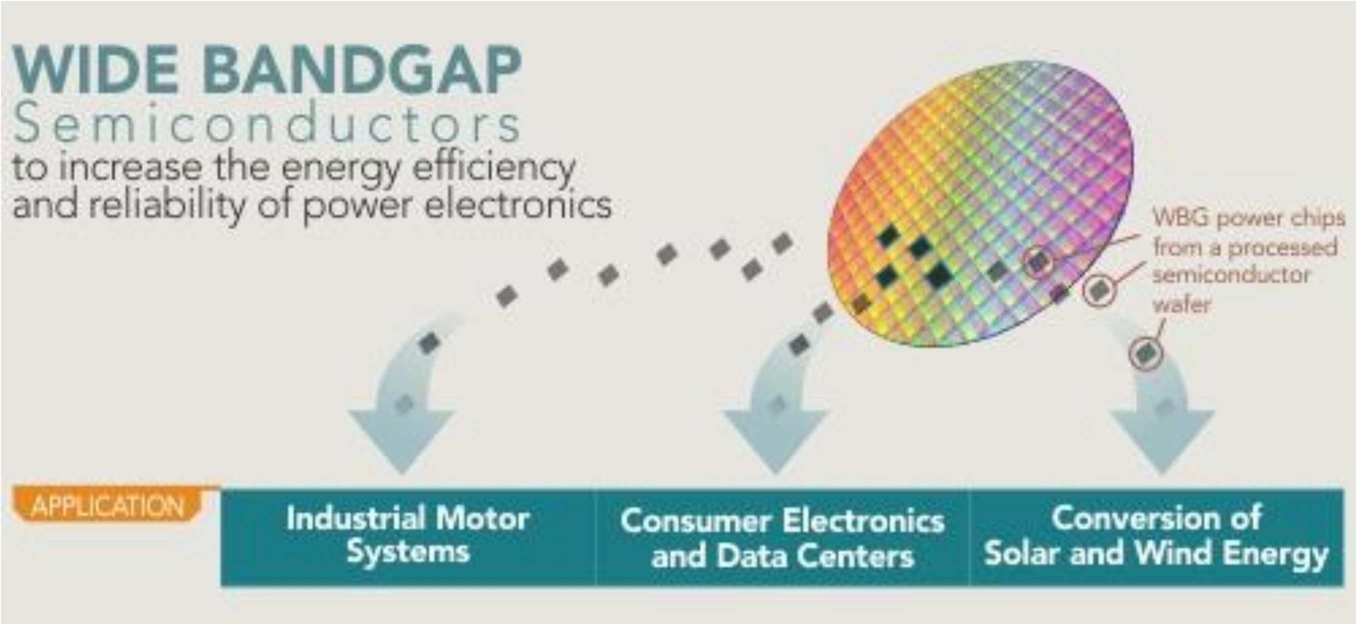


	Dy	Eu	Nd	Tb	Y	Li	Te
Lighting		✓		✓	✓		
Vehicles	✓		✓			✓	
Solar PV							✓
Wind	✓		✓				

Critical Materials - as defined by U.S. Department of Energy, *Critical Materials Strategy*, 2011.



Next Generation Power Electronics Manufacturing Innovation Institute



Institute Mission:
Develop advanced manufacturing processes that will enable large-scale production of wide bandgap semiconductors

- Higher temps, voltages, frequency, and power loads (compared to Silicon)
- Smaller, lighter, faster, and more reliable power electronic components
- $3.3 B market opportunity by 2020.[1]
- Opportunity to maintain U.S. technological lead in WBG

Poised to revolutionize the energy efficiency of electric power control and conversion

[1] Lux Research, 2012.

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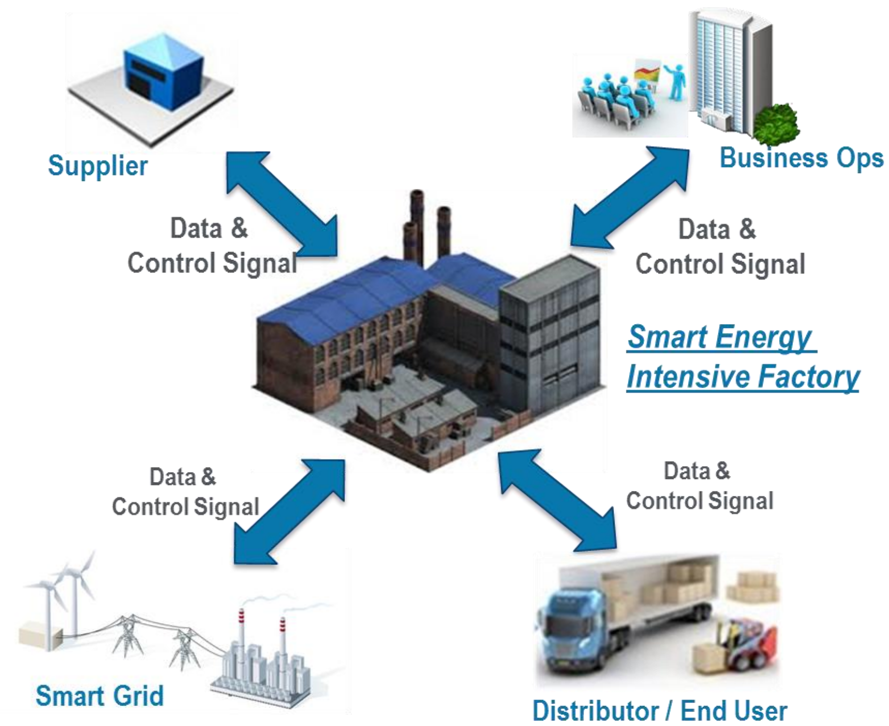
Broad Topical Areas

- **Platform Materials and Technologies for Energy Applications**
  - Critical Materials
  - 3D Printing / Additive Manufacturing
  - WBG Power Electronics
  - Advanced Composites & Lightweight Materials
  - Advanced Materials Manufacturing (Mat'l Genome, Nanomaterials, etc.)
  - 2D Manufacturing / Roll-to-Roll Processes
  - Next Generation Electric Machines
  - Value-Added Chemicals from Biology
- **Efficiency in Manufacturing Processes (Energy, CO_2)**
  - Advanced Sensors, Controls, Modeling and Platforms (ie. Smart Manf.)
  - Advanced Chemical Process Intensification
  - Grid Integration of Manufacturing (CHP and DR)
  - Water & Energy for Manufacturing
  - Alternative Fuels (Natural Gas) and Manufacturing
- **Emergent Topics in Manufacturing**

Advanced Controls, Sensors, Models & Platforms for Energy Intensive Process & Clean Energy Productivity



Smart factories will be interconnected with supply chain, distribution, and business systems.

- Encompass machine-to-plant-to-enterprise-to-supply-chain aspects of sensing, instrumentation, monitoring, control, and optimization
- Enable hardware, protocols and models for advanced industrial automation: requires a holistic view of data, information and models in manufacturing
- Leverage High Performance Computing for High Fidelity Process Models
- Significantly reduce energy consumption and GHG emissions & improve operating efficiency – **20% to 30% potential**
- Increase productivity and competitiveness across all manufacturing sectors: Special Focus on Energy Intensive Manufacturing Processes

Leverages AMP 2.0

Advanced Materials Manufacturing

leveraging unique capabilities for fast-tracking materials to market, while expanding and enhancing the tools & methods in the core

Core Effort for Advanced Materials

unique set of in-house capabilities in accelerated energy-materials development

Advanced Modeling, Computing, and Simulation Capabilities

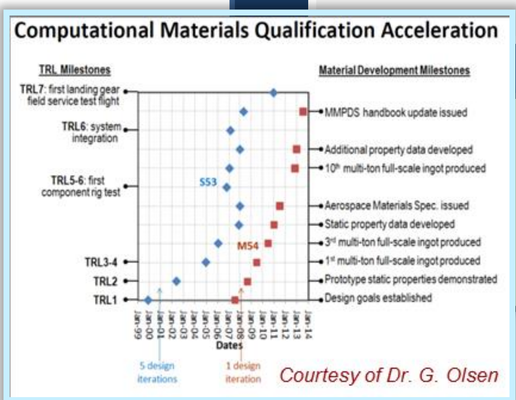
leveraging and expanding on the current MGI multi-physics, multi-scale computational base

feedback pathways

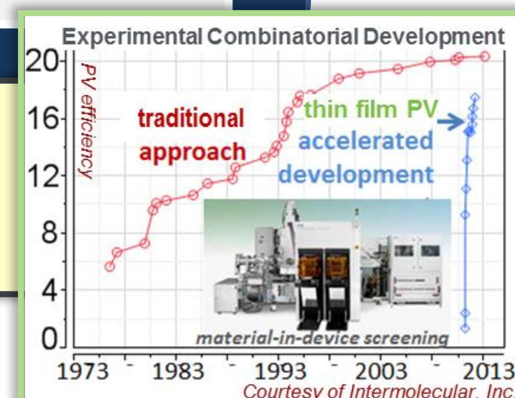
High Throughput Synthesis, Characterization & Analysis Capabilities

high productivity combinatorial discovery & development tailored to specific energy end uses

linkages in methods / data / intellectual property



Combines multi-physics, multi-scale computation with high-throughput synthesis and characterization for intelligent, focused RD&D in numerous energy technology thrusts, managed, e.g., in cross-cutting Materials Manufacturing Centers of Excellence (MMCOEs)



Leverages AMP 2.0

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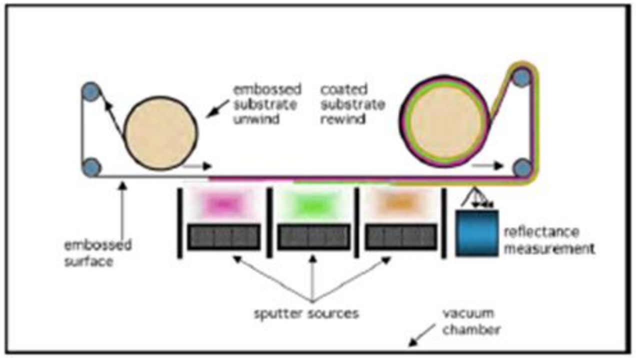
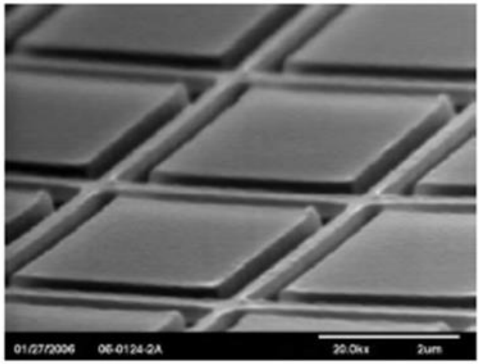
2D Fabrication / Advanced Roll-to-Roll Manufacturing

- **Technology development for the electronic manufacturing service (EMS) sectors to move from plate-to-plate standard lithography to continuous R2R processing.**
- **Miniaturization of critical feature sizes to the nanoscale**
- **Advancing tools and methods for process control, defect sensing, and real-time feedback**

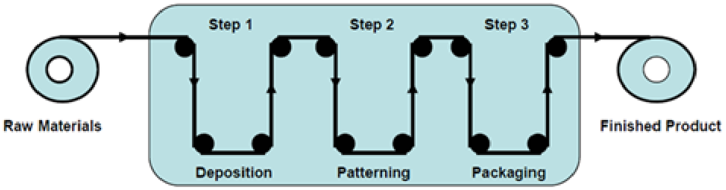
- **<u>Potential Energy Applications</u>:**

  Solar, Batteries, Fuel Cell MEAs, Separation Membranes, Building Envelopes, etc.





Prototype "Nano-Fab" using R2R at CAMM, Binghamton University (SUNY)



Idealized R2R Process Methodology

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4. **Process Intensification**

AMO Topical Areas

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- **Emergent Topics in Manufacturing**

Process Intensification

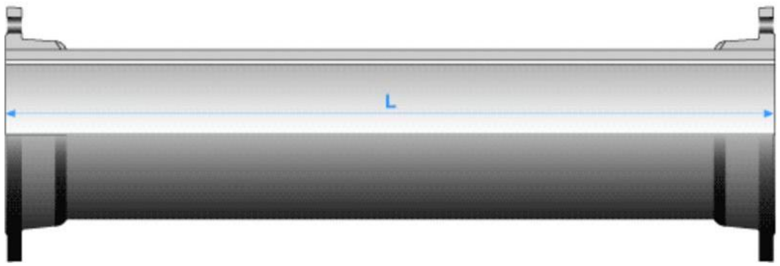
- Termed in 1970s by Kleemann et al. and Ramshaw[15,16]
- What does "process intensification" mean?

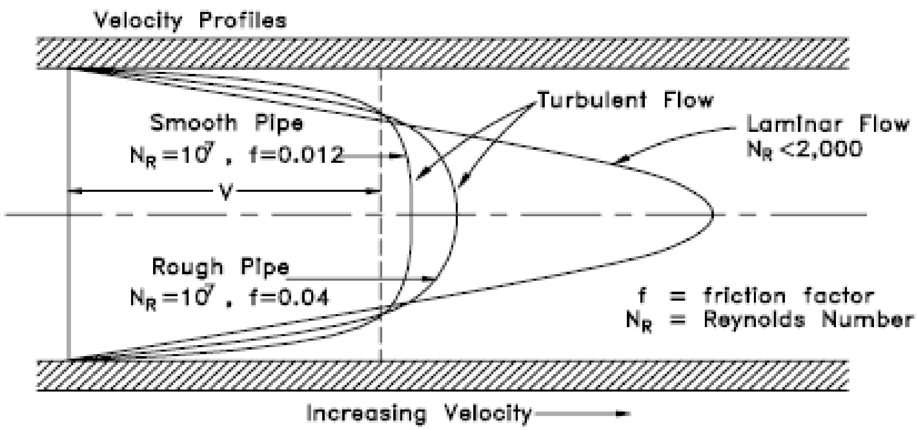
> ***Process intensification*** *is a chemical process with the precise environment it needs to flourish, results in better products, and processes which are* ***safer, cleaner, smaller, and cheaper****.*
>
> \- The BHR Group[19]

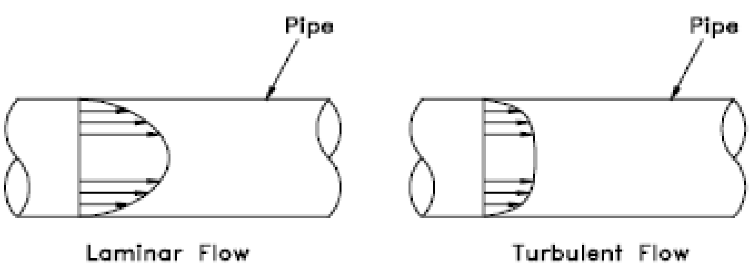
[15] G Kleemann, K Hartmann, Z Wiss. Tech Hochschule "Carl Schorlemmer" *Leuna Merseburg* 20:417, 1978
[16] C Ramshaw. *Chem. Eng*. 389:13, 1983.
[19] BHR Group: www.bhrgroup/pi/aboutpi.htm

Acknowledgement: Dane Boysen, ARPA-E

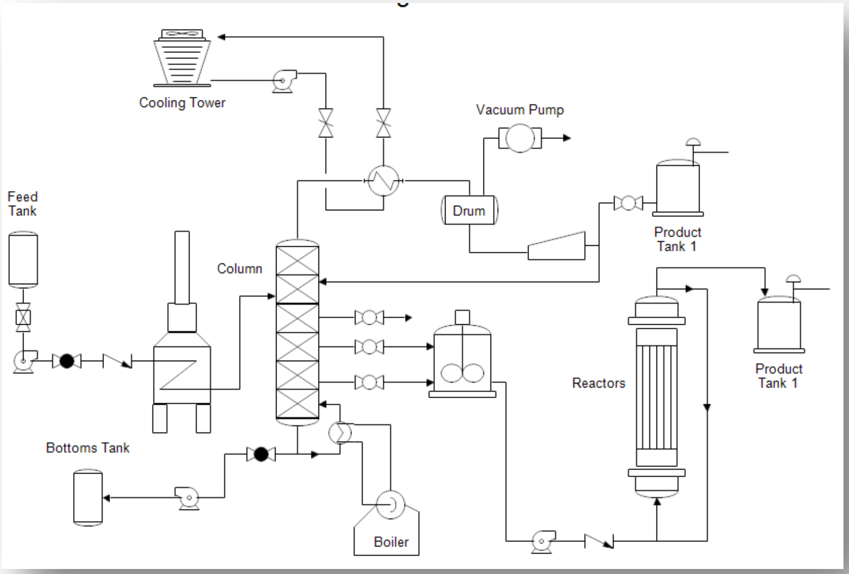
The Chemical Engineer







Process Flow Diagram



$$\frac{Cost_2}{Cost_1} = \left(\frac{Capacity_2}{Capacity_1}\right)^m$$

...the world is a pipe

The Chemist

- Reactions
  - ✓ Kinetics
  - ✓ Thermodynamics
  - ✗ Transport

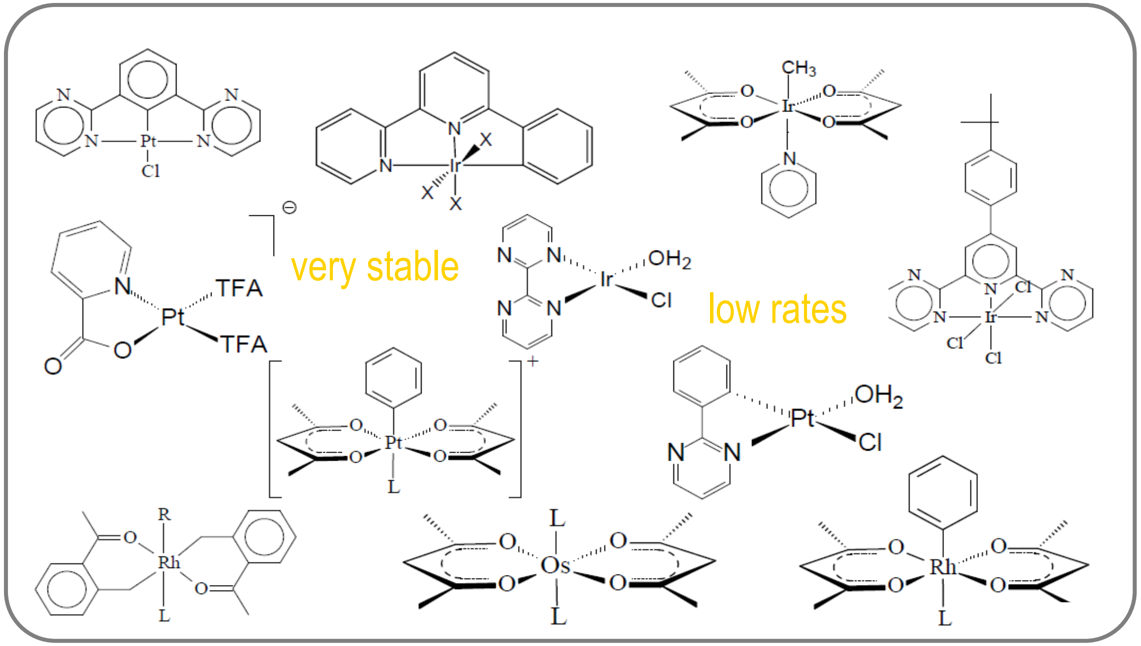
$$aA + bB \rightarrow cC + dD$$

$$[A](t) = [A]_0 \cdot e^{-kt}, \quad k = k_0 \cdot e^{-E_a / k_B T}$$

$$dU = TdS - pdV + \sum_i \mu_i dn_i$$

- Many new catalysts
  - ✓ High selectivity, S
  - ✓ High conversion, *X*
  - ✗ High yield, $Y = X \cdot S$

- No breakthrough in last 20 years



...the world is a beaker

Process Intensification Overview

- Objectives
  - Significantly enhance transport rates (chemical engineer)
  - Give every molecule exactly the same processing experience (chemist)

- Approach

  Develop processes that lead to dramatically smaller equipment with

  - Improved control of reactor kinetics
  - Higher selectivity/reduced waste
  - Higher energy efficiency
  - Reduced capital costs
  - Reduced inventory
  - Enhanced intrinsic safety
  - Fast response times

[20] David. Process Intensification: Engineering for Efficiency, Sustainability and Flexibility. Elsevier Butterworth-Heinemann, 2008.

Challenge for Scaling Chemical Manufacturing is not high cost,

it is the pace of Innovation

Linked to high risk!

Economies of Scale

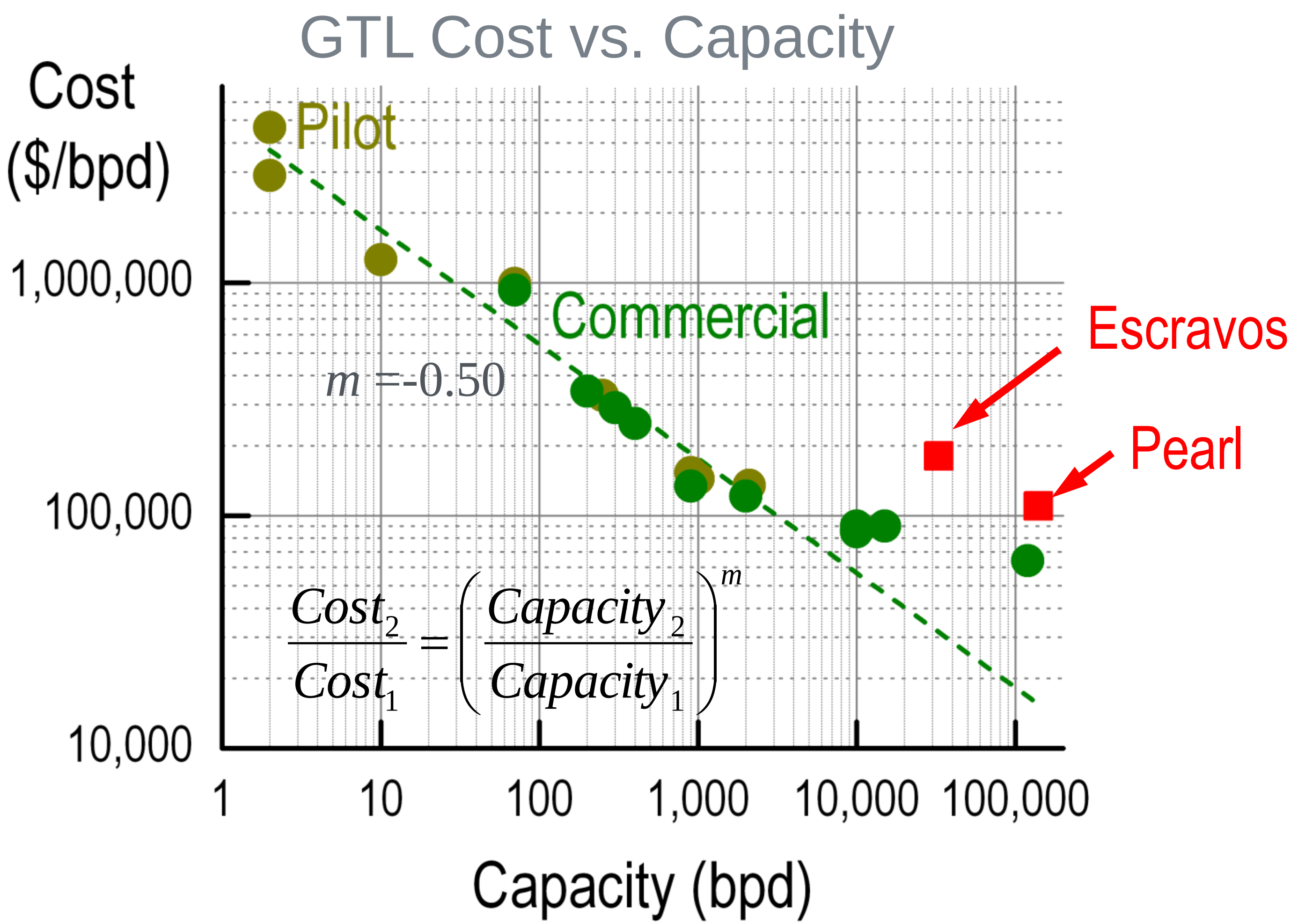
Current paradigm in the chemical process industry

- Economies of scale -- "bigger is better"
- Cost (materials) $\propto$ Area [D^2]
- Revenue (capacity) $\propto$ Volume [D^3]
- Williams equation[8]
- m = 0.38-0.90

$$\frac{Cost_2}{Cost_1} = \left(\frac{Capacity_2}{Capacity_1}\right)^m$$

[8] R. Williams. Standardizing cost data on process equipment. *Chemical Engineering*, 54(6):102, 1947

Economies of Scale



Source: PJA Tijm. *Gas to liquids, Fischer-Tropsch, advanced energy technology, future's pathway*. Feb 2010.

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Is Bigger Better?

Sasol-Chevron Fischer-Tropsch Reactor

[10] C. Kopp. The US Air Force Synthetic Fuels Program. Technical Report APA-TR-2008-0102. (2008)

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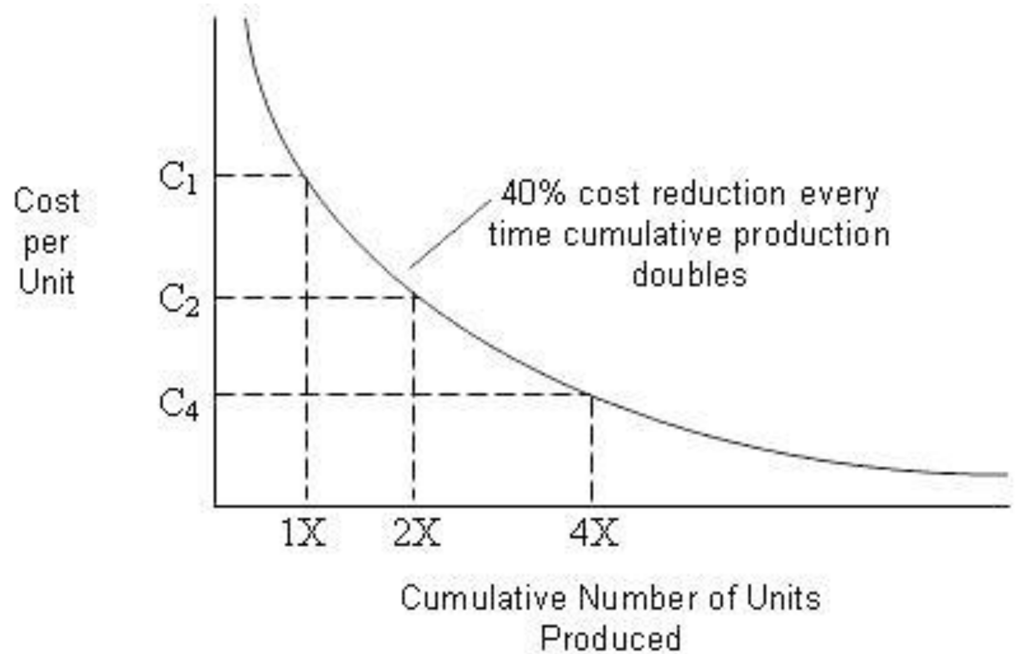
How do we get down new cost reduction learning curves?

Experience Learning Curves

- 1960s Bruce Henderson of Boston Consulting Group
- 15% cost reduction every doubling of output – the "85% experience curve"
- Henderson's Law[11]
  - n: number of units
  - a: elasticity of cost with regard to output

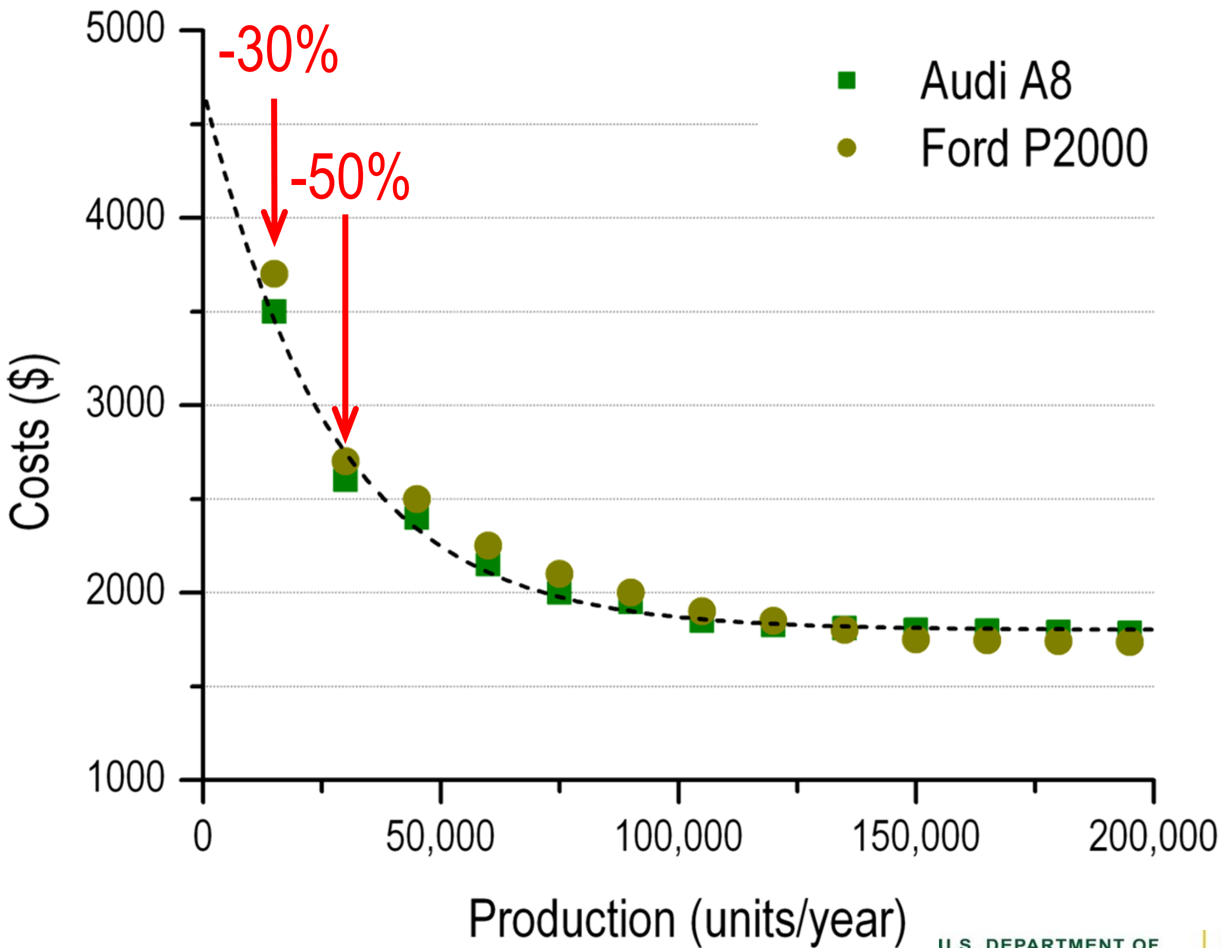


$$Cost_n = Cost_1 n^{-a}$$

[11] A.C. Hax, N.S. Majluf. Competitive cost dynamics: the experience curve. *Interfaces* 12(5):50-56, 1982.

Experience Learning Curves

Total Production Costs of Midsize Cars[12]



[12] A Kelkar, R Roth, J Clark. Automobile Bodies: Can Aluminum Be an Economical Alternative to Steel? JOM 53(8):28-32.2001

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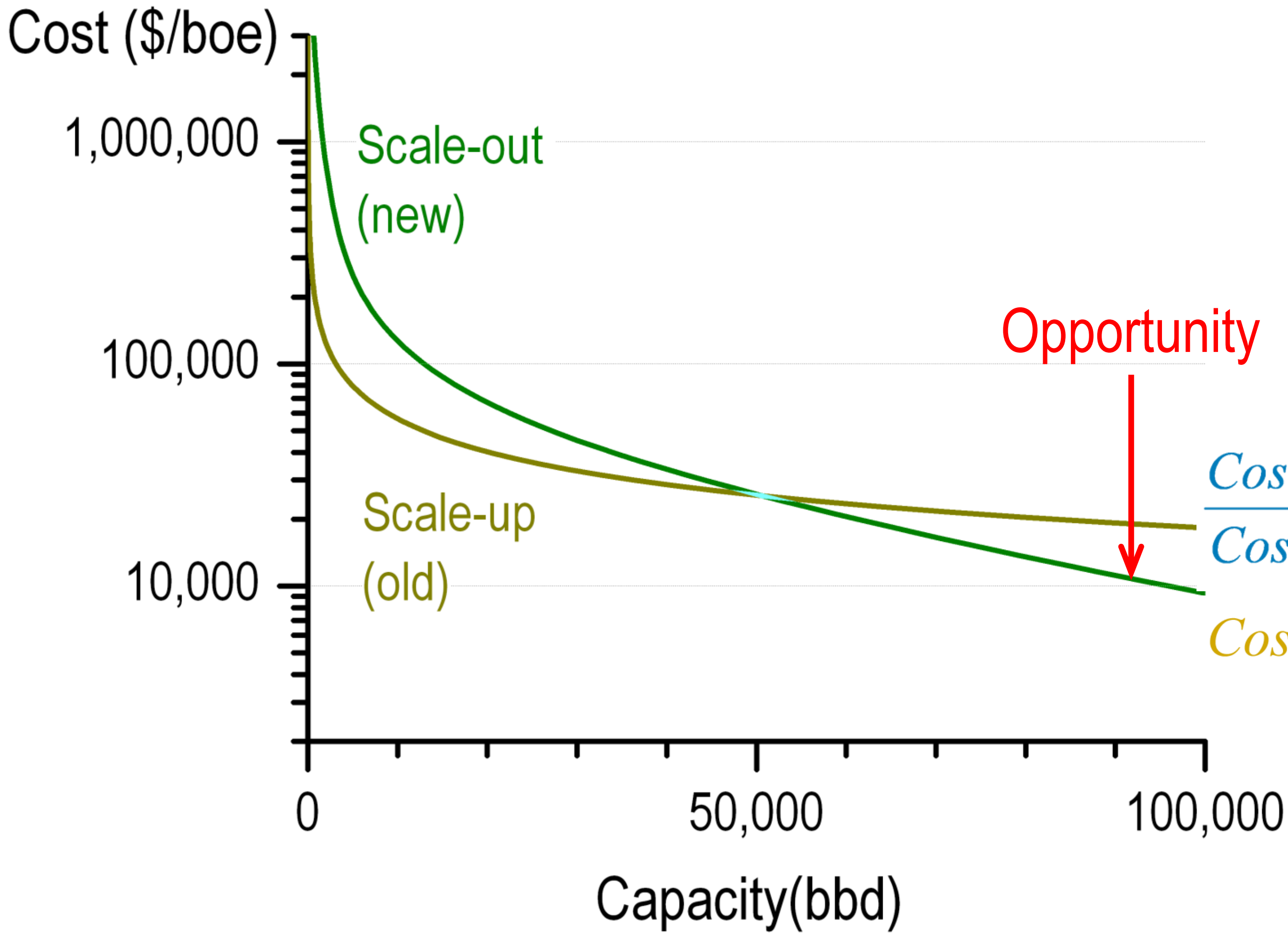
Paradigm Shift



$$\frac{Cost_2}{Cost_1} = \left(\frac{Capacity_2}{Capacity_1}\right)^m$$

$$Cost_n = Cost_1 n^{-a}$$

Vision

Scaled Modules

Defines challenges x3
Engineers system
Establish specs/standards

Evaluates performance
Assesses economics

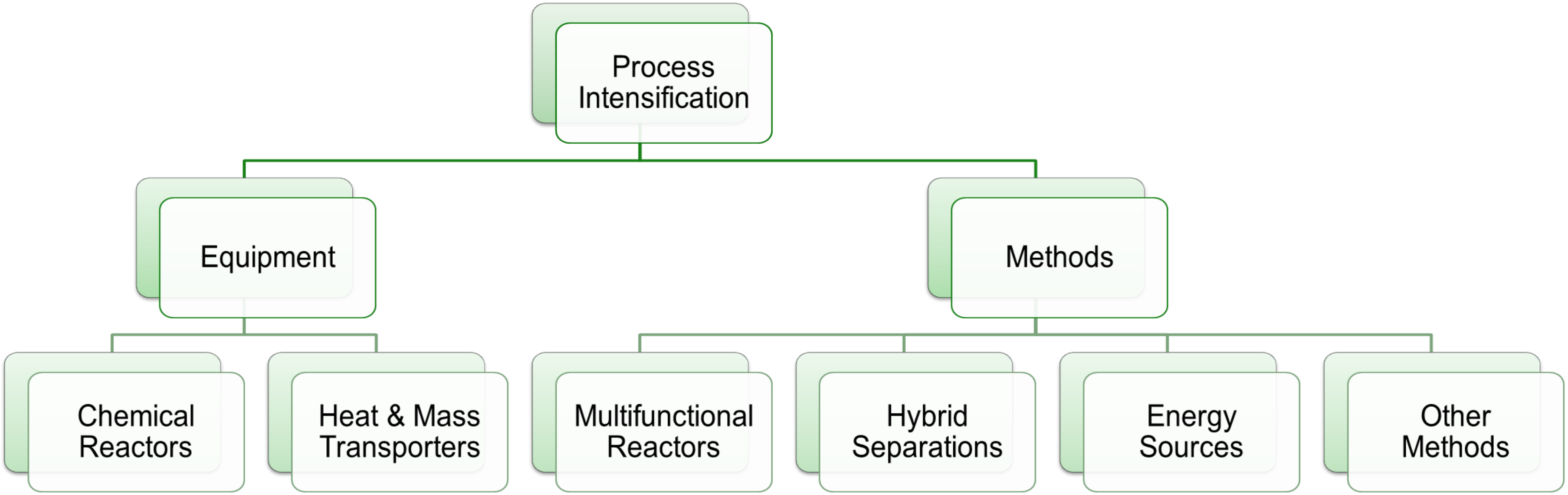
innovate

Integrate

Modules

Reactor innovations
Process intensification

Examples of Process Intensification



- Spinning disk reactor
- Static mixer reactor
- Static mixing catalysts
- Monolithic reactors
- Microreactors
- Heat exchange reactors
- Supersonic gas/liquid reactors
- Jet-impingement reactor
- Rotating packed-bed reactor

- Static mixers
- Compact heat exchanger
- Microchannel heat exchangers
- Rotor/stator mixers
- Rotating packed beds
- Centrifugal adsorber

- Reverse-flow reactors
- Reactive distillation
- Reactive extraction
- Reactive crystallization
- Periodic separating reactors
- Membrane reactors
- Reactive extrusion
- Reactive comminution
- Fuel cells

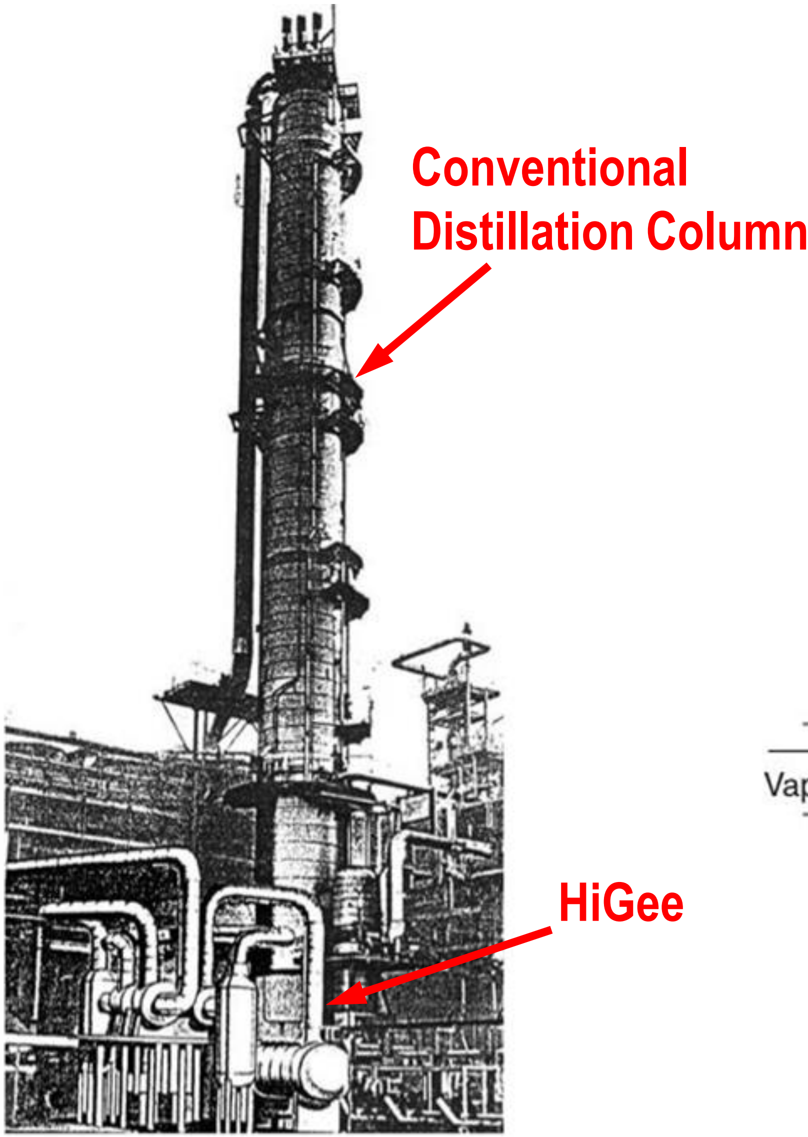
- Membrane adsorption
- Membrane distillation
- Adsorptive distillation

- Centrifugal fields
- Ultrasound
- Solar energy
- Microwaves
- Electric fields
- Plasma technology

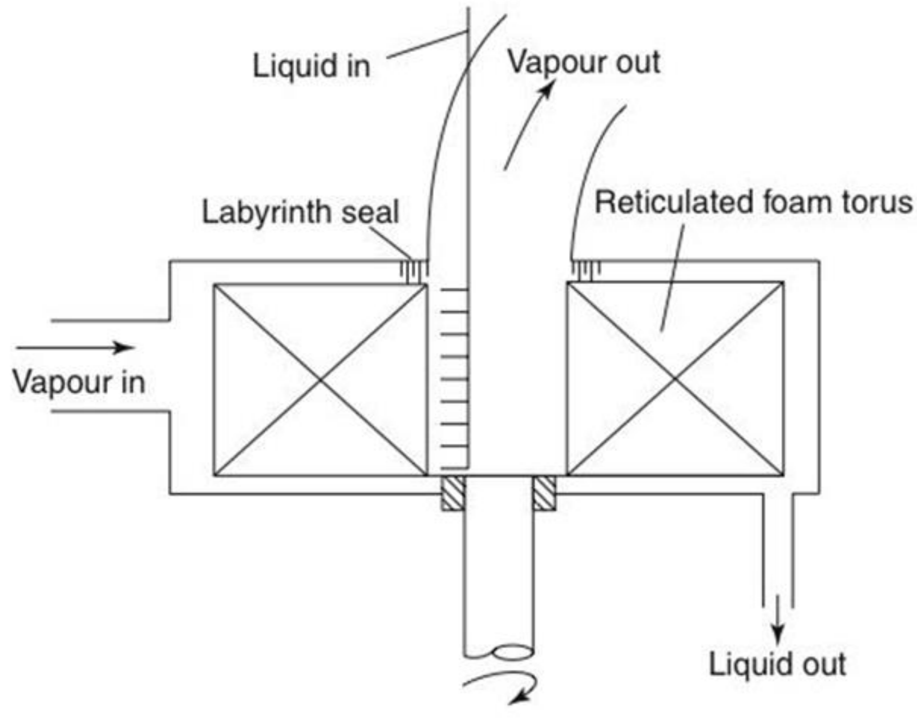
- Supercritical fluids
- Dynamic (periodic) reactor operation

Process Intensification: Examples of Developments

HiGEE Separation Units



L = liquid mass flux
G = gas mass flux
ρ_g = gas density
ρ_l = liquid density
a = packing area per unit volume
g = applied acceleration
E = packing voidage (capital E in the figure)
u_g = gas velocity.



[20] David. Process Intensification: Engineering for Efficiency, Sustainability and Flexibility. Elsevier Butterworth Heinemann, 2008.

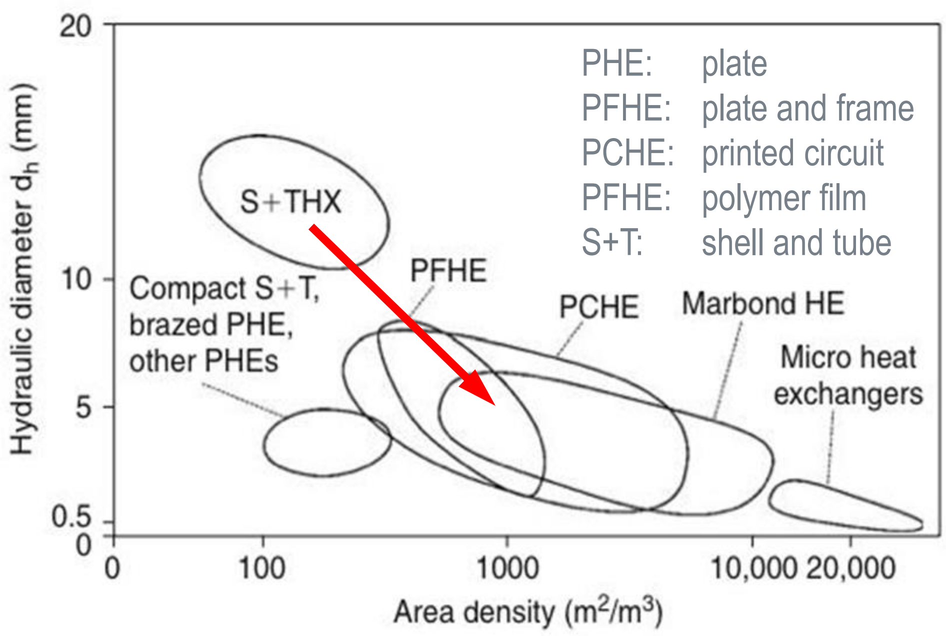
The Compact Heat Exchanger

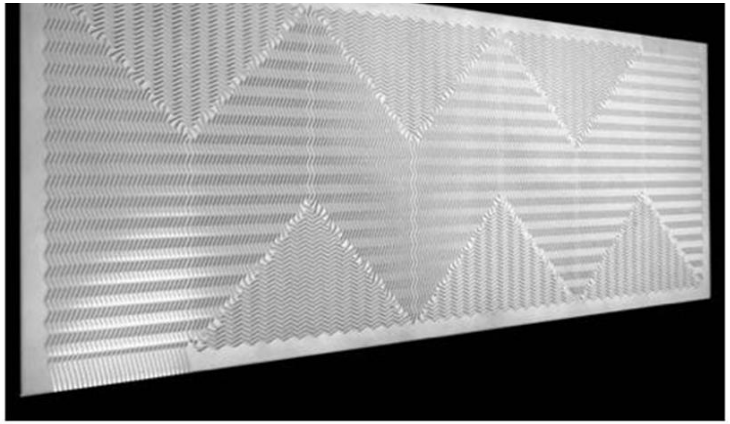
- Markets
  - Compact HEX,

    10% world market

    10% sales/year increase
  - World HEX

    1% market growth/year





[20] David. Process Intensification: Engineering for Efficiency, Sustainability and Flexibility, Elsevier Butterworth Heinemann, 2008.

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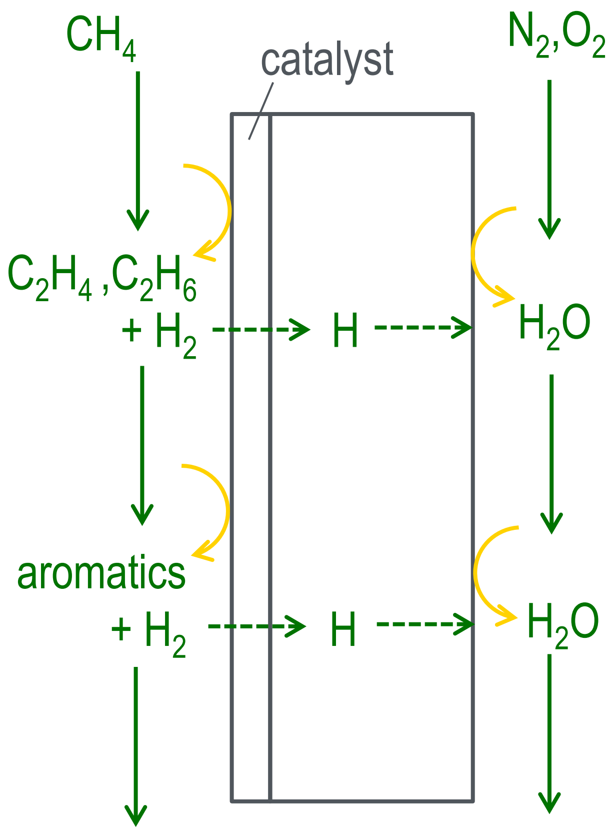
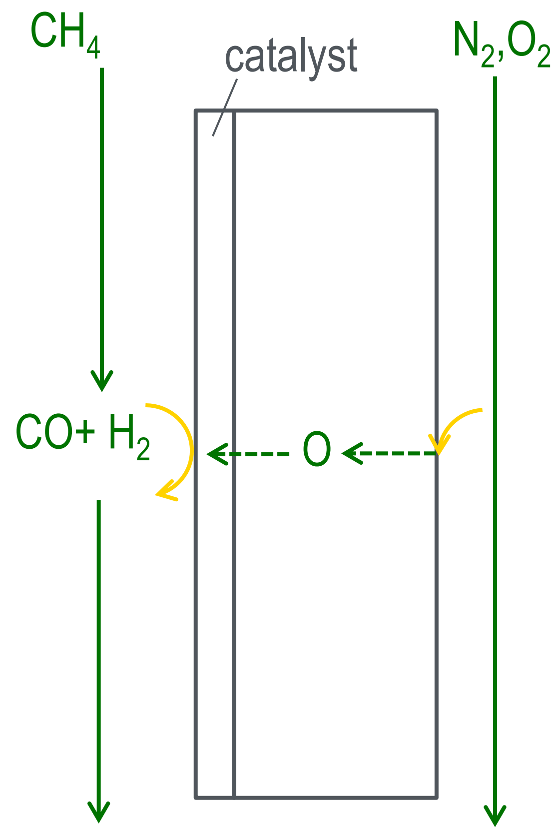
Catalytic Membrane Reactors

Hydrogen Transport Membrane



Overall Reaction: $2CH_4 + O_2 = C_2H_4 + 2H_2O$

Oxygen Transport Membrane



Overall Reaction: $CH_4 + 1/2O_2 = CO + 2H_2$

[20] David. Process Intensification: Engineering for Efficiency, Sustainability and Flexibility. Elsevier Butterworth Heinemann, 2008.

Possible Metrics

- Cost vs. Scale – bend scaling curve by x%?
- Scale-up Costs and Predictability?
- Product Costs:

  Product Transportation vs Supply Transportation?

  Capital Efficiency vs. Chemical Efficiency

Information Needed

- Quantitative High Level Targets and Opportunities
  ($/W, $/kg, energy efficiency, CO_2 intensity,…)

- Direct Industry Dialog on Specific Topics:
  Workshops: NSF: Sept 30-Oct 1
  DoD: Oct 8-9

- Quantitatively and Qualitatively: If this is such a good idea, why can't or won't industry do this itself?

- What is the Urgency? What issues first and why
  (Int'l landscape, changing energy, externalities)

Microfactories vs. Gigafactories

Example in Additive Manufacturing

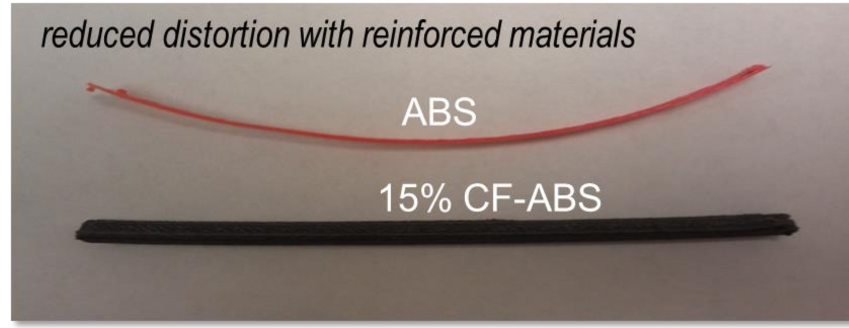
Can we Print a car with a small factory (process intensified), rather than an assembly line (traditional process)

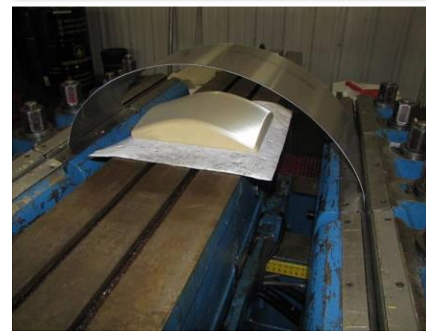
- Small Footprint Manufacturing
- Accelerated Innovation Cycles
- Sustainable Processes
- Higher Efficiency
- Reduced Risk of Stranded Capital Assets

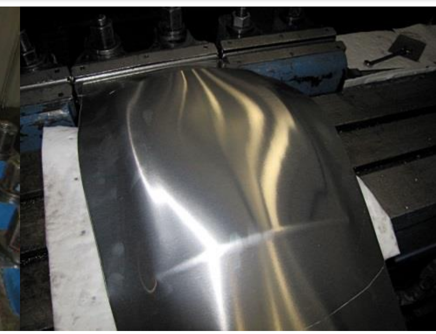
Large-Scale, Out-of-Oven Additive Manufacturing

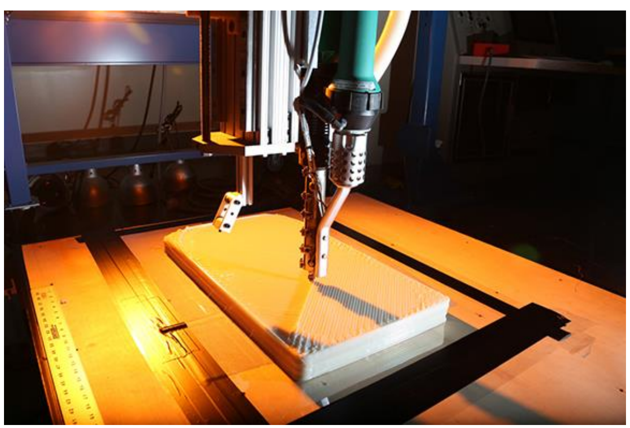
Big Area Additive Manufacturing (BAAM)

- **Pellet-to-Part**
  - **Pelletized feed replaces filament to enable 50x reduction in material cost**
- **Deposition rate >100x available additive systems**
- **H**igh deposition rates (~20 lbs/h)
  - FDM is 1 to 4 ci/hr
  - Large Scale is > 200 ci/hr to 400 ci/hr
- **Prototype system 8'x8'x8' build volume**
- **Initial interest by aerospace and composites tooling industry**









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Partnership with CINCINNATI®

CRADA

CINCINNATI INCORPORATED

ORNL and Cincinnati Incorporated collaborate to create commercial large-scale system

BAAM CI

BIG AREA ADDITIVE MANUFACTURING

Partnership to establish US-based large-scale AM equipment manufacturer

- **Targets tooling lead time and cost reduction**
- **Based on existing ORNL gantry system**
- **Cincinnati providing >$1M in cost share year one**
  - **First large-scale polymer AM system delivered to MDF, April 2014**
- **Interest from multiple automotive, aerospace and tooling industries**
- **Stretch form and hydroform tools demonstrated**

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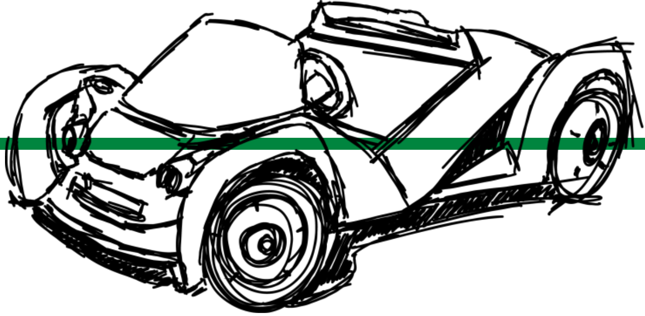
Partnership with

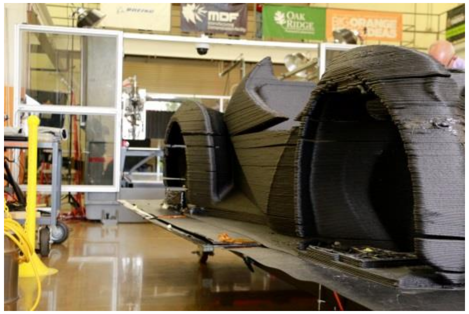
CRADA

LOCAL MOTORS



Extreme Innovation First 3D Printed “Strati” Car

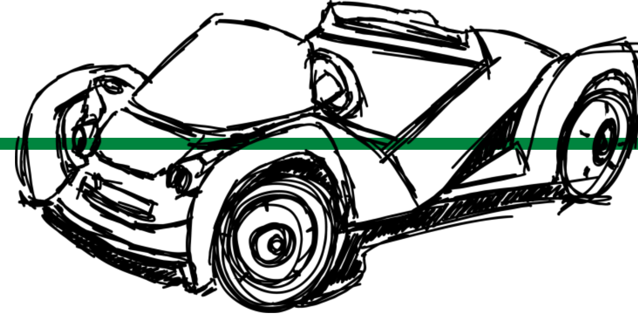
Rapid automotive design and innovation using large-scale polymer additive manufacturing



Partnership with

CINCINNATI
CINCINNATI INCORPORATED

LOCAL MOTORS



Extreme Innovation First 3D Printed "Strati" Car

Rapid automotive design and innovation using large-scale polymer additive manufacturing

IMTS 2014
International Manufacturing Technology Show
September 8 - 13, 2014 | McCormick Place | Chicago

See the Strati revealed

Friday 1 pm

AMT's ETC in N-650

https://energy.gov/eere/amo/downloads/printing-car-team-effort-innovation

https://www.youtube.com/watch?v=Uzgh8iSuTZA

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What does Success Look Like?

Energy Products Invented Here…

…And Competitively Made Here!

Thank You

Questions?

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