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

High Value Roll-to-Roll Manufacturing Workshop

December 2, 2015

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Advanced Manufacturing Office

www.manufacturing.energy.gov

Clean Energy and Manufacturing: Nexus of Opportunities

- Energy self-reliance
- Stable, diverse energy supply

- Competitiveness in clean energy
- Domestic jobs

- Clean air
- Climate change
- Health

<u>Clean Energy Manufacturing</u>

Making Products which Reduce Impact on Environment

<u>Advanced Manufacturing</u>

Making Products with Technology as Competitive Difference

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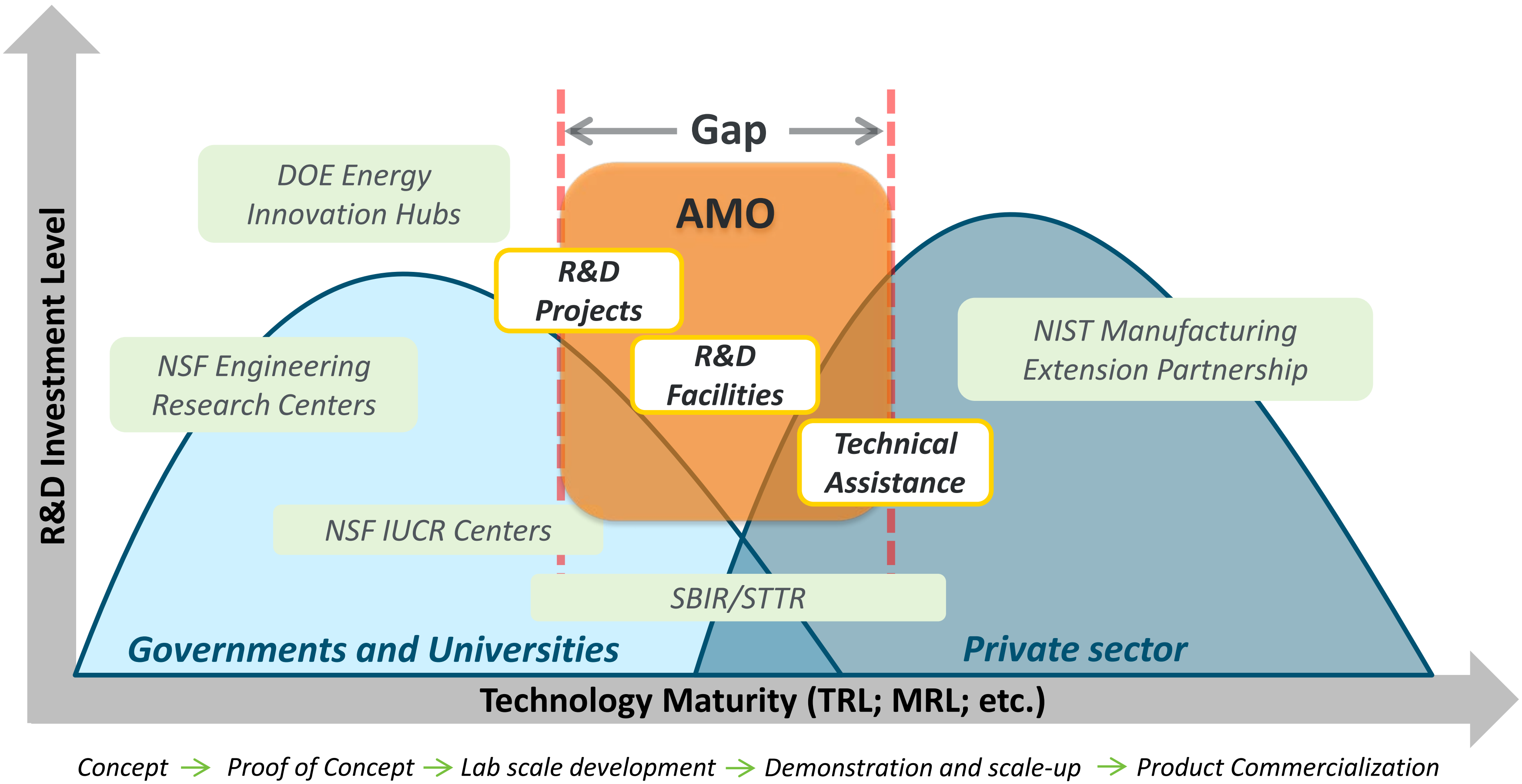
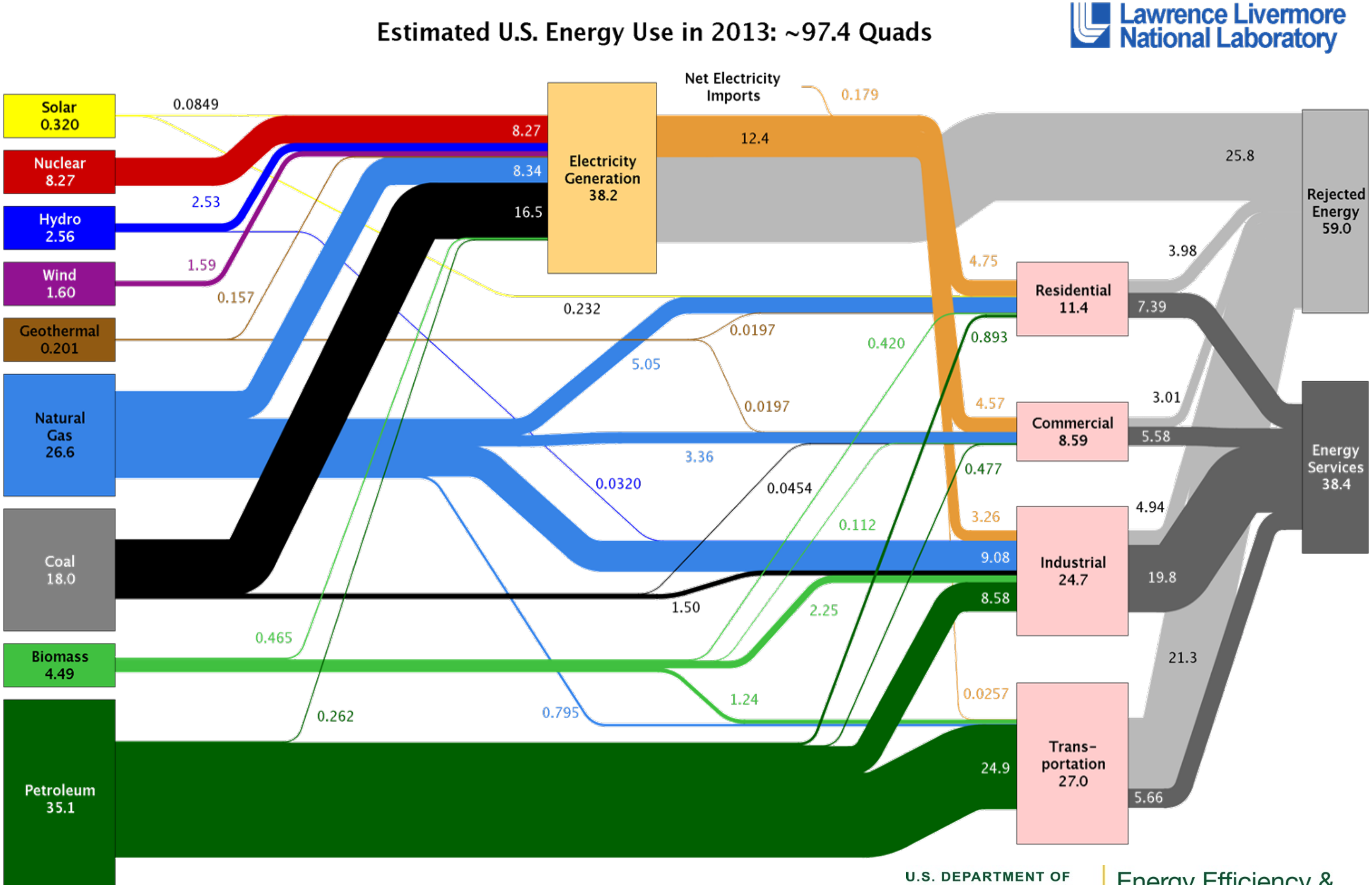
Bridging the Gap to Manufacturing

AMO: Advanced Manufacturing Office



Energy Consumption by Sector



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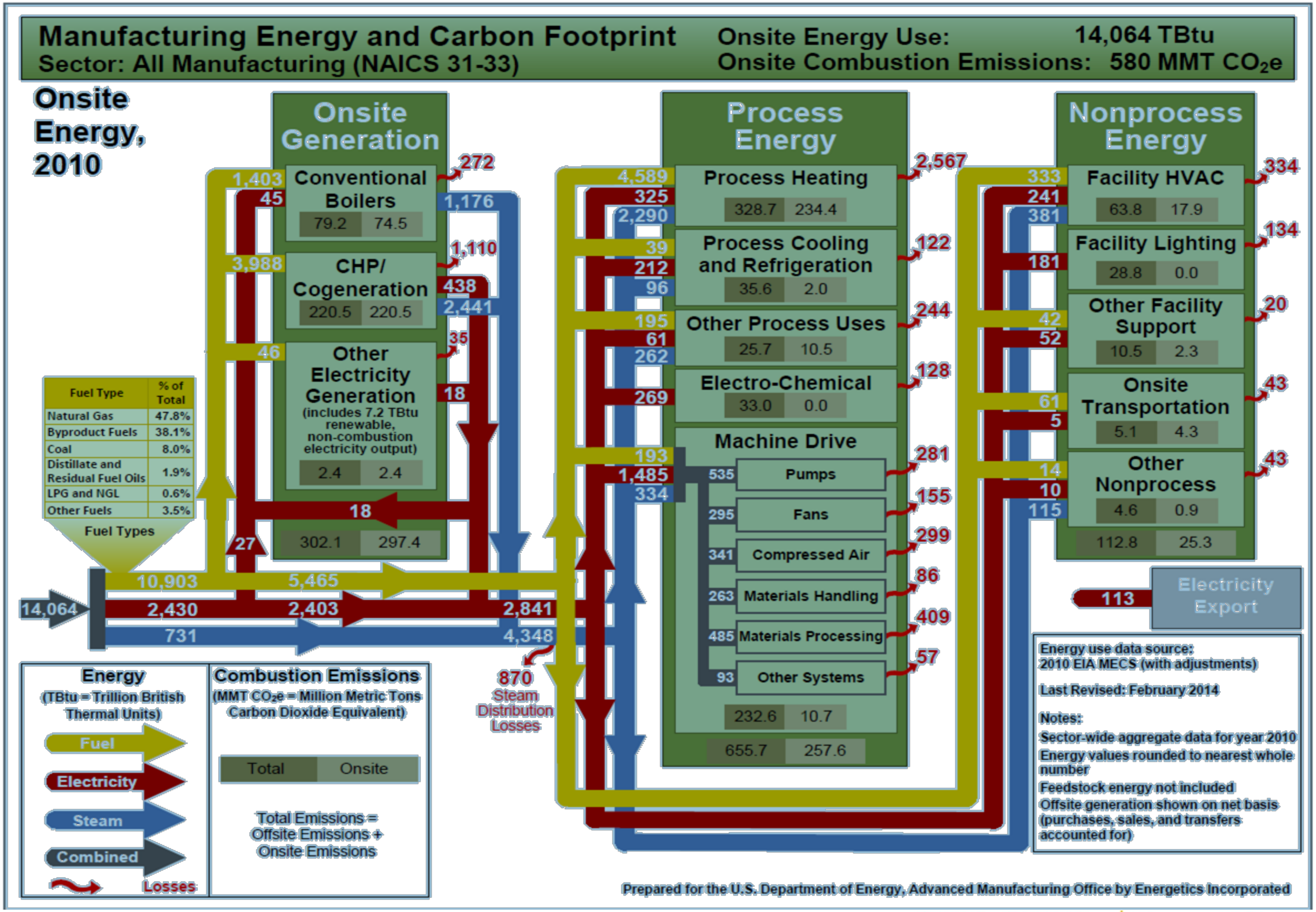
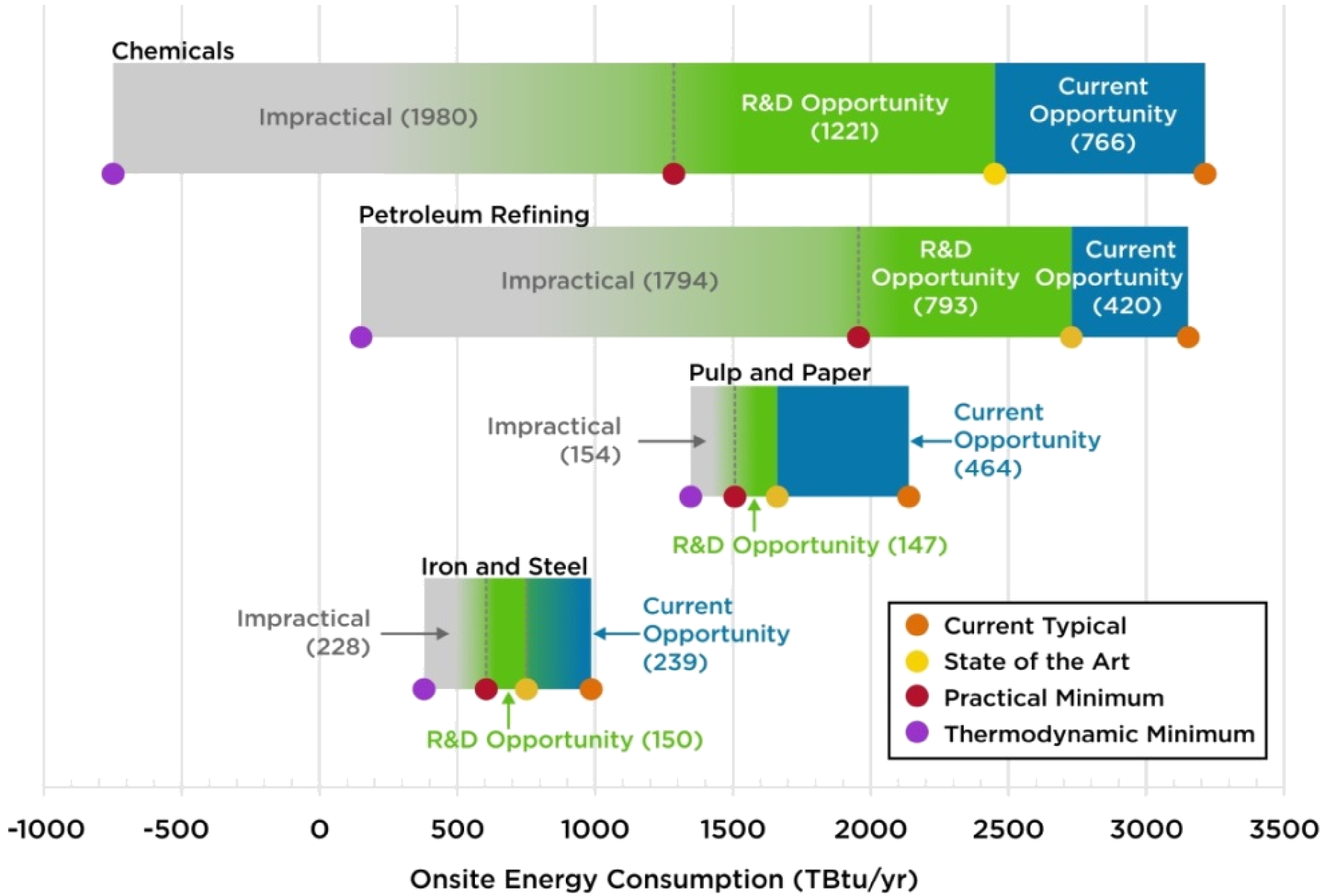
Deeper Look at Energy in Manufacturing



Bandwidth Studies: Energy Savings Potentials



Current opportunities represent energy savings that could be achieved by deploying the most energy-efficient commercial technologies available worldwide. R&D opportunities represent potential savings that could be attained through successful deployment of applied R&D technologies under development worldwide

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Energy Intensive Industries

Primary Metals
1608 TBTU

Petroleum Refining
6137 TBTU

Chemicals
4995 TBTU

Wood Pulp & Paper
2109 TBTU

Glass & Cement
716 TBTU

Food Processing
1162 TBTU






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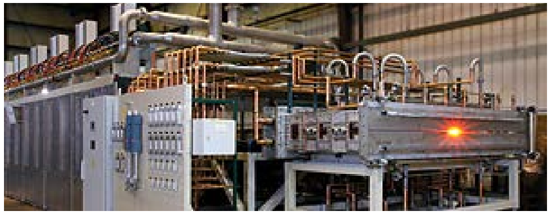
Processes for Clean Energy Materials & Technologies

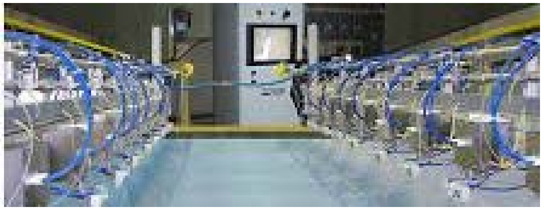
Energy Dependence: Energy Cost Considered in Competitive Manufacturing

Solar PV Cell



Carbon Fibers

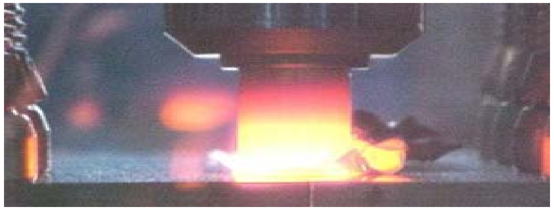
Light Emitting Diodes



Electro-Chromic Coatings

Membranes

EV Batteries



Multi-Material Joining

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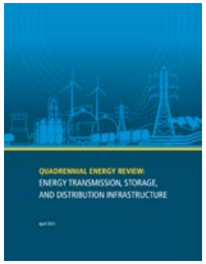
Advanced Manufacturing – Strategic Inputs

Climate Action Plan

(EOP / CEQ / OSTP 2014)

Advanced Manufacturing Partnership (AMP2.0)

(NEC / PCAST / OSTP 2014)



Quadrennial Energy Review

(DOE / EPSA 2015)

Quadrennial Technology Review

(DOE / Science and Technology 2015)

1) Broadly Applicable Efficiency Technologies for Energy Intensive and Energy Dependent Manufacturing

2) Platform Materials & Processes Technologies for Manufacturing Clean Energy Technologies

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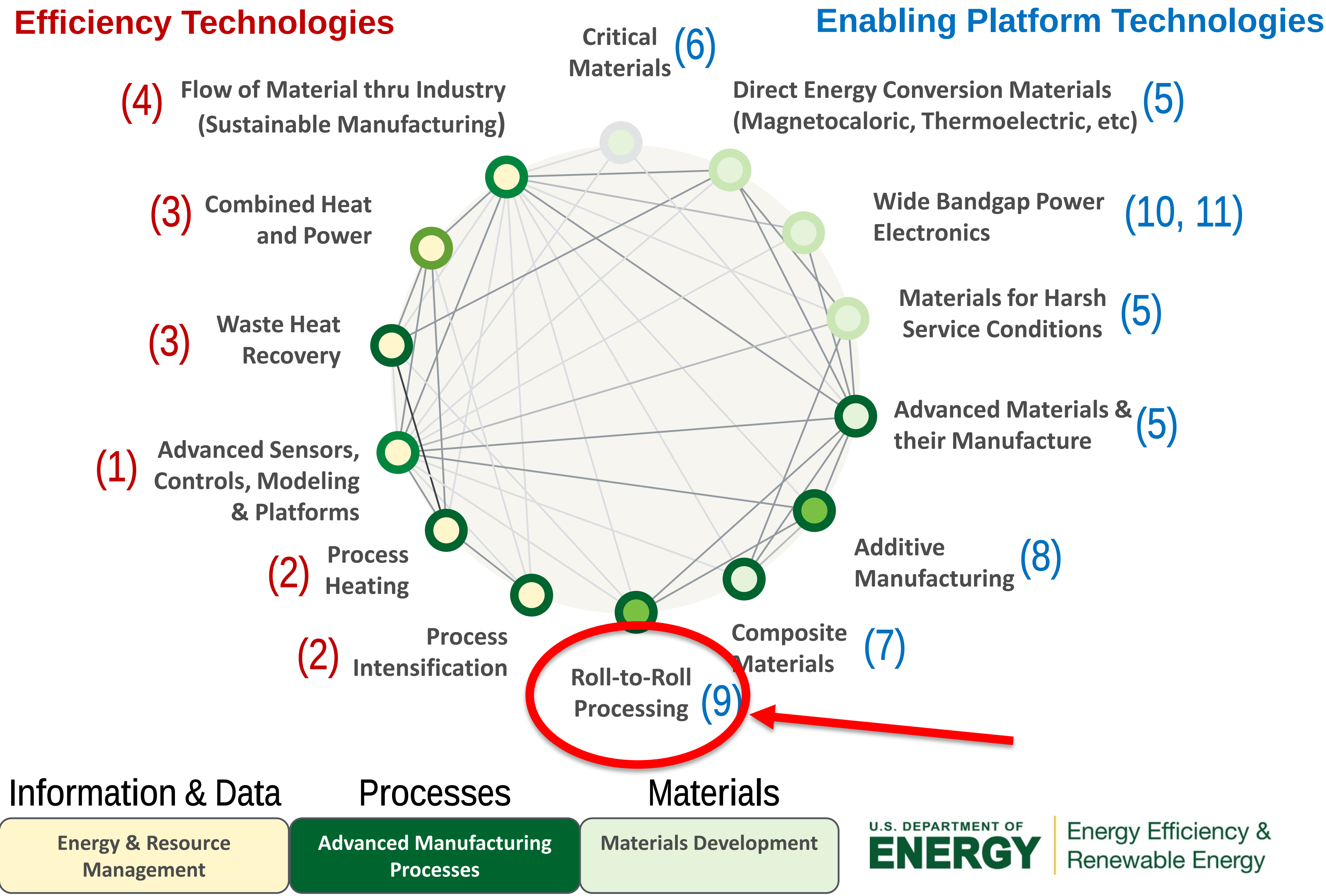
DOE QTR: Manufacturing Technology



Advanced Manufacturing Topical Priorities

Efficiency Technologies for Manufacturing Processes (Energy, CO_2)

(1) Advanced Sensors, Controls, Modeling and Platforms (HPC, Smart Manf.)
(2) Advanced Process Intensification
(3) Grid Integration of Manufacturing (CHP and DR)
(4) Sustainable Manufacturing (Water-Energy, New Fuels & Feedstocks)

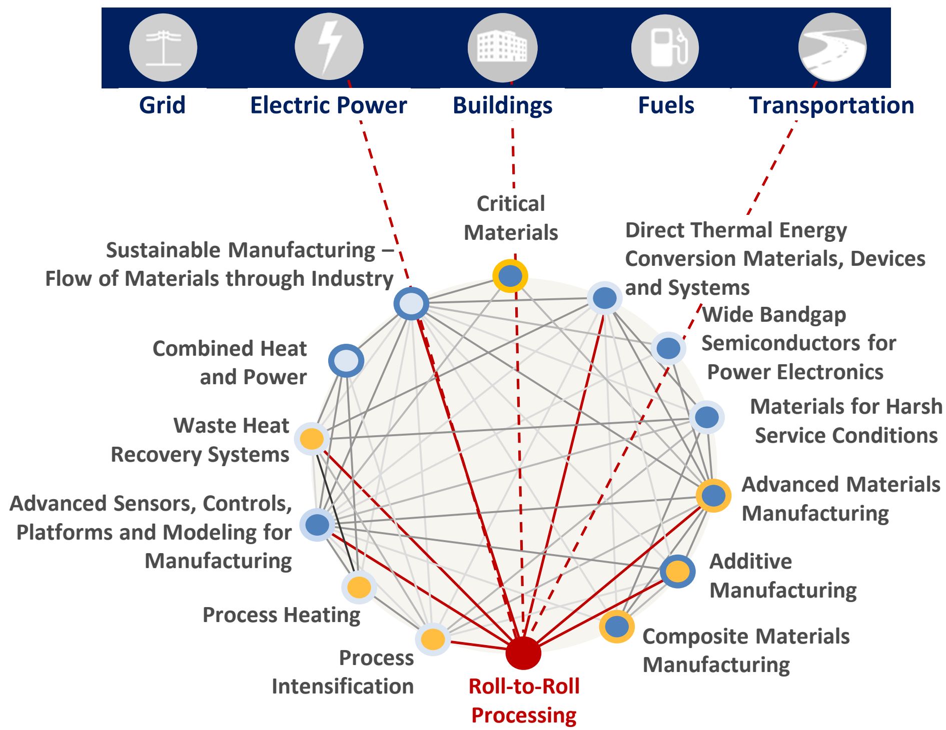
Platform Materials & Technologies for Clean Energy Applications

(5) Advanced Materials Manufacturing
(incl: Extreme Mat'l., Conversion Mat'l, etc.)
(6) Critical Materials
(7) Advanced Composites & Lightweight Materials
(8) 3D Printing / Additive Manufacturing
(9) 2D Manufacturing / Roll-to-Roll Processes
(10) Wide Bandgap Power Electronics
(11) Next Generation Electric Machines (NGEM)

QTR Manufacturing Focus Areas Mapped to Advanced Manufacturing Topical Areas for Technology Development

Roll-to-Roll Processing

Connections to other QTR Chapters and Technology Assessments



Key Extra-Chapter Connections

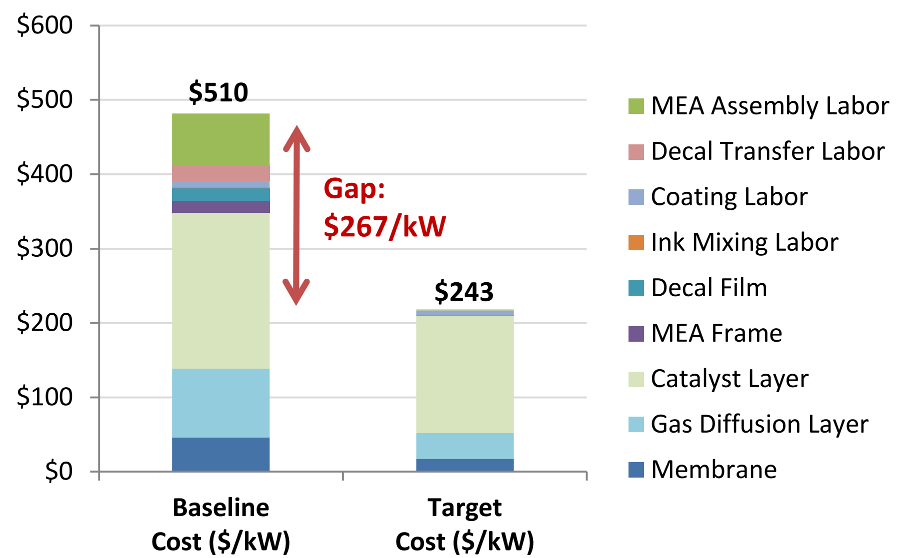
- **Electric Power:** *flexible solar panels*
- **Buildings:** *window insulation films*
- **Transportation:** *battery electrodes*

Ch. 6 – Roll-to-Roll Processing Technology Assessment

Scope

- Roll-to-roll (R2R) applications such as flexible solar panels, printed electronics, thin film batteries, and membranes
- Deposition processes such as evaporation, sputtering, chemical vapor deposition, and atomic layer deposition
- Metrology for inspection and quality control

Strategy for meeting cost targets for automotive fuel cell membrane electrode assembly using roll-to-roll processing techniques*



*Source: Manufacturing Fuel Cell Manhattan Project, presented by the Benchmarking and Best Practices Center of Excellence, Office of Naval Research, ACI Technologies, 2012.

Modalities of Support

Technology Assistance: (Dissemination of Knowledge)

Better Plants, ISO-50001 / SEP, Industrial Assessment Centers, Combined Heat and Power Tech Assistance Centers, Energy Management Tools & Training

Technology Development Facilities: (Innovation Consortia)

Critical Materials Hub, Manufacturing Demonstration Facility (Additive), Power America NNMI, IACMI NNMI, CyclotronRoad, HPC4Manufacturing

Technology Development Projects: (Individual R&D Projects)

Individual Projects Spanning AMO R&D Space - University, Small Business, Large Business and National Labs. Each a Project Partnership (Cooperative Agreement).

Shared R&D Facilities & Consortia

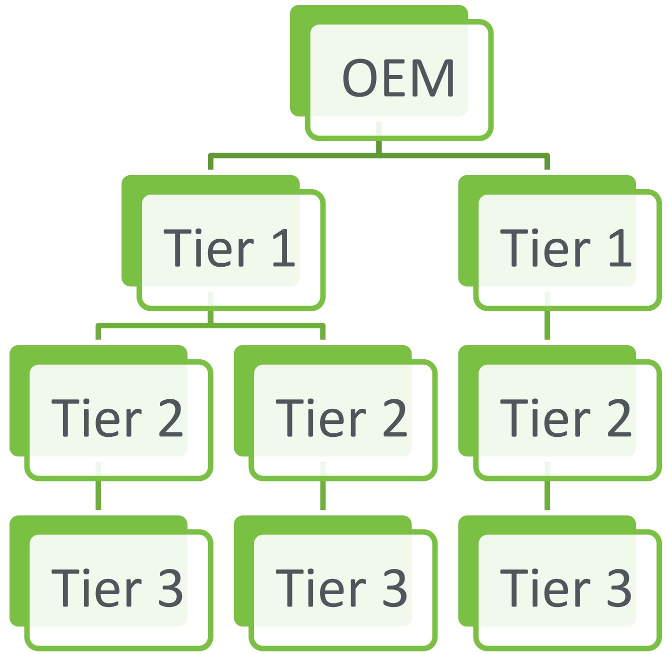
Address market disaggregation to rebuild the industrial commons

Then

Ford River Rouge Complex, 1920s

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

Now



How could we get innovation into manufacturing today?

- **RD&D Consortia based Eco-Systems**
- **Public-private partnership to scale**

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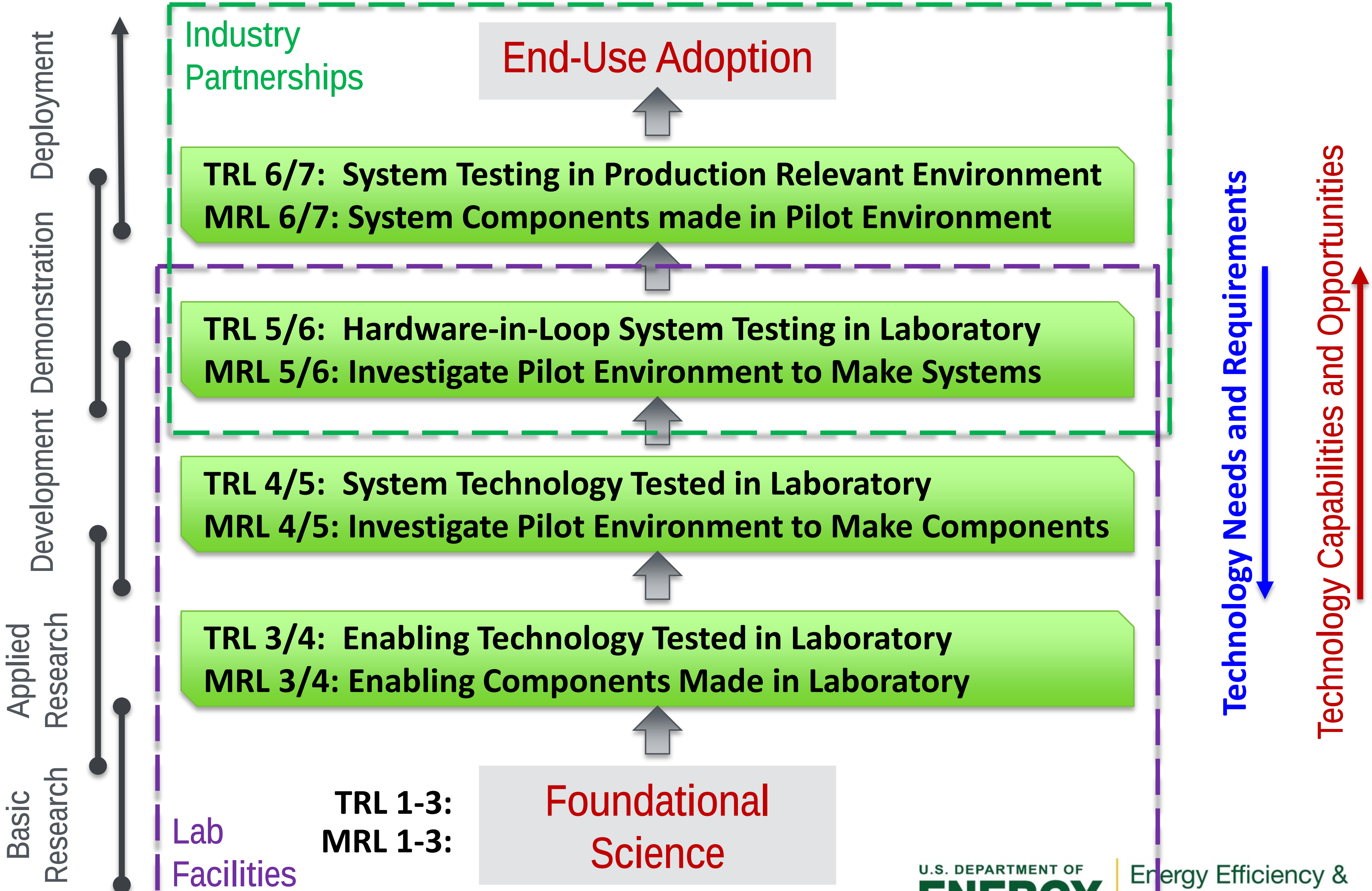
Manufacturing Technology Maturation



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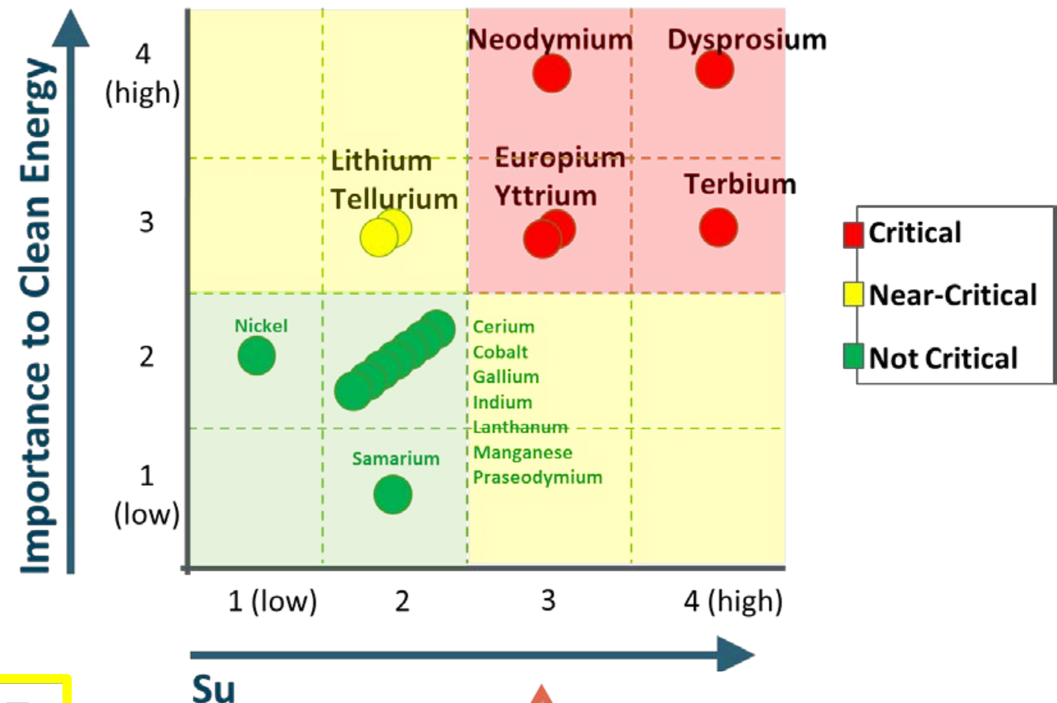
Critical Materials Institute

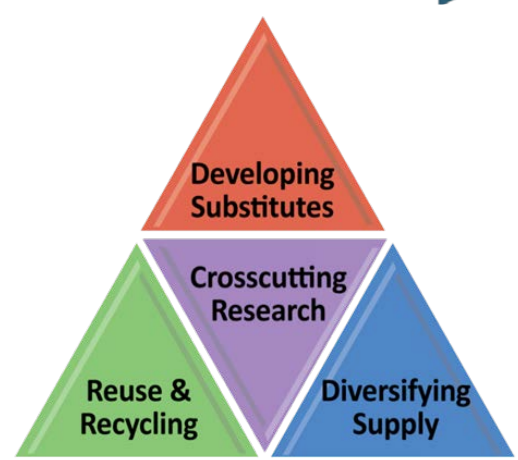
Accelerating Energy Innovations

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.

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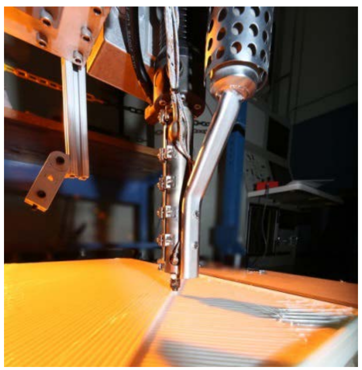
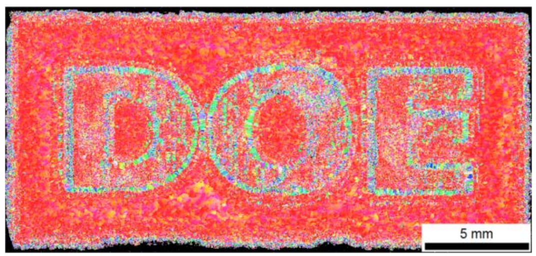
Manufacturing Demonstration Facility

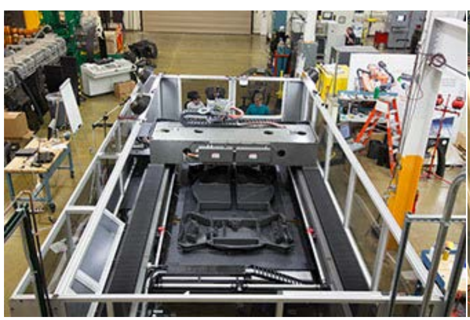
Supercomputing Capabilities

Spallation Neutron Source

America Makes







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.

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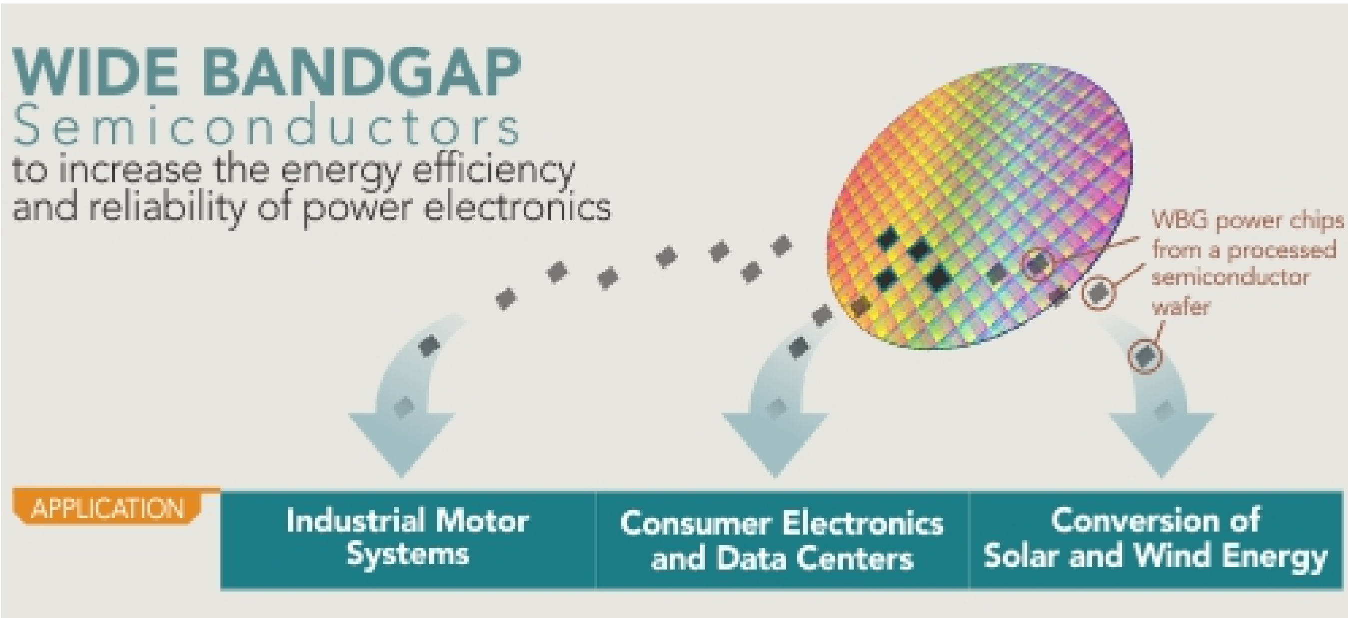
PowerAmerica:
Next Generation Power Electronics Manufacturing Institute



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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Institute for Advanced Composite Materials Innovation (IACMI)

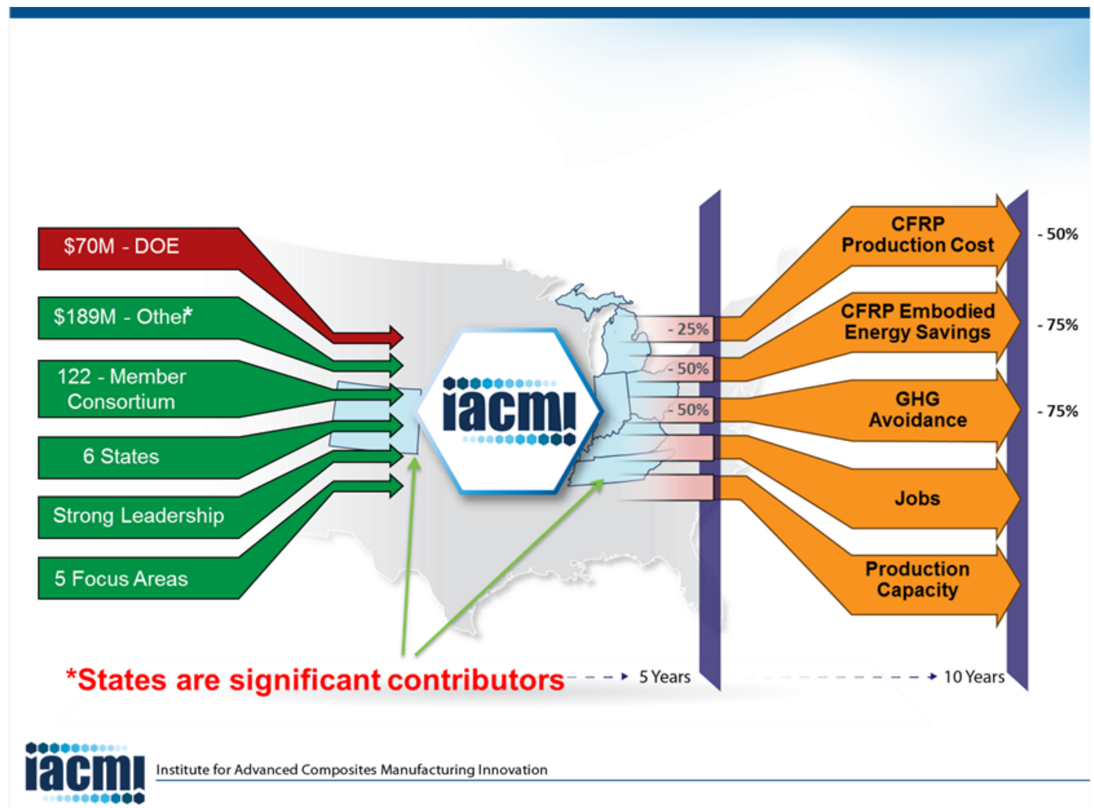
Objective

Develop and demonstrate innovative technologies that will, within 10 years, make advanced fiber-reinforced polymer composites at…

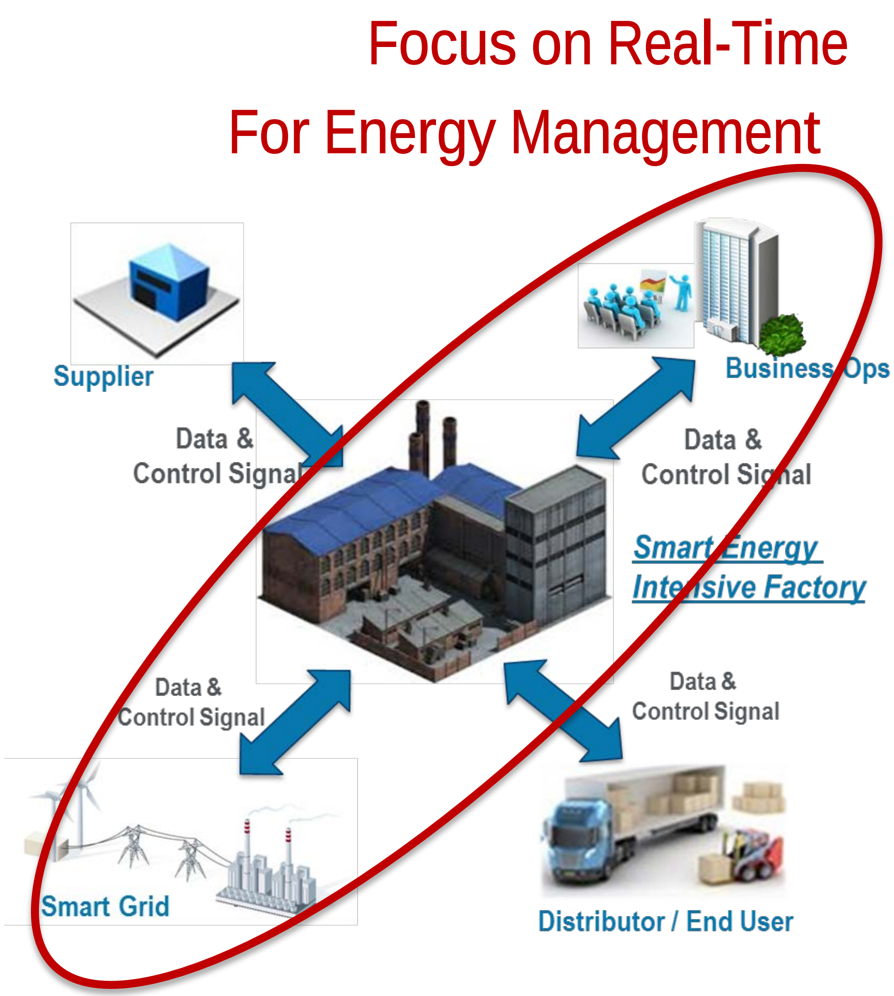
50% Lower Cost

Using 75% Less Energy

And reuse or recycle >95% of the material



SMART Manufacturing: Advanced Controls, Sensors, Models & Platforms for Energy Applications



- Encompass machine-to-plant-to-enterprise real time sensing, instrumentation, monitoring, control, and optimization <u>of energy</u> **(>50% improvement in energy productivity)**
- Enable hardware, protocols and models for advanced industrial automation: requires a holistic view of data, information and models in manufacturing at Cost Parity (>**50% reduction in installation cost**)
- Significantly reduce energy consumption and GHG emissions & improve operating efficiency – (**15% Improvement in Energy Efficiency)**
- Increase productivity and competitiveness across all manufacturing sectors:

  Special Focus on <u>Energy Intensive</u> &
  <u>Energy Dependent</u> Manufacturing Processes

Leverage AMP 2.0 and QTR

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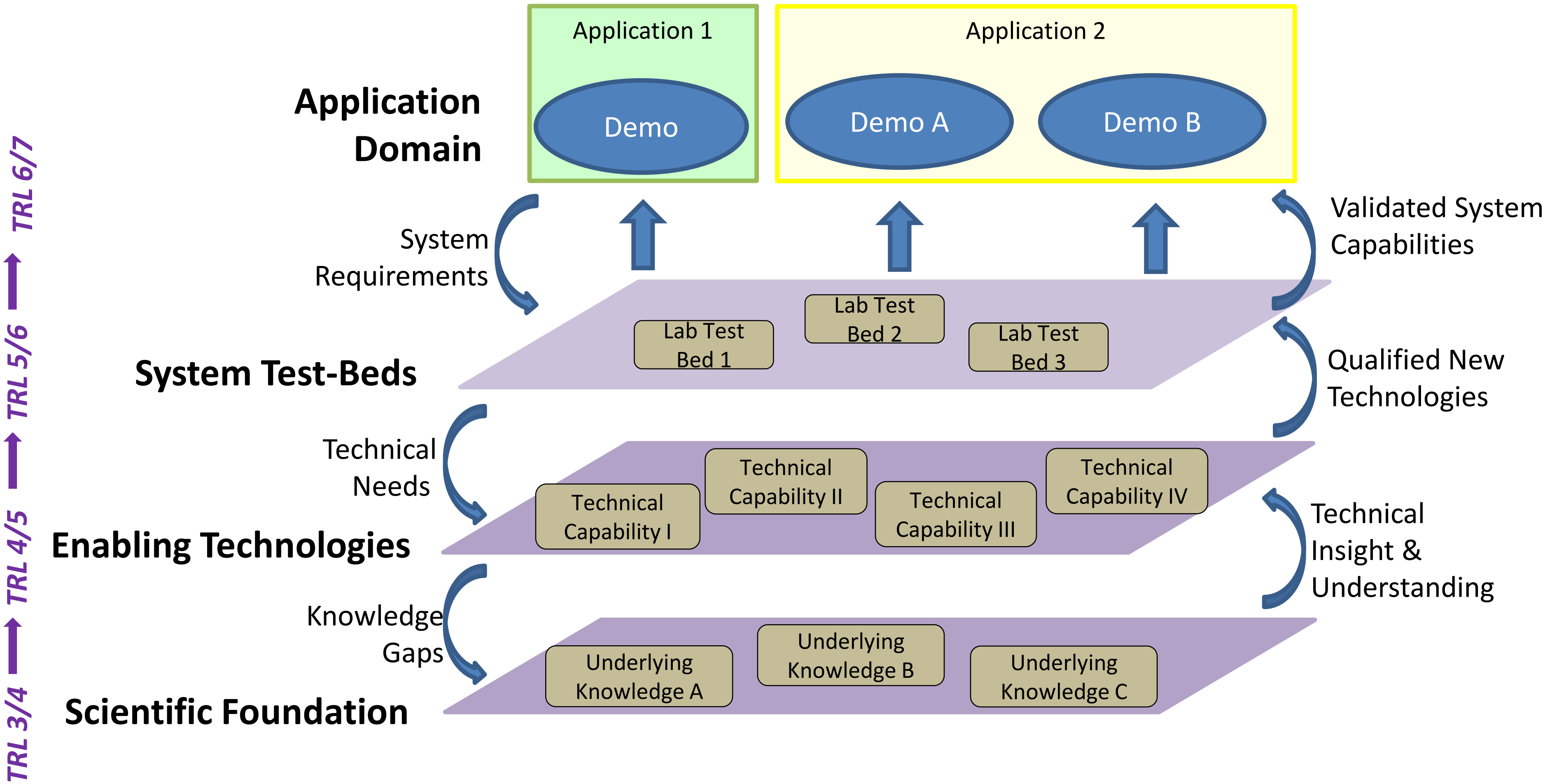
Technical Challenge Hierarchy

Multi-Disciplinary Technology Translation



LIKE QUANTIFICATION OF POSSIBLE REQUIREMENTS, NEEDS & GAPS

What does Success Look Like?

Energy Products Invented Here…

…And Competitively Made Here!

<u>Today's Workshop</u>

High Value Roll-to-Roll Processing

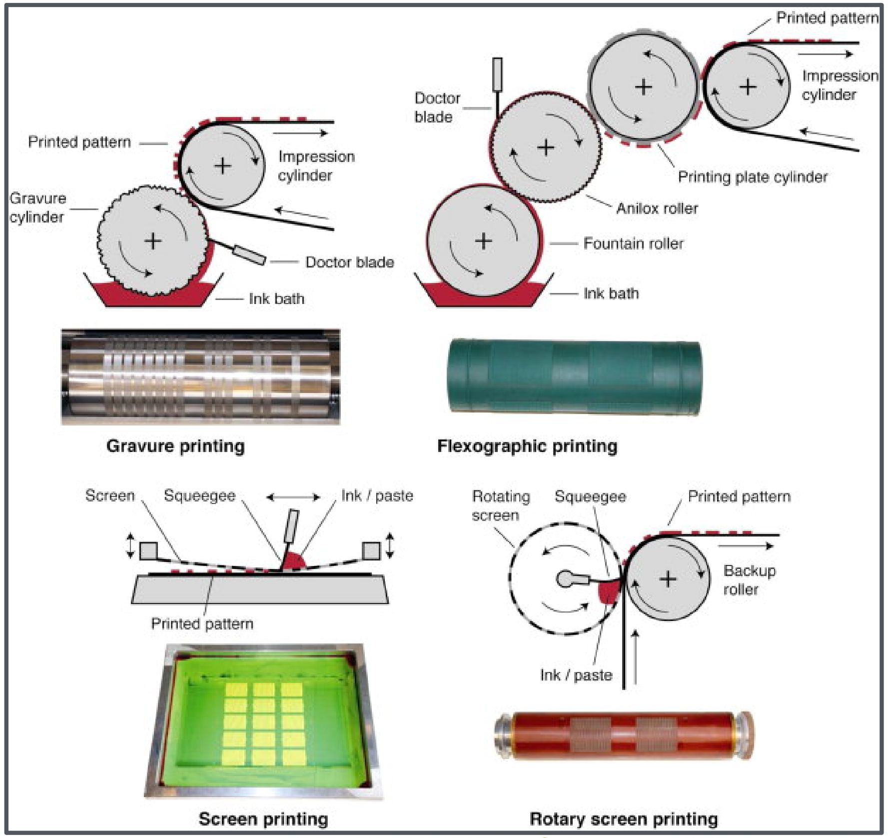
Why HV-R2R at the Department of Energy?

Motivation

Ultra-high-quality, high-throughput, energy efficient roll-to-roll manufacturing processes that are cost-competitive (High Value Roll-to-Roll) can both **enable advanced clean energy applications**, particularly in the nanomanufacturing sector, as well as **capture significant energy savings** compared to traditional manufacturing processes.

Challenge

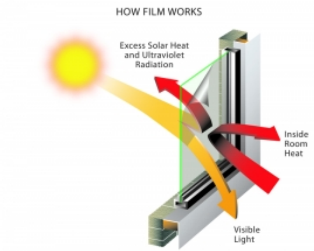
Although R2R processes have been around for more than forty years, rapid evolution of use, application and require dramatic improvements in quality, feature size, consistency, metrology and process modularity in order to maintain cost competitive. DOE is focused on identifying the key technologies and processes that will **unlock high-value roll-to-roll across a number of industries**.

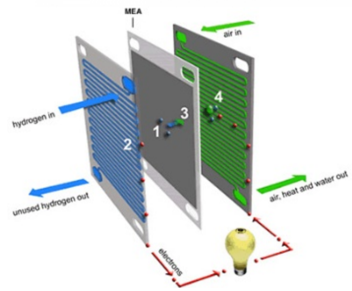


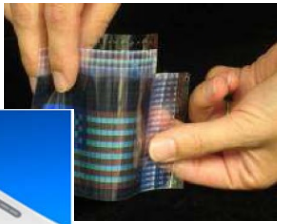
R2R Processing diagrams for organic electronics/thin films

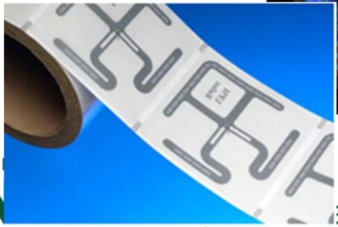
Traditional and “Cutting Edge” R2R Applications

- Multilayer capacitors (MLC, i.e. NPO to XR7/Relaxer/etc.)
- Thick and thin-film substrates (Al2O3, AlN, Si3N4, SiC, GaN, MgO, ZrO)
- Thick-film sensor materials (temperature sensors, positioners, transducers, e.g. negative temperature coefficient thermistors, Piezoelectric/lead zirconate titanate (PZT), active/passive, selective gas)
- Fabric (clothing textiles, fiber reinforce mat/fiberglass/carbon/polymer)
- Anti-static, release, reflective and anti-reflective coatings (glass, MylarTM, polyethylene)
- Barrier coatings (thermal and environmental)
- Fuel cells (laminar solid oxide fuel cells (SOFC), proton exchange membranes (PEM), membrane electrode assemblies and gas diffusion media)
- Batteries (laminar Li ion, etc.)
- Flexible electronics for displays, heaters, sensors, circuit substrates, consumer appliances, etc.
- Metal ribbon (transformer “coils”, etc.)
- Paper industry
- Chemical separation membranes (RO, catalyst)
- CIGS Photovoltaic (PV) and other flexible PV products



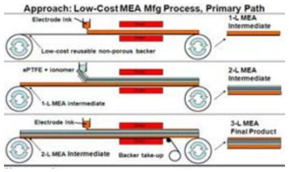




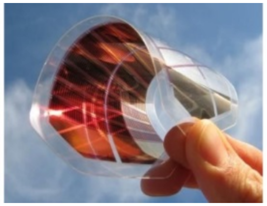


Specific Interests in R2R

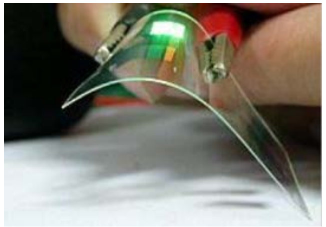
- **DOE**
  - FCTO – FCEVs, PEM fuel cells, fuel cell backup power, Hydrogen gas separation
  - SETO – CIGS PVs, flexible PVs
  - BTO – Airflow panel membranes, electrochromic window coatings, sensors
  - AMO – CdTe solar cells, solar reactive coatings, battery/super-capacitor/superconducting cable/sensor technologies
  - OFE - Polymeric and ceramic/metallic membranes for CO2 separation
  - NREL – Defect diagnostics, quality control for scale-up of fuel cells on weblines
- **DOD**
  - Micro-electronics for flat panel displays, thin film transistor arrays for flexible displays, digital x-ray detectors, flexible reflective displays, self-aligned imprint lithography, zinc-polymer battery chemistries, R2R processed OLED, flexible Si CMOS chips on paper
- **NSF**
  - Nanomanufacturing research
- **Others -**
  - Organic-based TFTs for displays and RFID, flexible electronic OLED displays, anodes and cathodes in a continuous process, planarization, imprint embossing and patterning, alternative materials and membranes, functional hybrids, viscoelastic fluids, thermoelectrics, micro-electronics lithography printing



PEM Membranes



Flex Electronics



OLEDS

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From R2R to HV-R2R

R2R processing is already used to make a number of traditional and "cutting edge" products, but has a number of limiting factors. **HV-R2R** processes:

- Higher throughput
- Larger area
- Ultra-high quality and film-to-film consistency
- Smaller feature size
- Capable of very thin to macro-scale thicknesses
- Flexibility in processing--ability to manufacture a range of products with minimal changes to processing lines

while remaining **cost-competitive** with current approaches.

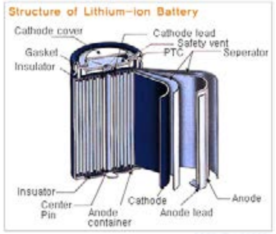
Importance of HV-R2R Technology

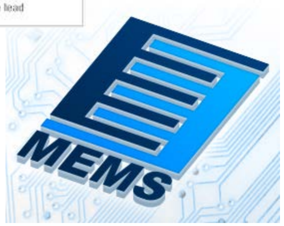
High Value Roll to Roll (HV R2R)

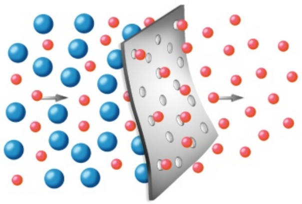
- Energy efficient, low environmental impact and ultra-low cost for energy saving applications
- Requires information exchange, resource partnering, open discussion of ideas, discoveries, and best practices while protecting the proprietary information and intellectual property of the community.

Markets

- Lithium ion battery demand is predicted to reach $70B by 2019
- Electronic Manufacturing Services industries have an annual demand of $300B for flexible electronics
- In 2005 the POP domestic market for commercial flat panel displays for advertising space is about $40 billion
- The Global micro-electro-mechanical systems (MEMS) market is projected at $1 trillion per year
- R2R produced membranes are used for gas and liquid separations at an annual demand of $1.7B
- OLED lighting can reduce energy by 0.22 quads, saving $20 billion, and environmental pollution emissions by 3.7 million metric tons

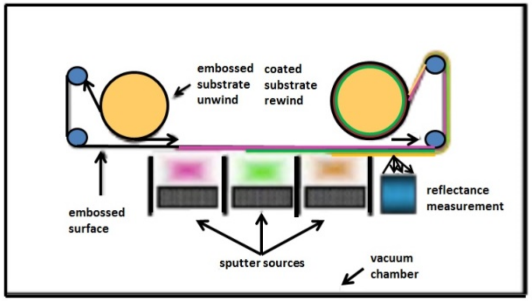


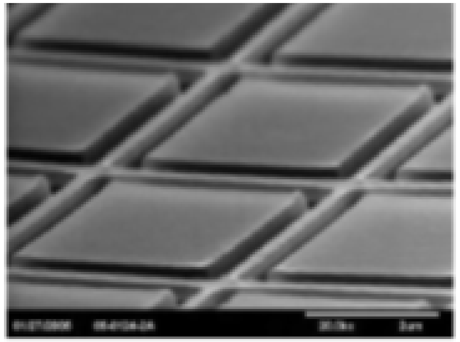




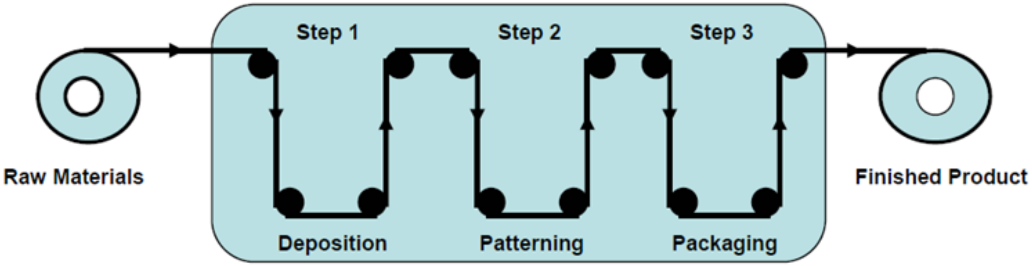
Previous workshops on R2R

- **Technology Areas**
  - Membranes (Fossil and Separation)
  - Flexible Electronics (active &passive)
  - Battery Technology
  - PEM Fuel Cells
  - Photovoltaics
  - Formatted, Higher Quality Depositions
  - Institute for Clean Energy Production (ICE-P)





- **Manufacturing Issues**
  - Scalable Solutions
  - Metrology
  - Quality systems
  - Process Control



Example Outcomes from Workshop

- **What are ambitions but feasible metrics for success?**
  1) Reducing possible feature size by an order of magnitude while maintaining product consistency and cost
  2) Increasing area size by order of magnitude while maintaining throughput and cost
  3) Developing modular processes capable of producing wide range of 2D products
- **What are the technical pathways needed to achieve this?**
  1) New real-time characterization tools integrated into process lines
  2) Equipment that can meet atomic layer to macroscale features
  3) Shared infrastructure and/or "open source" manufacturing test facilities to build modular processing capabilities
- **Where are the gaps?**
  1) Industry won't invest in shared infrastructure
  2) Novel processes have high capital cost limiting investment in scale-up
  3) Variance and limits of current tools and methods

Workshop Structure

Breakout Sessions

- 5 Sessions
  - Advanced Deposition Processing and Printing for ALD, Thin, Mid and Thick-film Size-Scale
  - Unique Metrology and Quality Systems for Specific R2R Applications
  - Membranes & Substrates and Associated Functional Materials and Technologies for Crosscutting Applications
  - Process and Equipment Needs Transitioning Plate to Plate to Continuous R2R Additive Process Technologies
  - Continuous Processing/Process Development Needs (both plate and web based, on-web and post-process requirements)
- Staff will take real-time notes
- Results of each breakout session will be presented in a plenary session for each day

Types of information

- **Be Specific**
- **Be Candid—Chatham House Rules (notes non-attributed)**
- **Give Quantifiable metrics**
  - What are the most important variables (e.g. is film variation more important than throughput)?
  - For the most important variables, what are the **game changer metrics** for parameters like throughput, feature size, surface area, etc.?
  - What are the **actual numbers** (e.g. 100x faster processing, 100x larger thickness range, etc.)?
- **Provide High level of detail**
  - What specific technologies are needed to meet these game changer metrics?
  - Why hasn't the private sector already made these investments?
  - What specific form of public-private partnership would best accelerate HV-R2R? What would be counterproductive?

Thank You

Back up slides

AMO Elements

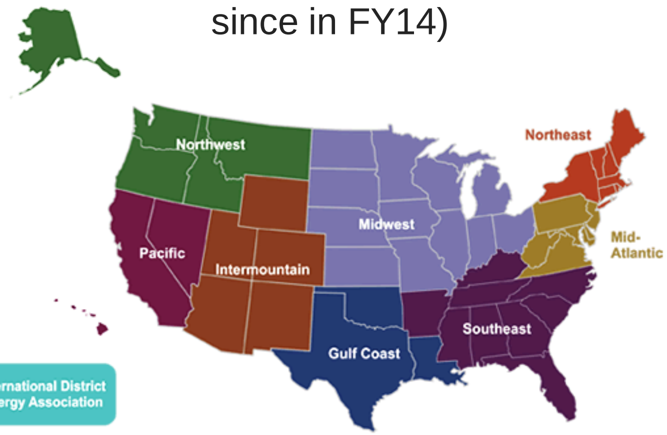
Three partnership-based approaches to engage industry, academia, national labs, and state & local government:

1. **Technical Assistance** – driving a corporate culture of continuous improvement and wide scale adoption of proven technologies, such as CHP, to reduce energy use in the industrial sector
2. **Research and Development Projects**
3. **Shared R&D Facilities**

Industrial Technical Assistance

Efficient On-Site Energy

Clean Energy Application Centers
(to be called Technical Assistance Partnerships since in FY14)



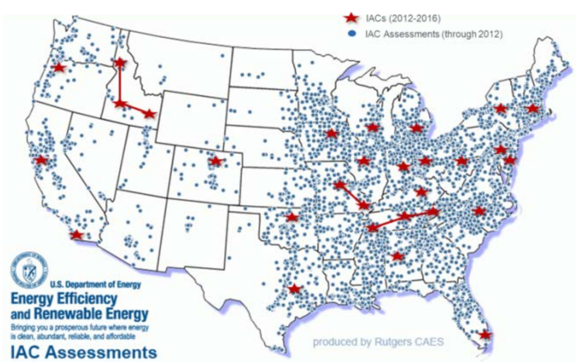
International District Energy Association

Energy-Saving Partnership

Better Buildings, Better Plants,
Industrial Strategic Energy Management

Student Training & Energy Assessments

University-based Industrial Assessment Centers



Better Plants
U.S. DEPARTMENT OF ENERGY

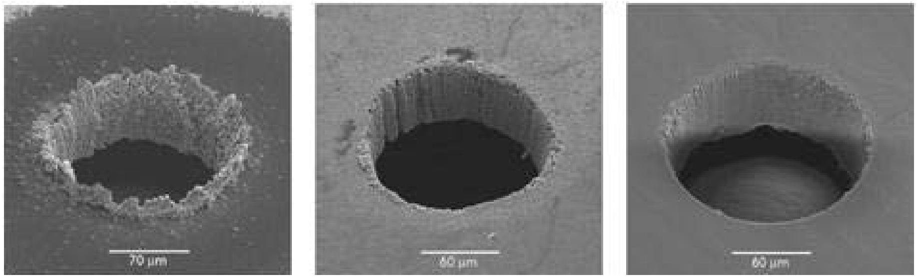
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

AMO Elements

Three partnership-based approaches to engage industry, academia, national labs, and state & local government:

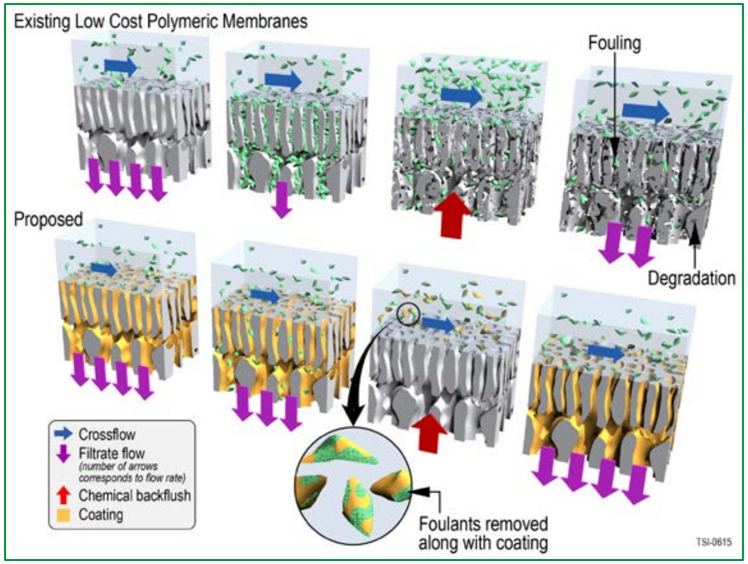
1. **Technical Assistance**
2. **Research and Development Projects -** to support innovative manufacturing processes and next-generation materials
3. **Shared R&D Facilities**

R&D Projects: Manufacturing Processes



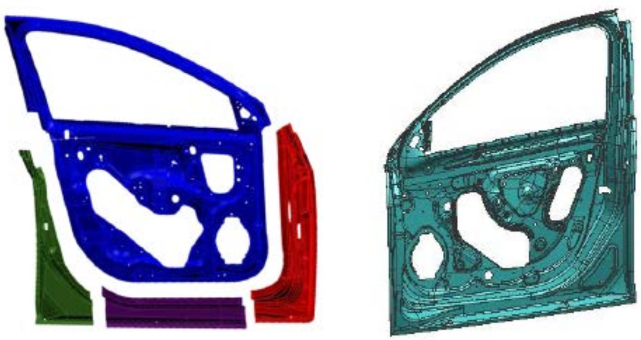
Ultrafast, femtosecond pulse lasers (right) will eliminate machining defects in fuel injectors.

Image courtesy of Raydiance.



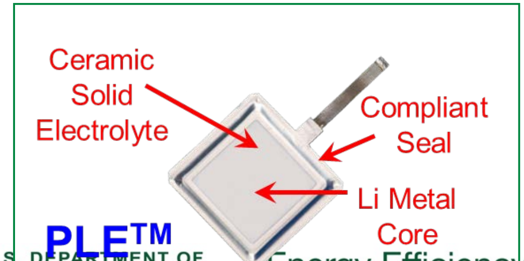
Protective coating materials for high-performance membranes, for pulp and paper industry.

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

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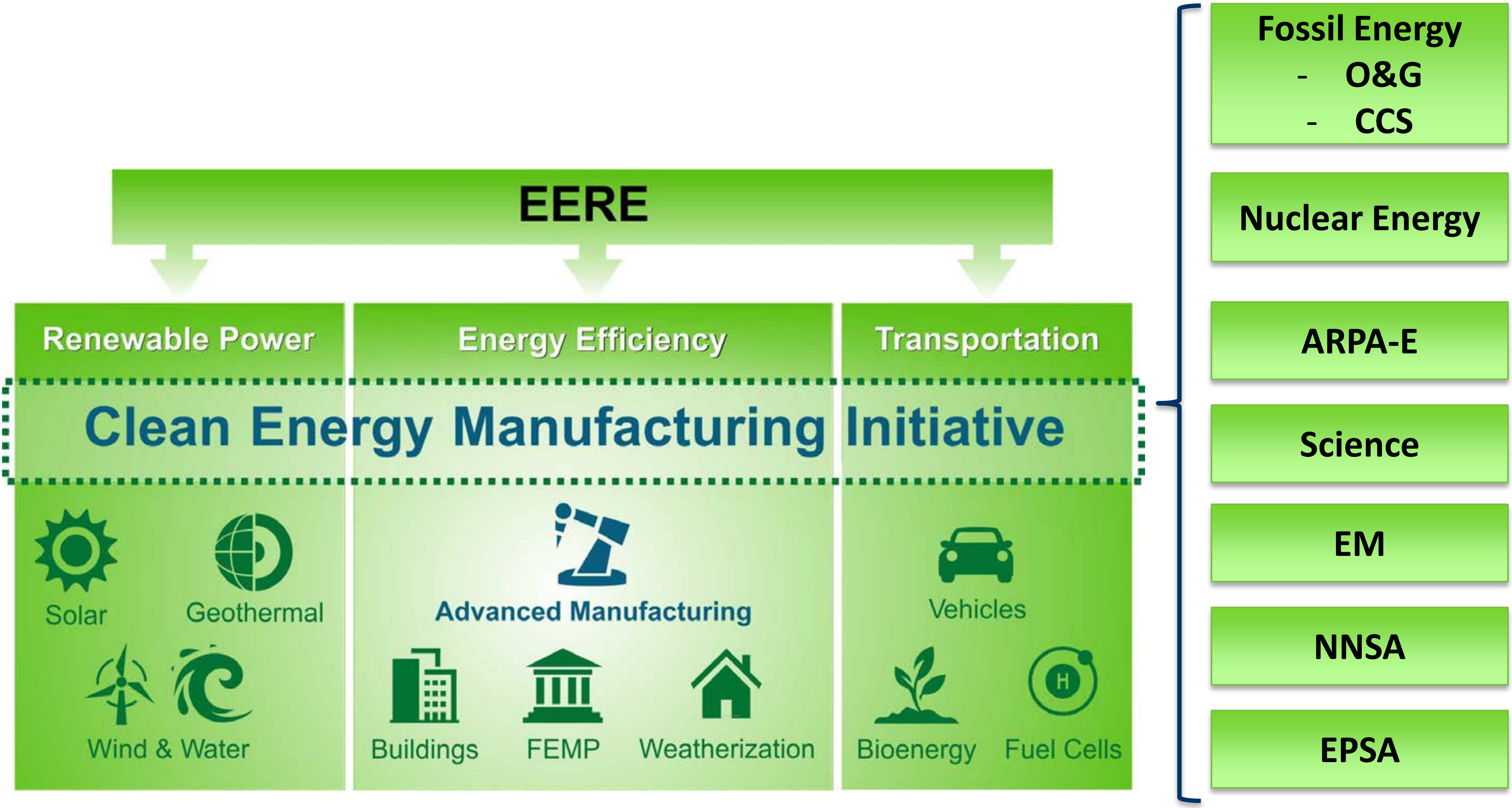
Three partnership-based approaches to engage industry, academia, national labs, and state & local government:

1. **Technical Assistance**
2. **Research and Development Projects**
3. **Shared R&D Facilities** - affordable access to physical and virtual tools, and expertise, to foster innovation and adoption of promising technologies

Topical Engagment with Industry

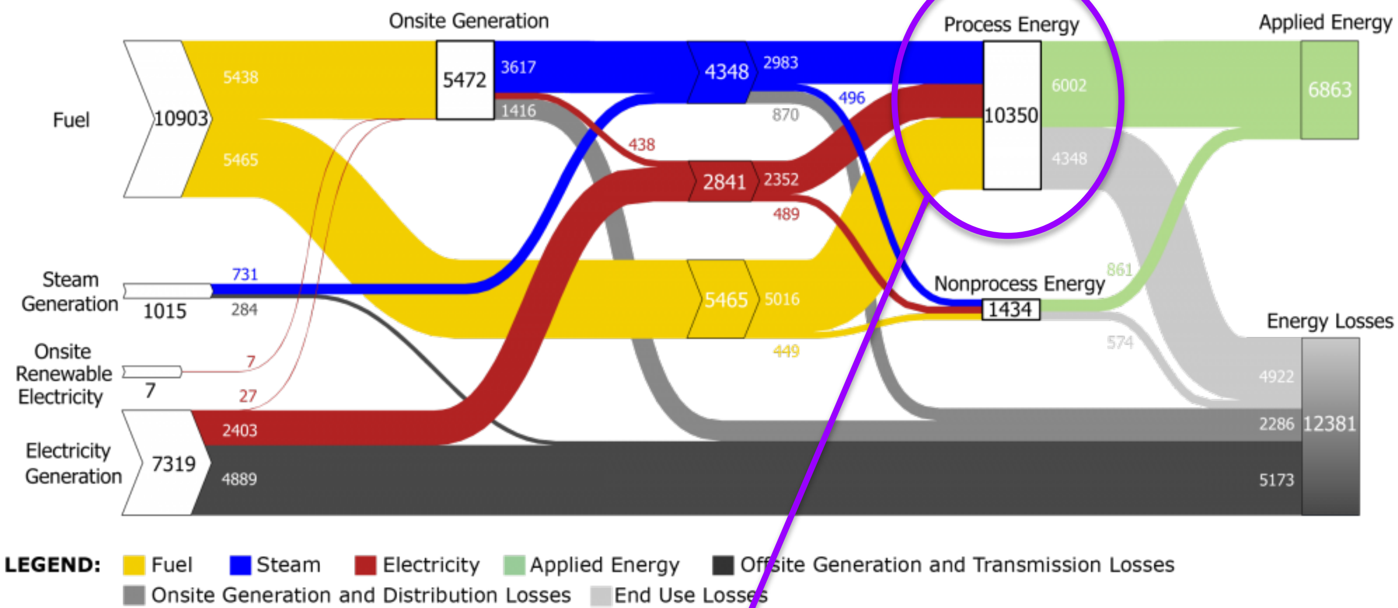
Advanced Materials	→ Materials in Extreme Conditions
	→ Sustainable Materials in Manufacturing
Process Intensification	→ Process Intensification (Chemical)
	→ Process Intensification (Thermal)
Roll-to-Roll Processing	→ Functional Membrane Structures
Advanced Sensors, Controls, Models, Platforms	→ Smart Manufacturing

Clean Energy Manufacturing Initiative – Across DOE

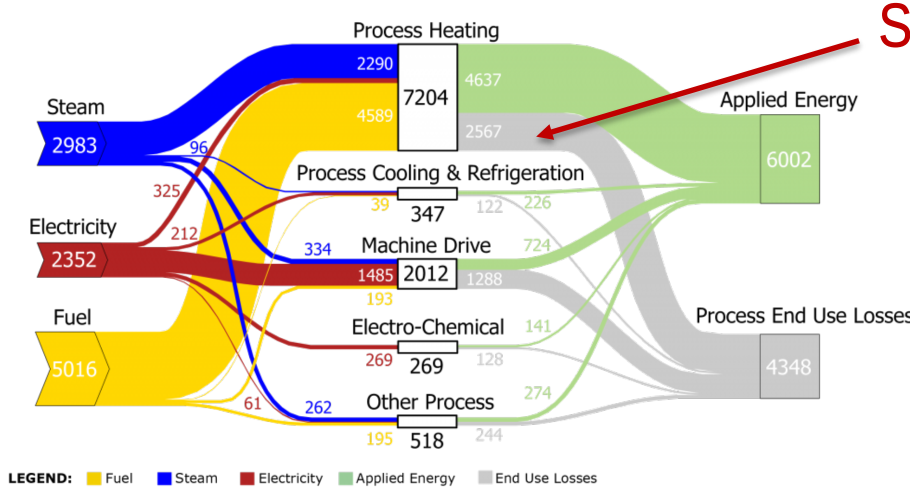


Energy Use in the Manufacturing Sector

U.S. Manufacturing Sector (TBtu), 2010



Process Energy (TBtu), 2010



Separations and Reactions

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Advanced Materials DOE-Wide Challenges

Mission: Material challenges are at the core of many DOE imperatives - advances in energy generation and use as well as our national nuclear security

Drivers: The past decade has seen tremendous progress in tools development for materials research along with need for accelerated pace of materials advancement

- The confluence of new theories, novel synthesis and characterization capabilities, and new computer platforms that extend capabilities to the atomic and nano-scale with the urgent demand for new and improved energy technologies
- 2015 Quadrennial Technology Review, National Lab Summit, Materials Genome Initiative, AMP 2.0, Stockpile Stewardship and Management Plan

Challenge Focus: Materials RDD&D that involves close coordination between Office of Science, Technology Offices, and National Security Offices to form a cohesive network of capabilities:

(1) Materials Design & Synthesis

(2) Functional (Applied) Design

(3) Process Scale-up

(4) Qualification

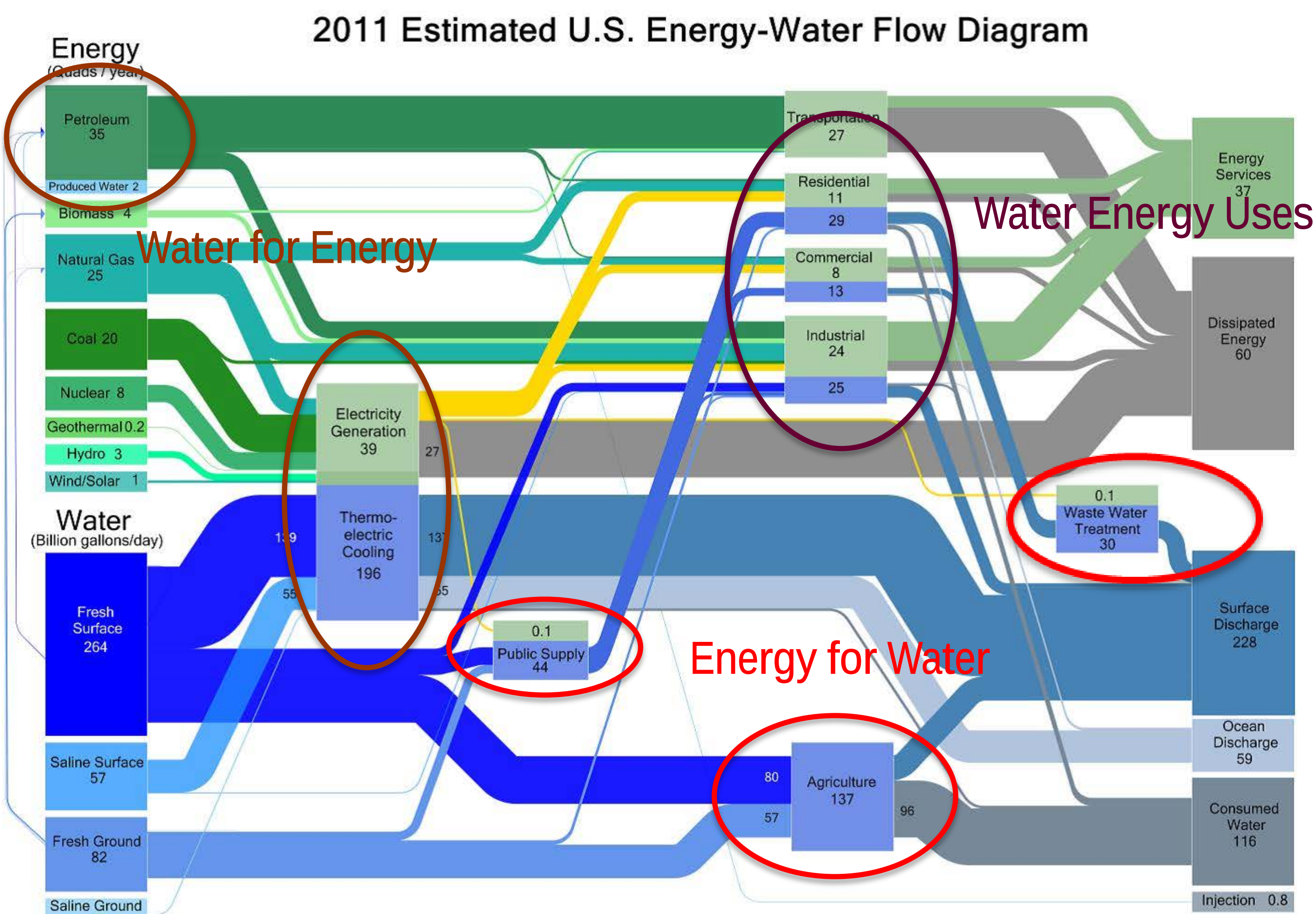
(5) Data Management & Informatics

Unprecedented opportunity to impact the materials development cycle from scientific discovery to technological innovation and deployment

Possible Impact Areas of Cross-Cutting Technology for Energy Intensive Industry Sectors

	Chemicals & Bio-chemicals	Petroleum Refining	Primary Metals	Forest & Food Products	Clean Water
SMART Manufacturing	●	●	●	●	●
Process Intensification	●	●	●	●	●
CHP & Grid Integration	●	●	●	●	●
Sustainable Manufacturing	●		●	●	●

Water and Energy in Sustainable Manufacturing



Energy reported in Quads/year. Water reported in Billion Gallons/Day.

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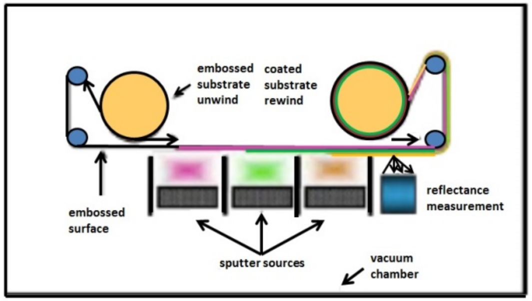
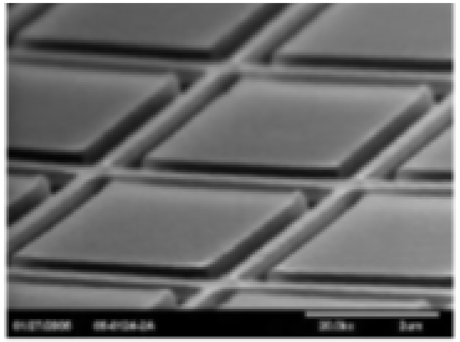
Previous workshops on R2R

- **Technology Areas**
  - Membranes (Fossil and Separation)
  - Flexible Electronics (active &passive)
  - Battery Technology
  - PEM Fuel Cells
  - Photovoltaics
  - Formatted, Higher Quality Depositions
  - Institute for Clean Energy Production (ICE-P)





- **Manufacturing Issues**
  - Scalable Solutions
  - Metrology
  - Quality systems
  - Process Control