High Value Roll-to-Roll Manufacturing Workshop

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Clean Energy and Manufacturing: Nexus of Opportunities

Clean Energy Solutions

- Competitiveness in clean energy
- Domestic jobs

Security

- Energy self-reliance
- Stable, diverse energy supply

Environment

- Clean air
- Climate change
- Health

Clean Energy Manufacturing
Making Products which Reduce Impact on Environment

Advanced Manufacturing
Making Products with Technology as Competitive Difference
Bridging the Gap to Manufacturing

AMO: Advanced Manufacturing Office

R&D Investment Level

Technology Maturity (TRL; MRL; etc.)

Governments and Universities

Private sector

DOE Energy Innovation Hubs

NSF Engineering Research Centers

NSF IUCR Centers

SBIR/STTR

R&D Projects

R&D Facilities

Technical Assistance

NIST Manufacturing Extension Partnership

Gap

Concept ➔ Proof of Concept ➔ Lab scale development ➔ Demonstration and scale-up ➔ Product Commercialization
Energy Consumption by Sector

Estimated U.S. Energy Use in 2013: ~97.4 Quads

Solar 0.320
Nuclear 8.27
Hydro 2.56
Wind 1.60
Geothermal 0.201
Natural Gas 26.8
Coal 18.0
Biomass 4.49
Petroleum 35.1

Energy Services 38.4
Rejected Energy 59.0

Energy Efficiency & Renewable Energy
Deeper Look at Energy in Manufacturing

Manufacturing Energy and Carbon Footprint
Sector: All Manufacturing (NAICS 31-33)

Onsite Energy Use: 14,064 TBtu
Onsite Combustion Emissions: 580 MMT CO₂e

Onsite Energy, 2010

Conventional Boilers
- Conventional Boilers: 1,176

CHP/ Cogeneration
- CHP/ Cogeneration: 3,988

Other Electricity Generation
- Distillate and Residual Fuels: 3,384
- LPG and NG: 61
- Other Fuels: 262

Other Process Uses
- Electro-Chemical: 330
- Machine Drive: 536
- Pumps: 20
- Fans: 296

Process Energy
- Process Heating: 328.7
- Process Cooling and Refrigeration: 234.4
- Other Process Uses: 25.7
- Electro-Chemical: 33.0

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Nonprocess Energy
- Facility HVAC: 638.8
- Facility Lighting: 28.8
- Other Facility Support: 10.5
- Other Nonprocess: 4.6

Energy use data source: 2010 EIA MECS (with adjustments)
Last Revised: February 2014
Notes:
- Sector-wide aggregate data for year 2010
- Energy values rounded to nearest whole number
- Feedback energy not included
- Offsite generation shown on net basis (purchases, sales, and transfers accounted for)

Prepared for the U.S. Department of Energy, Advanced Manufacturing Office by Energetics Incorporated
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.
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
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
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)

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

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

Quadrennial Technology Review
(DOE / Science and Technology 2015)
DOE QTR: Manufacturing Technology

Efficiency Technologies

1. Advanced Sensors, Controls, Modeling & Platforms
2. Process Heating
3. Combined Heat and Power
4. Flow of Material thru Industry (Sustainable Manufacturing)
5. Critical Materials
6. Direct Energy Conversion Materials (Magnetocaloric, Thermoelectric, etc)
7. Composites
8. Additive Manufacturing
9. Roll-to-Roll Processing
10. Wide Bandgap Power Electronics
11. Materials for Harsh Service Conditions

Enabling Platform Technologies

- Energy & Resource Management
- Advanced Manufacturing Processes
- Materials Development

Advanced Manufacturing Topical Priorities

**Efficiency Technologies for Manufacturing Processes (Energy, CO₂)**

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

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*

Key Extra-Chapter Connections
- Electric Power: flexible solar panels
- Buildings: window insulation films
- Transportation: battery electrodes

Modalities of Support

**Technology Assistance**: (Dissemination of Knowledge)

**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

Now

Ford River Rouge Complex, 1920s

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

How could we get innovation into manufacturing today?

- RD&D Consortia based Eco-Systems
- Public-private partnership to scale
Manufacturing Technology Maturation

**TRL 6/7:** System Testing in Production Relevant Environment  
**MRL 6/7:** System Components made in Pilot Environment

**TRL 5/6:** Hardware-in-Loop System Testing in Laboratory  
**MRL 5/6:** Investigate Pilot Environment to Make Systems

**TRL 4/5:** System Technology Tested in Laboratory  
**MRL 4/5:** Investigate Pilot Environment to Make Components

**TRL 3/4:** Enabling Technology Tested in Laboratory  
**MRL 3/4:** Enabling Components Made in Laboratory

**Foundational Science**

**TRL 1-3:**  
**MRL 1-3:**

**End-Use Adoption**
Critical Materials Institute

A DOE Energy Innovation Hub

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

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

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^1 Lux Research, 2012.
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

*States are significant contributors*
SMART Manufacturing: Advanced Controls, Sensors, Models & Platforms for Energy Applications

Focus on Real-Time For Energy Management

- Encompass machine-to-plant-to-enterprise real time sensing, instrumentation, monitoring, control, and optimization of energy (>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 Energy Intensive & Energy Dependent Manufacturing Processes

Leverage AMP 2.0 and QTR
Technical Challenge Hierarchy
Multi-Disciplinary Technology Translation

Application Domain

Science Foundation

Enabling Technologies

System Test-Beds

Validated System Capabilities

Qualified New Technologies

Technical Insight & Understanding

Like quantification of possible requirements, needs & gaps
What does Success Look Like?

Energy Products Invented Here...

...And Competitively Made Here!
Today’s Workshop

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.
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/metalllic 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
**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**
Efficient On-Site Energy
Clean Energy Application Centers
(to be called Technical Assistance Partnerships since in FY14)

Energy-Saving Partnership
Better Buildings, Better Plants, Industrial Strategic Energy Management

Student Training &
Energy Assessments
University-based Industrial Assessment Centers
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.*

Energy-efficient large thin-walled magnesium die casting, for 60% lighter car doors.
*Graphic image provided by General Motors.*

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

A water-stable protected lithium electrode.
*Courtesy of PolyPlus*
AMO Elements

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 Engagement with Industry

- Advanced Materials
- Process Intensification
- Roll-to-Roll Processing
- Advanced Sensors, Controls, Models, Platforms

- Materials in Extreme Conditions
- Sustainable Materials in Manufacturing
- Process Intensification (Chemical)
- Process Intensification (Thermal)
- Functional Membrane Structures
- Smart Manufacturing
Clean Energy Manufacturing Initiative – Across DOE

EERE

Renewable Power

Energy Efficiency

Transportation

Clean Energy Manufacturing Initiative

Fossil Energy
- O&G
- CCS

Nuclear Energy

ARPA-E

Science

EM

NNSA

EPSA
Energy Use in the Manufacturing Sector

U.S. Manufacturing Sector (TBtu), 2010

LEGEND:  Fuel  Steam  Electricity  Applied Energy  End Use Losses

Process Energy (TBtu), 2010

Separations and Reactions
**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

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<th>Petroleum Refining</th>
<th>Primary Metals</th>
<th>Forest &amp; Food Products</th>
<th>Clean Water</th>
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Water and Energy in Sustainable Manufacturing


Energy for Water

Water for Energy

Water Energy Uses

Energy for Water

Water for Energy

Energy reported in Quads/year. Water reported in Billion Gallons/Day.
Previous workshops on R2R

• **Technology Areas**
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  - PEM Fuel Cells
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