Quadrennial Technology Review (QTR): Technology Assessment - Sustainable Manufacturing/Flow of Materials Through Industry

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Sustainable Manufacturing Workshop
Portland, OR
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The QTR is a comprehensive assessment of science and energy technology R&D opportunities to address our nation's energy-linked economic, environmental, and security challenges.
Administration priorities

• **The Climate Action Plan** (June 2013):
  – Cut carbon emissions in the United States
  – Prepare the United States for the impacts of climate change
  – Lead international efforts to address global climate change

• **Quadrennial Energy Review (QER)**: Analyze government-wide energy policy, particularly focused on energy infrastructure.

• **Quadrennial Technology Review (QTR)**: Analysis of the most promising R&D opportunities across energy technologies leading towards a clean energy economy.

The resulting analysis and recommendations of the QTR 2015 will inform the national energy enterprise and will guide the Department of Energy’s programs and capabilities, budgetary priorities, industry interactions, and national laboratory activities.
Expanded Scope of QTR 2015

The QTR evaluates major changes since the first volume of the QTR was published in 2011 and provides forward leaning analysis to inform DOE’s strategic planning and decision making, via:

- **Systems Analyses** – to evaluate the power, buildings, industry, and transportation sectors, enabling a set of options going forward.

- **Technology Assessments** – Examines in detail, the technical potential and enabling science of key technologies out to 2030.

- **Road Maps** – Uses these analyses and assessments to extend R&D Roadmaps and frame the R&D path forward.
## QTR 2015

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http://energy.gov/quadrennial-technology-review-2015
Sustainable Manufacturing Technology Assessment

Approach—Outline a framework to better capture economy-wide affect energy and GHG emissions, and to help characterize improvement opportunities, including:

- Changes in materials and industrial/manufacturing processes
- Material flows and manufactured products
- Cross-sectoral and life cycle impacts
- Embodied Energy & GHGs

![Flowchart]

- Energy reductions
- Emissions reductions
- Use and re-use energy/emissions reductions
- Increased value-added
- Improved quality / Improved service
Sustainable Manufacturing Technology Assessment

Approach—Outline a framework to better capture economy-wide affect energy and GHG emissions, and to help characterize improvement opportunities, including:

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- Embodied Energy & GHGs

Materials → Manufacture → Transport → Intermediate Use → End Use/Re-use → Disposal

- Energy reductions
- Emissions reductions
- Use and re-use energy/emissions reductions
- Increased value-added
- Improved quality / Improved service

Target Technologies
Targeted technologies are impactful, for example:

- **Transformative**: Results in significant change in the life-cycle impact (energetic or economic) of manufactured products.

- **Pervasive**: Creates value in multiple supply chains, diversifies the end use/markets, applies to many industrial/use domains in both existing and new products and markets.

- **Globally Competitive**: Represents a competitive/strategic capability for the United States.

- **Significant in Clean Energy Industry**: Has a quantifiable energetic, environmental or economic value.
U.S. Economy-Wide Energy Demand

U.S. Economy: 95 Quads

- Manufacturing: 24.4 Quads (26%)
- Residential: 20.0 Quads (21%)
- Commercial: 17.4 Quads (18%)
- Transportation: 16.8 Quads (28%)
- Non-Manufacturing Industrial: 6.5 Quads (7%)

2012 Data

Industry and Manufacturing Energy Use

Industry: 31 Quads

- Natural Gas: 8.4 Quads (27%)
- Coal: 1.5 Quads (5%)
- Renewables: 2.3 Quads (7%)
- LPG: 0.4 Quads (1%)
- Petroleum (non-fuel): 2.6 Quads (8%)
- Petroleum: 3.2 Quads (11%)
- Electricity: 6.8 Quads (22%)

Manufacturing: 24.3 Quads

- Electricity Retail Sales to Industry: 3.4 Quads (11%)
- Non-Manufacturing Industrial: 6.5 Quads (21%)
- Transportation: 26.8 Quads (28%)
- Residential: 20.0 Quads (21%)
- Commercial: 17.4 Quads (18%)

U.S. Economy: 95 Quads

Fuel mix shows diverse nature of industry energy use

2012 Data


* Renewables consist primarily of biomass energy (2.2 Quads), with the remainder from onsite hydroelectric, geothermal, wind and solar energy.
Industry and **Manufacturing** Energy Use

**U.S. Economy: 95 Quads**

**Manufacturing:** 24.4 Quads

- **Natural Gas**: 6.5 Quads (27%)
- **Coal**: 1.5 Quads (6%)
- **Renewables***: 2.3 Quads (9%)
- **Electricity Losses**: 5.0 Quads (22%)
- **LPG (Feedstock)**: 2.2 Quads (9%)
- **Petroleum (non-fuel)**: 1.7 Quads (7%)
- **Petroleum**: 2.0 Quads (8%)

*Renewables consist primarily of biomass energy (2.238 Quads), with the remainder from onsite hydroelectric, geothermal, wind and solar energy.

2012 Data

Minus feedstocks = 19.2 Quads

Manufacturing: 24.4 Quads

U.S. Economy: 95 Quads

2012 Data


* Renewables consist primarily of biomass energy (2.238 Quads), with the remainder from onsite hydroelectric, geothermal, wind and solar energy.
Minus feedstocks = 19.2 Quads

Manufacturing: 24.4 Quads

U.S. Economy: 95 Quads

2012 Data


* Renewables consist primarily of biomass energy (2.238 Quads), with the remainder from onsite hydroelectric, geothermal, wind and solar energy.
Minus feedstocks = 19.2 Quads

Manufacturing: 24.4 Quads

Of the 24.4 Quads of manufacturing energy demand → 6.9 Quads are applied.

U.S. Economy: 95 Quads

2012 Data


* Renewables consist primarily of biomass energy (2.238 Quads), with the remainder from onsite hydroelectric, geothermal, wind and solar energy.
Systems approach to industrial & manufacturing analysis

Energy Use in Manufacturing Process
New products or processes may lead to change in energy use in manufacturing sector.

Energy Use in Environment
Change occurs in energy use across sectors as a result of deployment of new product.
**System Bounds:**
Impacted by Manufacturing

Manufacturing, facility, and supply-chain improvements reduce the 12 quads lost within the industrial sector

**Industrial Systems**
31 quads

**U.S. Energy Economy**
95 quads*

<table>
<thead>
<tr>
<th>Sector</th>
<th>Energy Use</th>
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</thead>
<tbody>
<tr>
<td>Transportation Sector</td>
<td>27 quads</td>
</tr>
<tr>
<td>Residential Sector</td>
<td>20 quads</td>
</tr>
<tr>
<td>Industrial Sector</td>
<td>31 quads</td>
</tr>
<tr>
<td>Commercial Sector</td>
<td>17 quads</td>
</tr>
</tbody>
</table>

Energy-efficient technologies reduce the 58 quads lost throughout the U.S. Energy Economy

**Supply-Chain Systems**
Network of facilities and operations involved in moving materials through industry, from extraction of raw materials to the production of finished goods.

**Example: Petroleum Refining**
- Refining Industry: ~4 quads
- Refining Industry: ~26 TBtu
- Facility Steam: ~5 TBtu
- Atmospheric Distillation Unit: ~4 TBtu
- Hydrocracker: ~2 TBtu
- Catalytic Reformer: ~3 TBtu

**Production/Facility Systems**
Equipment, process flow, and energy strategies that comprise a goods-producing facility

**Manufacturing Systems/Unit Operations**
Equipment used for manufacturing process and nonprocess unit operations

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*2012, EIA

- Technologies for clean & efficient manufacturing
- Technologies to improve energy use in transportation
- Technologies to improve energy use in buildings
- Technologies to improve energy production and delivery

Note: 1 quad = 1,000 TBtu
Drivers to Reduce Energy & Emissions through the Product Life Cycle

**Energy Intensity** e.g.:
- Process efficiency
- Process integration
- Waste heat recovery

**Carbon Intensity**, e.g.:
- Process efficiency
- Feedstock substitution
- Green chemistry
- Biomass-based fuels
- Renewables

**Use Intensity** e.g.:
- Recycling
- Reuse and remanufacturing
- Material efficiency and substitution
- By-products
- Product-Service-Systems
Energy Intensity Improvements

Technical Energy Savings Opportunities:

**Energy Intensity e.g.:**
- Process efficiency
- Process integration
- Waste heat recovery

**Carbon Intensity, e.g.:**
- Process efficiency
- Feedstock substitution
- Green chemistry
- Biomass-based fuels
- Process changes
- Renewables

**Use Intensity e.g.:**
- Recycling
- Reuse and remanufacturing
- Material efficiency and substitution
- By-products
- Product-Service-Systems

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**Source:** DOE/AMO, Energy Bandwidth Studies (2015)

**Note:** 1 quad = 1000 TBtu
Carbon Intensity Improvements

Direct emissions with efficiency improvements only...

Example analysis using the Buildings, Industry, Transport, Electricity Scenario (BITES) tool

Energy Intensity e.g.:
- Process efficiency
- Process integration
- Waste heat recovery

Carbon Intensity, e.g.:
- Process efficiency
- Feedstock substitution
- Green chemistry
- Biomass-based fuels
- Process changes
- Renewables

Use Intensity e.g.:
- Recycling
- Reuse and remanufacturing
- Material efficiency and substitution
- By-products
- Product-Service-Systems

Agriculture, mining, construction: Opportunities for advanced engines, biofuels, etc.

Carbon capture and sequestration (CCS) technologies offer additional opportunities
### Use Intensity Improvements

<table>
<thead>
<tr>
<th></th>
<th>Primary</th>
<th>Secondary</th>
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<tbody>
<tr>
<td>Current average</td>
<td>26,000</td>
<td>2,200</td>
</tr>
<tr>
<td>Practically achievable</td>
<td>20,000</td>
<td>925</td>
</tr>
<tr>
<td>Current savings potential</td>
<td>6,000 btu/lb</td>
<td>1,275</td>
</tr>
<tr>
<td>Theoretical minimum</td>
<td>10,200</td>
<td>510</td>
</tr>
</tbody>
</table>

Energy Intensity e.g.:
- Process efficiency
- Process integration
- Waste heat recovery

Carbon Intensity, e.g.:
- Process efficiency
- Feedstock substitution
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Use Intensity e.g.:
- Recycling
- Reuse and remanufacturing
- Material efficiency and substitution
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**Expanded Technology Opportunity Space:**
- **Materials Shift** – To enable increase of secondary aluminum by manufacturing
- **End-of-life shift** – To enable greater capture and use of landfill + scrap export
- **Systems-wide** – Materials & product design, manufacturing, use and re-use.

**Aluminum Materials Flows**
- U.S. and Canada, 2009 Billions of Pounds
# Systems approach in the QTR Industry & Manufacturing chapter:

<table>
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<th>System Level</th>
<th>As defined in the QTR</th>
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<tr>
<td>Manufacturing Systems/Unit Operations</td>
<td><em>Technology and equipment used for manufacturing process and nonprocess unit operations</em></td>
</tr>
<tr>
<td>Production/Facility Systems</td>
<td><em>Equipment, process flow, and energy strategies that comprise a goods-producing facility</em></td>
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<tr>
<td>Supply-Chain Systems</td>
<td><em>Facilities and operations involved in moving materials through an industry, from the extraction of raw materials to the production of finished goods.</em></td>
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</table>
## Technology opportunities exist at each systems level

<table>
<thead>
<tr>
<th>System Level</th>
<th>Examples</th>
<th>R&amp;D Opportunity Examples</th>
</tr>
</thead>
</table>
| **Manufacturing Systems/Unit Operations** | • Composites/curing system  
• Chemicals separation system  
• Low thermal-budget process heating | • Transition from autoclave to out-of-the autoclave technology  
• Transition from distillation to membranes  
• Smart manufacturing equipment |
| **Production/Facility Systems**           | • Petroleum refinery  
• Vehicle assembly plant  
• Facility steam systems  
• Enterprise computer/control systems | • Process intensification  
• Smart enterprise systems  
• Advanced CHP systems  
• Grid-friendly equipment |
| **Supply-Chain Systems**                  | • Steel industry  
• Transportation equipment industry  
• Distributed manufacturing | • Recyclability/design for re-use  
• Alternative materials development  
• Use of low-carbon fuels and feedstocks  
• Technology opportunities to transform markets |
Technology Assessments at their principal manufacturing systems level:

<table>
<thead>
<tr>
<th>System Level</th>
<th>QTR Manufacturing Technology Assessments</th>
</tr>
</thead>
</table>
| **Manufacturing Systems/Unit Operations** | • Process Heating  
• Process Intensification  
• Roll-to-Roll Processing  
• Additive Manufacturing |
| **Existing Processes; New Approaches** | |
| **Production/Facility Systems** | • Combined Heat and Power Systems  
• Waste Heat Recovery Systems  
| **Fuel Flexibility and Waste Energy; Data and Automation** | |
| **Supply-Chain Systems** | • Advanced Materials Manufacturing  
• Critical Materials  
• Sustainable Manufacturing  
• Direct Thermal Energy Conv. Materials, Devices & Systems  
• Materials for Harsh Service Conditions  
• Wide Bandgap Semiconductors for Power Electronics  
• Composite Materials |
Energy, Carbon and Use Intensity Improvements

**Energy Intensity e.g.:**
- Process efficiency
- Process integration
- Waste heat recovery

**Carbon Intensity, e.g.:**
- Process efficiency
- Feedstock substitution
- Green chemistry
- Biomass-based fuels
- Process changes
- Renewables

**Use Intensity e.g.:**
- Recycling
- Reuse and remanufacturing
- Material efficiency and substitution
- By-products
- Product-Service-Systems
Energy, Carbon and Use Intensity Improvements

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- Reuse and remanufacturing
- Material efficiency and substitution
- By-products
- Product-Service-Systems
<table>
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<th>Chemical [references]</th>
<th>Conventional process</th>
<th>Feedstock&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Conversion pathway</th>
<th>Life cycle energy reduction GJ/t product (%)</th>
<th>Life cycle GHG reduction t CO₂-eq/t product (%)</th>
<th>Development stage</th>
<th>Cost ratio (bio-/fossil-based)</th>
</tr>
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<tbody>
<tr>
<td>Bio-adipic acid [69,75] (benzene derivative)</td>
<td>Petroleum-based, benzene building block</td>
<td>Glucose from sugar beet</td>
<td>Bio-chemical &amp; Thermal-chemical</td>
<td>30.4–58.9 GJ/t (29–57%)</td>
<td>9.8–17.4 t CO₂-eq/t (NA)</td>
<td>Pilot plant, commercialization in 1–2 years</td>
<td>0.8–0.7</td>
</tr>
<tr>
<td>Bio-polyactic acid PLA &lt;sup&gt;76,77&lt;/sup&gt; (substitute)</td>
<td>50% PE, 50% polypropylene (PP) from ethylene, propylene (PLA replace PP and PE as plastics)</td>
<td>Corn starch</td>
<td>Bio-chemical</td>
<td>22–50 GJ/t (29–66%)</td>
<td>0.8–3.0 t CO₂-eq/t (17–63%)</td>
<td>Commercialized</td>
<td>0.9–1.3</td>
</tr>
<tr>
<td>Bio-polyethylene terephthalate PET &lt;sup&gt;78&lt;/sup&gt; (ethylene, xylene derivative)</td>
<td>Petroleum based PET produced from ethylene glycol and purified terephthalic acid/dimethyl terephthalate</td>
<td>Maize and sugarcane</td>
<td>Bio-chemical &amp; thermo-chemical</td>
<td>13–22 GJ/t (24–32%)</td>
<td>1–2 t CO₂-eq/t PET (41–43%)</td>
<td>Commercialized</td>
<td>Comparable price with petroleum-based PET</td>
</tr>
<tr>
<td>Bio-ethylene &lt;sup&gt;67,71&lt;/sup&gt;</td>
<td>Steam cracking of NGL/naphtha/gas oil</td>
<td>Sugarcane, lignocelluloses, maize starch</td>
<td>Bio-chemical</td>
<td>40–100%</td>
<td>40%</td>
<td>Commercialized</td>
<td>1.1–2.3</td>
</tr>
<tr>
<td>Bio-polyethylene &lt;sup&gt;8**&lt;/sup&gt; (ethylene derivative)</td>
<td>Polyethylene (PE) from ethylene</td>
<td>Corn starch or sugar cane</td>
<td>Bio-chemical</td>
<td>29.3–67.6 GJ/t (40–88%)</td>
<td>2.1–4.2 t CO₂-eq/t (120–200%)</td>
<td>Commercialized</td>
<td>Depends on bio-ethylene production</td>
</tr>
<tr>
<td>Bio-polyhydroxyalkanoate (PHA) &lt;sup&gt;8**,67,77&lt;/sup&gt; (substitute)</td>
<td>Polyethylene (PE) from ethylene (PHA replace PE as biodegradable plastics)</td>
<td>Agriculture residues, corn starch, sugar cane, lignocelluloses</td>
<td>Bio-chemical</td>
<td>−35 to 58.9 GJ/t (−47% to 77%)</td>
<td>−2.6 to 2.8 t CO₂-eq/t (−160% to 175%)</td>
<td>Commercialized</td>
<td>4.9–5.4</td>
</tr>
<tr>
<td>Methanol &lt;sup&gt;79&lt;/sup&gt;</td>
<td>Methane</td>
<td>CO₂ captured from power plant; CO generated by thermochemical splitting of CO₂ using solar thermal energy; H₂ generated by water gas shift of H₂O and CO</td>
<td>Methanol synthesis from CO/H₂</td>
<td>10 kWh/kg (98%)</td>
<td>2.4 t CO₂-eq/t (350%)&lt;sup&gt;c&lt;/sup&gt;</td>
<td>Commercialized</td>
<td>2.7</td>
</tr>
<tr>
<td>Methanol &lt;sup&gt;80&lt;/sup&gt;</td>
<td>Methane</td>
<td>CO₂ captured from power plant; H₂ generated by electrolysis supplied by wind farm</td>
<td>Direct methanol synthesis from CO₂/H₂</td>
<td>NA</td>
<td>1.1 t CO₂-eq/t (59%)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup> As reported in the source study.

<sup>b</sup> Negative values indicate emerging pathway is more energy and/or GHG intensive than the conventional pathway; percent savings greater than 100% are attributable to avoided emissions.

<sup>c</sup> Large GHG emissions reductions are attributable to carbon capture and renewable energy.
Technology Assessments - Current technology status, R&D needs, and potential impacts.

Legend

Manufacturing systems level in chapter
Secondary impacts assessed

Critical Materials

Direct Thermal Energy Conversion Materials, Devices and Systems

Wide Bandgap Semiconductors for Power Electronics

Materials for Harsh Service Conditions

Advanced Materials Manufacturing

Additive Manufacturing

Composite Materials

Roll-to-Roll Processing

Process Intensification

Process Heating

Advanced Sensors, Controls, Platforms and Modeling for Manufacturing

Waste Heat Recovery Systems

Combined Heat and Power Systems

Sustainable Manufacturing / Flow of Materials through Industry

Advanced Technologies

Advanced Manufacturing

Technology Assessments - Current technology status, R&D needs, and potential impacts.

Manufacturing Systems – Unit Operations

Production / Facility Systems – Energy and Resource Utilization

Beyond the Plant Boundaries – Supply Chain and Life Cycle
Sustainable Manufacturing Technology Assessment – Scope:

- Supply chain issues, from resource extraction to end of life (Life Cycle Analysis)
- Flow diagrams to demonstrate supply chain issues
- Material efficiency: mechanisms for reducing demand for materials (e.g., lightweighting, scrap reduction, increased material longevity)
- Design for Re-use / Recycling

Connections to other QTR Chapters and Technology Assessments
Sustainable Manufacturing Technology Assessment—Connections

Cross-Energy Connections

- **Electric Power**: management of water & energy resources
- **Buildings**: recycling and materials substitution/minimization

Connections to other QTR Chapters and Technology Assessments

- Grid
- Electric Power
- Buildings
- Fuels
- Transportation

Sustainable Manufacturing – Flow of Materials through Industry

- Critical Materials
- Direct Thermal Energy Conversion
- Materials, Devices and Systems
- Wide Bandgap Semiconductors for Power Electronics
- Materials for Harsh Service Conditions
- Advanced Materials Manufacturing
- Additive Manufacturing
- Composite Materials Manufacturing
- Process Heating
- Process Intensification
- Roll-to-Roll Processing
- Advanced Sensors, Controls, Platforms and Modeling for Manufacturing
- Waste Heat Recovery Systems
- Combined Heat and Power
Sustainable Manufacturing Technology Assessment—Connections

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- **Electric Power**: management of water & energy resources
- **Buildings**: recycling and materials substitution/minimization

Connections to other QTR Chapters and Technology Assessments

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Sustainable Manufacturing – Flow of Materials through Industry

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- Additive Manufacturing
- Composite Materials Manufacturing
- Roll-to-Roll Processing
- Advanced Sensors, Controls, Platforms and Modeling for Manufacturing
- Process Heating
- Process Intensification

Intra-Manufacturing Connections

- **Critical Materials**: materials substitution
- **Process Heating**: shared ownership of equipment to maximize production intensity
- **Materials for Harsh Service Conditions / Advanced Materials Manufacturing**: materials to increase durability or facilitate re-use
- **Combined Heat and Power / Process Intensification**: modular equipment design for easier reconfiguration, upgrade and repair
- **Additive Manufacturing**: distributed manufacturing; raw material minimization
- **Composite Materials**: Lightweight materials manufacturing for life-cycle energy savings
- **Advanced Sensors, Controls, Platforms, and Modeling for Manufacturing**: smart technologies to enable track & trace of materials through the life cycle
- **Waste Heat Recovery**: optimization of heat flows to maximize production intensity and minimize waste heat losses

Electric Power:
- management of water & energy resources

Buildings:
- recycling and materials substitution/minimization
Sustainable Manufacturing Technology Assessment Connections

Cross-Energy Connections

- **Electric Power**: management of water & energy resources
- **Buildings**: recycling and materials substitution/minimization

Connections to other QTR Chapters and Technology Assessments

- Grid
- Electric Power
- Buildings
- Fuels
- Transportation

Sustainable Manufacturing – Flow of Materials through Industry

- Critical Materials: materials substitution
- Process Heating: shared ownership of equipment to maximize production intensity
- Materials for Harsh Service Conditions / Advanced Materials Manufacturing: materials to increase durability or facilitate re-use
- Combined Heat and Power / Process Intensification: modular equipment design for easier reconfiguration, upgrade and repair
- Additive Manufacturing: distributed manufacturing; raw material minimization
- Composite Materials: Lightweight materials manufacturing for life-cycle energy savings
- Advanced Sensors, Controls, Platforms, and Modeling for Manufacturing: smart technologies to enable track & trace of materials through the life cycle
- Waste Heat Recovery: optimization of heat flows to maximize production intensity and minimize waste heat losses
Technology Highlights – Use Intensity Improvements

Additive Manufacturing

Applications in Multiple Sectors
- Lightweight components for the transportation sector
- Advanced tooling for manufacturing
- Custom products and small-batch production
- Accelerated design cycles for rapid product development

R&D Challenges
- Fabrication of large products
- Distributed manufacturing
- Time-quality optimization
- Materials efficiency

Energy, cost, and environmental impacts (throughout life cycle) are application dependent.

Case Study: Optimized Aircraft Bracket

- 65% weight reduction
- 81% reduction in buy-to-fly ratio
- 66% energy savings
- Most savings occur in use phase

1.09 kg

0.38 kg

Life-Cycle Energy Savings for Additive Manufactured Aircraft Bracket

Source: MFI and LIGHTEnUP Analysis
Note: 1 quad = 1 × 10^9 MMBtu
Technology Highlights – Use Intensity Improvements

Additive Manufacturing

Applications in Multiple Sectors

- Lightweight components for the transportation sector
- Advanced tooling for manufacturing
- Custom products and small-batch production
- Accelerated design cycles for rapid product development

R&D Challenges

- Fabrication of large products
- Distributed manufacturing
- Time-quality optimization
- Materials efficiency

Energy, cost, and environmental impacts (throughout life cycle) are application dependent.

Impacts from Aircraft Fleet-Wide Adoption of Additive Manufacturing

Annual Energy Savings for Fleet-Wide Adoption of Additive Manufactured Components in Aircraft

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Slow Adoption</th>
<th>Mid-Range Adoption</th>
<th>Rapid Adoption</th>
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<tbody>
<tr>
<td>Slow Adoption</td>
<td>new aircraft only</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mid-Range Adoption</td>
<td>new aircraft and new parts</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rapid Adoption</td>
<td>new aircraft, new parts, and accelerated replacement</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Annual Energy Savings (TWh/year)

- 2030: Slow Adoption (0.5), Mid-Range Adoption (4.7), Rapid Adoption (5.5)
- 2040: Slow Adoption (4.7), Mid-Range Adoption (42.0), Rapid Adoption (98.3)
- 2050: Slow Adoption (24.9), Mid-Range Adoption (91.2), Rapid Adoption (115.7)

Energy Savings Breakdown: Over 95% of savings occur in use phase


Note: 1 quad = 1,000 TWh
• Carbon Fiber (CF) is currently ~ 5x more energy intensive than steel:
• Improved CF is ~ ½ energy intensity than PAN:
• Significantly improved materials and manufacturing energy improves net energy footprint
The Circular Economy

- Renewables flow management
  - Regenerate
  - Substitute materials
  - Virtualise
  - Restore

- Stock management

1. Hunting and fishing
2. Can take both post-harvest and post-consumer waste as an input

Circular Economy – In December 2015, the European Commission 2030 targets for recycling municipal waste (65%) and packaging waste (75%).
“The European Commission’s clear and consistent recycling definitions are very encouraging. The proposal to move the point of measurement of recycling to after the sorting phase rather than at the collection phase will ensure that Member States report on real recycling results.”

“About one million tonnes of aluminium scrap was exported in 2014, this is an economic waste making Europe even more reliant on imports. This could be avoided through greater investment in European collection and sorting infrastructure. Exporting scrap is like exporting the energy embedded in the metal. If we recycled this quantity here in Europe we would save the equivalent of the annual energy consumption of countries such as Latvia or Luxembourg.”

http://www.euractiv.com/sections/sustainable-dev/europe-should-continue-strive-ideal-circular-economy-320140
<table>
<thead>
<tr>
<th>Strategy</th>
<th>Scenario examples</th>
<th>Examples of enabling technologies</th>
<th>2015 QTR, Technology Assessment References</th>
<th>Actors</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Substitution</strong></td>
<td>Non-critical material in place of critical material</td>
<td>Super-vacuum die casting process using a new magnesium alloy(^1), Materials Genome Initiative, biofuel substitution for petroleum based fuels and chemicals, blended cement geo-polymers(^6)</td>
<td>Advanced Materials Manufacturing; Composite Materials Manufacturing; Wide Band Gap Semiconductors for Power Electronics; Critical Materials; Process Intensification; QTR Chapter 5</td>
<td>Designers</td>
</tr>
<tr>
<td><strong>Property</strong></td>
<td>Improving the properties of materials and products to facilitate re-use or increase durability</td>
<td>Improving heat transfer to increase WHR; improving properties to make some materials suitable for AM</td>
<td>Materials for Harsh Service Conditions; Waste Heat Recovery Systems; Additive Manufacturing; Direct Thermal Energy Conversion Materials, Devices and Systems</td>
<td>Producers</td>
</tr>
<tr>
<td><strong>Yield</strong></td>
<td>Reducing material loss during processing; tessellation</td>
<td>Membrane coating for the black liquor-to-fuel concentration process(^1), coating material to reduce surface deposits in ethylene production(^1), hybrid system for industrial wastewater treatment and reuse(^1), combined microbial reverse electro dialysis technology with waste heat recovery to convert effluents into electricity and products(^1), additive manufacturing, near net-shape processing</td>
<td>Additive Manufacturing; Process Intensification; Roll to Roll Processing; Advanced Materials Manufacturing</td>
<td>Producers</td>
</tr>
</tbody>
</table>

Considerations as we start this workshop....

- What sustainable manufacturing technologies and system improvements* could yield the greatest economy-wide impacts?
- How can we sustainably leverage domestic energy resources (e.g., NG)?
- What timely investments could potentially enable U.S. leadership and open markets?

*for example:
- Developing and Using Alternative/Sustainable Feedstocks
- Reduction of Waste in Manufacturing Processes
- End-of-Life Management
- Materials, Water and Energy Management
- Sustainable Design and Decision-Making
Back-Up Slides
Critical Materials

Intra-Manufacturing Connections

- Sustainable Manufacturing: materials substitution
- Advanced Sensors, Controls, Platforms, and Modeling for Manufacturing: models to minimize critical materials use
- Advanced Materials Manufacturing: computational techniques to develop critical material alternatives

Cross-Energy Connections

- Electric Power: permanent magnets for wind turbines
- Buildings: phosphors for LED lighting
- Transportation: dysprosium and other rare earths for motors; platinum for fuel cell catalysts

Scope

- Dynamic nature of criticality
- Permanent magnets for wind turbines and electric vehicles
- Phosphors for energy efficient lighting
- Supply diversity and global material criticality
**Direct Thermal Energy Conversion Materials, Devices and Systems**

**Intra-Manufacturing Connections**
- **Materials for Harsh Service Conditions**: thermal conversion materials and devices for high-temperature or corrosive environments
- **Roll-to-Roll**: thermoelectric device fabrication via roll-to-roll
- **Waste heat recovery**: novel energy conversion materials, devices and systems for waste heat to power
- **Additive Manufacturing**: additive manufacturing of thermoelectric modules
- **Advanced Sensors, Controls, Platforms and Modeling for Manufacturing**: thermal control systems; power for wireless sensor networks

**Cross-Energy Connections**
- **Electric Power**: water withdrawal for power plant cooling; waste heat recovery in power plants
- **Buildings**: thermoelectric heat pumps for HVAC
- **Transportation**: direct thermal energy conversion for internal combustion engines

**Scope**
- Thermoelectric materials (including new proven materials such as Skutterudites and Half-Heusler alloys)
- New manufacturing processes such as wafer-base manufacturing to replace pick-and-place
- Waste heat recovery equipment
- Thermoelectric generation of electricity (cost target: $1/Watt)
**Intra-Manufacturing Connections**
- **Sustainable Manufacturing**: smaller-footprint electronics with reduced cooling requirements
- **Advanced Sensors, Controls, Platforms and Modeling for Manufacturing**: variable frequency drives and motor speed control
- **Advanced Materials Manufacturing**: low-cost, commercial-scale production methods for wide bandgap devices

---

**Cross-Energy Connections**
- **Grid**: solid state transformers for power flow control; inverters for renewable energy
- **Buildings**: variable speed drives for HVAC systems; AC-to-DC and DC-to-AC adapters
- **Transportation**: Power electronics for electric vehicles

---

**Scope**
- Opportunities for silicon carbide (SiC) and gallium nitride (GaN) to replace silicon (Si) in power electronics
- Applications include AC adapters, data centers, and inverters for renewable energy generation
Materials for Harsh Service Conditions

Cross-Energy Connections

- **Fuels**: corrosion in offshore drilling equipment; ash fouling in biomass conversion equipment; hydrogen embrittlement in H₂ pipelines
- **Electric Power**: radiation-resistant fuel cladding; high-temperature alloys for nuclear reactors and gas and steam turbines
- **Transportation**: corrosion-resistant lightweight materials

Intra-Manufacturing Connections

- **Sustainable Manufacturing / Advanced Materials Manufacturing**: materials to increase durability or facilitate re-use; materials genome techniques for new materials development
- **Composite Materials**: lightweight, durable structural components for automobiles; erosion-resistant composites for wind turbine blades and turbomachinery
- **Direct Thermal Energy Conversion**: thermal conversion materials and devices for high-temperature or corrosive environments
- **Advanced Sensors, Controls, Platforms and Modeling for Manufacturing**: computational modeling to support advanced materials development;

Scope

- Materials for extreme environments including high temperatures, high pressures, corrosive chemicals, heavy mechanical wear, nuclear radiation, and hydrogen exposure
Advanced Materials Manufacturing

Intra-Manufacturing Connections

- **Additive Manufacturing**: material formulations for additive techniques
- **Roll-to-Roll**: thin- and thick-film substrate production; multilayer alignment
- **Sustainable Manufacturing / Materials for Harsh Service Conditions**: materials to increase durability or facilitate re-use; materials genome techniques for new materials development
- **Advanced Sensors, Controls, Platforms and Modeling for Manufacturing**: computational modeling to support advanced materials development; controls and sensors to support advanced manufacturing techniques
- **Wide Bandgap Semiconductors**: low-cost, commercial-scale production methods for wide bandgap devices

Cross-Energy Connections

- **Electric Power**: Materials genome techniques to screen materials for use in carbon capture and storage (CCS) applications
- **Buildings**: Advanced building envelope materials
- **Transportation**: Predictive design, modeling, and simulation for vehicle product development

Scope

- Broad-brush discussion of next generation materials, technical barriers, and opportunities
- Emerging processes for advanced materials production
- Materials Genome and computational manufacturing as related to Clean Energy Manufacturing
Additive Manufacturing

Intra-Manufacturing Connections

- Advanced Sensors, Controls, Platforms and Modeling for Manufacturing: metrology and control systems for improved quality, defect detection, and throughput
- Process Intensification: microchannel reactor fabrication
- Roll-to-Roll Manufacturing: common technology needs for additive 2-D (roll-to-roll) and 3-D (additive manufacturing) printing technologies
- Composite Materials: 3-D printing of reinforced polymers and other composites
- Advanced Materials Manufacturing: material formulations for additive techniques
- Direct Thermal Energy Conversion: additive manufacturing of thermoelectric modules

Cross-Energy Connections

- Fuels: fuel cells
- Electric Power: custom electrical components in substations; complex parts for power plants; tooling for large castings for power plants
- Buildings: heat exchangers for HVAC systems; window frames
- Transportation: Prototyping and tooling in automotive applications; fuel cells

Scope

- Structural composite materials for lightweighting, including automotive, wind, and gas storage applications
- Forming and curing technologies for thermosetting and thermoplastic polymer composites
Composite Materials

Intra-Manufacturing Connections

- Additive Manufacturing: 3-D printing of reinforced polymers and other composites
- Materials for Harsh Service Conditions: lightweight, durable structural components for automobiles; erosion-resistant composites for wind turbine blades and turbomachinery
- Advanced Sensors, Controls, Platforms and Modeling for Manufacturing: inspection techniques for quality control; automated tape laying and automated tape placement
- Sustainable Manufacturing: Lightweight materials manufacturing for life-cycle energy savings

Cross-Energy Connections

- Fuels: hydrogen fuel storage
- Electric Power: lightweight wind turbine blades
- Transportation: compressed gas storage for mobile applications; automotive lightweighting

Scope

- Structural composite materials for lightweighting, including automotive, wind, and gas storage applications
- Forming and curing technologies for thermosetting and thermoplastic polymer composites
**Roll-to-Roll Processing**

**Intra-Manufacturing Connections**
- **Advanced Sensors, Controls, Platforms and Modeling for Manufacturing**: metrology and control systems for improved quality, defect detection, and throughput
- **Process Intensification**: roll-to-roll for production of separation membranes
- **Additive Manufacturing**: common technology needs for additive 2-D (roll-to-roll) and 3-D (additive manufacturing) printing technologies
- **Direct Thermal Energy Conversion**: thermoelectric device fabrication via roll-to-roll
- **Advanced Materials Manufacturing**: thin- and thick-film substrate production; multilayer alignment

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

**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
Process Intensification

Intra-Manufacturing Connections

• Process Heating / Waste Heat Recovery: integrated control systems; replacement of batch operations with continuous ones; facility integration to enable re-use of exhaust gases in lower-temperature processes
• Combined Heat and Power / Sustainable Manufacturing: modular equipment design for easier reconfiguration, upgrade and repair
• Roll-to-Roll Processing: roll-to-roll for production of separation membranes
• Additive Manufacturing: microchannel reactor fabrication
• Advanced Sensors, Controls, Platforms, and Modeling for Manufacturing: on-line data acquisition and modeling for process control; enterprise-wide operations optimization

Cross-Energy Connections

• Fuels: natural gas and modular production
• Electric Power: chemical conversion of biofeedstocks; separations for CCS
• Buildings: membranes for dehumidification
• Transportation: adsorbent systems for compressed gas storage

Scope

• Process intensification equipment and methods
• Separations technologies
• Feedstock use and feedstock conversion technologies
• Focus on the energy-intensive chemical sector
**Process Heating Systems**

**Intra-Manufacturing Connections**
- **CHP**: integration of CHP with process heating equipment
- **Sustainable Manufacturing**: shared ownership of equipment to maximize production intensity
- **Waste Heat Recovery**: waste heat recovery from process heating equipment; facility integration to enable re-use of exhaust gases in lower-temperature processes
- **Process Intensification**: integrated control systems; replacement of batch operations with continuous ones

**Cross-Energy Connections**
None, as this is a manufacturing-specific technology

**Scope**
- Low thermal budget technologies
- Sensors and process controls for process heating equipment
- Process heating energy saving opportunities, e.g. waste heat recovery, non-thermal drying, and low-energy processing
- Fuel, electricity, steam, and hybrid systems
Advanced Sensors, Controls, Platforms, and Modeling for Manufacturing

Intra-Manufacturing Connections

Connections spanning all manufacturing technologies, including: integrated sensors and controls for increased manufacturing throughput, efficiency, and quality control; computational models for simulations and accelerated materials development

Cross-Energy Connections

- **Grid**: advanced metering; sensors for power flow
- **Electric Power**: grid integration
- **Buildings**: advanced sensors for lighting and HVAC
- **Transportation**: vehicles engine control systems

Scope

- Smart systems and advanced controls
- Advanced sensors and metrology, including power/cost sensors and component tracking across the supply chain
- Distributed manufacturing
- Predictive maintenance
- Product customization
- HPC, cloud computing and optimization algorithms
Waste Heat Recovery Systems

Connections to other QTR Chapters and Technology Assessments

Intra-Manufacturing Connections
- CHP: heat recovery in CHP systems
- Sustainable Manufacturing: optimization of heat flows to maximize production intensity and minimize waste heat losses
- Direct Thermal Energy Conversion: novel energy conversion materials, devices and systems for waste heat to power
- Advanced Sensors, Controls, Platforms and Modeling for Manufacturing: sensors to monitor temperature, humidity, and lower explosion limits to enable increased exhaust gas recycling; predictive models for combustion
- Process Intensification: integrated control systems; replacement of batch operations with continuous ones
- Process Heating: waste heat recovery from process heating equipment; facility integration to enable re-use of exhaust gases in lower-temperature processes

Cross-Energy Connections
- Electric Power: waste heat recovery opportunities in electric generation
- Buildings: heat exchangers in HVAC systems
- Transportation: waste heat recovery from internal combustion engines

Scope
- Waste heat recovery technologies, including recuperators, recuperative burners, stationary and rotary regenerators, and shell-and-tube heat exchangers
- Major waste heat sources such as blast furnaces, electric arc furnaces, melting furnaces, and kilns
- Opportunities for low, medium, and high-temperature waste heat recovery
Combined Heat and Power Systems

Intra-Manufacturing Connections
- Sustainable Manufacturing / Process Intensification: modular design for easier reconfiguration, upgrade and repair
- Waste Heat Recovery: heat recovery in CHP systems
- Advanced Sensors, Controls, Platforms, and Modeling for Manufacturing: models to support development of high-efficiency CHP configurations; improved controls for grid integration
- Process Heating: integration of CHP with manufacturing equipment

Cross-Energy Connections
- Grid: CHP for distributed generation
- Electric Power: CHP for distributed generation

Scope
- Supply chain issues, from resource extraction to end of life (Life Cycle Analysis)
- Flow diagrams to demonstrate supply chain issues Material efficiency: mechanisms for reducing demand for materials (e.g., lightweighting, scrap reduction, increased material longevity)
- Design for Re-use / Recycling
Sustainable Manufacturing / Flow of Materials through Industry

Intra-Manufacturing Connections
- Critical Materials: materials substitution
- Process Heating: shared ownership of equipment to maximize production intensity
- Materials for Harsh Service Conditions / Advanced Materials Manufacturing: materials to increase durability or facilitate re-use
- Combined Heat and Power / Process Intensification: modular equipment design for easier reconfiguration, upgrade and repair
- Additive Manufacturing: distributed manufacturing; raw material minimization
- Composite Materials: Lightweight materials manufacturing for life-cycle energy savings
- Advanced Sensors, Controls, Platforms, and Modeling for Manufacturing: smart technologies to enable track & trace of materials through the life cycle
- Waste Heat Recovery: optimization of heat flows to maximize production intensity and minimize waste heat losses

Cross-Energy Connections
- Electric Power: management of water & energy resources
- Buildings: recycling and materials substitution/minimization

Scope
- Supply chain issues, from resource extraction to end of life (Life Cycle Analysis)
- Flow diagrams to demonstrate supply chain issues Material efficiency: mechanisms for reducing demand for materials (e.g., lightweighting, scrap reduction, increased material longevity)
- Design for Re-use / Recycling
Introduction - Flow of Energy through the U.S. Economy

Estimated U.S. Energy Use in 2012: ~95.1 Quads

Source: LLNL 2013. Data is based on DOE/EIA-0035(2013-05), May, 2013. 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 63% 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-NI-116527
Introduction – Flow of Energy Through Manufacturing

U.S. Manufacturing Sector (TBtu), 2010

Note: 1 quad = 1,000 TBtu
Driver – Energy Intensity Improvements

Technical Energy Savings Opportunities: Iron & Steel Industry
2015 Bandwidth Study – potential by major process area

Source: DOE/AMO, Iron & Steel Industry Energy Bandwidth Study (2014)

Note: 1 quad = 1000 TBtu
**Technology Assessment – Additive Manufacturing**

**Example: Optimized Aircraft Bracket**

**Conventional Machining - Buy-to-Fly Ratio 8:1**

- **Primary Processing** (15.9 MJ/kg)
  - Ingot (918 MJ/kg embodied energy)

- **Secondary Processing** (8.72 kg)
  - Mill Product (slab, billet, etc.)

- **Final Processing**
  - Machined Product

- **Finished Part**

**Additive Manufacturing - Buy-to-Fly Ratio 1.5:1**

- **Atomization** (14.8 MJ/kg)
  - Powder

- **Final Processing** (0.38 kg)
  - Electron Beam Melting (EBM)

- **Finished Part**

*“Average” conventional bracket 1.09 kg, “average” AM bracket 0.38 kg

<table>
<thead>
<tr>
<th>Process</th>
<th>Final part kg</th>
<th>Ingot consumed kg</th>
<th>Raw mat’l MJ</th>
<th>Manuf MJ</th>
<th>Transport MJ</th>
<th>Use phase MJ</th>
<th>End of life</th>
<th>Total energy per bracket MJ</th>
<th>Total energy per (120 brackets) MJ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machining</td>
<td>1.09</td>
<td>8.72</td>
<td>8,003</td>
<td>952</td>
<td>41</td>
<td>217,949</td>
<td>Not considered</td>
<td>226,945</td>
<td>27.3 MM</td>
</tr>
<tr>
<td>EBM (Optimized)</td>
<td>0.38</td>
<td>0.57</td>
<td>525</td>
<td>115</td>
<td>14</td>
<td>76,282</td>
<td>Not considered</td>
<td>76,937</td>
<td>9.2 MM</td>
</tr>
</tbody>
</table>

**Key assumptions:**
- Ingot embodied (source) energy 918 MJ/kg (255 kWh/kg)[5]
- Forging 1.446 kWh/kg[5] , Atomization 1.343 kWh/kg[6,7,8], Machining 9.9 kWh/kg removed[9], SLM 29 kWh/kg[10, 11], EBM 17 kWh/kg[10]
- 11 MJ primary energy per kWh electricity
- Machining pathway buy-to-fly 33:1[15], supply chain buy point = forged product (billet, slab, etc.)
- AM pathway buy-to-fly 1.5:1, supply chain buy point = atomized powder
- Argon used in atomization and SLM included in recipes but not factored into energy savings in this presentation

*Source: MFI and LIGHTEnUP Analysis*
Driver – Carbon Intensity

Direct emissions with efficiency improvements, ...

Example analysis using the Buildings, Industry, Transport, Electricity Scenario (BITES) tool
Driver – Use Intensity: Aluminum Example

Materials Shift – To enable increase of secondary aluminum
End-of-life shift – To enable greater capture and use of landfill + scrap export
Systems-wide – Materials & product design, manufacturing, use and re-use.

Materials Shift

A. Materials shift
   - Secondary 9.1
   - Import 1.7

B. End-of-life shift
   - Post-Consumer 16.7
     - Opportunities:
       - sorting, recycle friendly allows (RFA),
       - design for re-use, urban mining
   - Landfill 4.1
   - Scrap Export 3.5

C. Process improvements
   - Primary 7.0
   - Manufacturing 17.8
     - Opportunities:
       - next-gen processes (e.g., additive mfg)
       - materials for increased export potential

Product Import 1.7

Product Export 2.8

Recycle 9.1