A Perspective on Energy Use and Progression of Emerging Advanced Manufacturing Technologies

Joe Cresko - Advanced Manufacturing Office, DOE

Aspen Global Change Institute
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How can we better inform the scale and speed needed for technology / policy options?

What can we do better?

- **Prioritize** → Can we develop practical approaches to prioritize the next generation of industrial technologies → (based on life cycle energy and carbon productivity)?

- **Communicate** → Can we provide clear, compelling information that can impact technology/policy decision-making.

What you’ll see in this presentation → Context (a little bit about sectors, energy, technologies....)
U.S. Economy: 95 Quads

- Manufacturing: 24.4 quads (26%)
- Transportation: 26.8 quads (28%)
- Residential: 20.0 quads (21%)
- Commercial: 17.4 quads (18%)
- Non-Manufacturing Industrial: 6.5 quads (7%)

2012 Data
U.S. Manufacturing Energy Use

2012 Data

U.S. Economy: 95 Quads

Manufacturing: 24.4 Quads

* Renewables consist primarily of biomass energy (2.3 Quads), with the remainder from onsite hydroelectric, geothermal, wind and solar energy.

Manufacturing 24.4 26%
Non-Manufacturing Industrial 6.5 7%
Electricity Retail Sales to Industry 2.8 11%

Transportation 26.8 28%
Residential 20.0 21%
Commercial 17.4 18%
U.S. Manufacturing Energy Use

Minus feedstocks = 19.2 Quads

U.S. Economy: 95 Quads

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Minus feedstocks = 19.2 Quads

Manufacturing: 24.4 Quads

Of the 19.2 Quads of manufacturing energy demand → 6.9 Quads are applied.

U.S. Economy: 95 Quads

2012 Data

* Renewables consist primarily of biomass energy (2.3 Quads), with the remainder from onsite hydroelectric, geothermal, wind and solar energy.
Opportunity Space for Manufacturing

• Improve the energy and carbon productivity of U.S. manufacturing.

• Reduce life cycle energy and resource impacts of manufactured goods.

Manufacturing Goods

More efficient manufacturing reduces energy losses.

More efficient manufacturing enables technologies that improve energy use throughout the economy:
  • Transportation
  • Buildings
  • Energy Production and Delivery

Use of Manufactured Goods

U.S. Energy Economy by Sector
95.1 quadrillion Btus, 2012

Energy Losses

Transportation 26.8
Residential 20
Commercial 17.4
Non-Mfg 6.5
Industrial Manufacturing 24.4

Energy consumption by sector from EIA Monthly Energy Review, 2012
Industrial non-manufacturing includes agriculture, mining, and construction
US economy energy losses determined from LLNL Energy Flow Chart 2012 (Rejected Energy)
Manufacturing energy losses determined from DOE AMO Sankey/Footprint Diagrams (2010 data)
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
- Biomass-based fuels
- Renewables

Use Intensity e.g.:
- Circular Economy
- Design for Re-X (recycling reuse and remanufacturing)
- Material efficiency and substitution

New Processes
New Materials
Improved Products by Next Generation Materials and Processes.
How to quantify the opportunity space? Start with current energy use within the manufacturing sector...

U.S. Manufacturing Sector (TBtu), 2010

Note: 1 quad = 1,000 TBtu

... and investigate energy savings potentials – Bandwidth studies.

<table>
<thead>
<tr>
<th>Year</th>
<th>Manufacturing sector bandwidth studies:</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td>Chemicals, Iron &amp; Steel, Pulp &amp; Paper, Petroleum Refining</td>
</tr>
<tr>
<td>2017</td>
<td>Aluminum, Advanced High Strength Steel, Titanium, Magnesium, Carbon Fiber Reinforced Polymer Composites, Glass Fiber Reinforced Polymer Composites</td>
</tr>
</tbody>
</table>

**Lightweight materials bandwidth studies:**
- Aluminum
- Advanced High Strength Steel
- Titanium
- Magnesium
- Carbon Fiber Reinforced Polymer Composites
- Glass Fiber Reinforced Polymer Composites

**Water/energy studies:**
- Desalination Bandwidth Study

**Energy bandwidth studies** can frame the range (or *bandwidth*) of potential energy savings in manufacturing, and technology opportunities to realize those savings.

<table>
<thead>
<tr>
<th>Current</th>
<th>Typical</th>
<th>State of the Art</th>
</tr>
</thead>
<tbody>
<tr>
<td>Practical</td>
<td>Minimum</td>
<td>Impractical</td>
</tr>
<tr>
<td>Theoretical</td>
<td>Minimum</td>
<td></td>
</tr>
</tbody>
</table>

![Image of bar chart showing energy bandwidth studies]
Bandwidth analyses are bottom-up studies starting at the manufacturing process/unit operation level.…

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


Note: 1 quad = 1000 TBtu
... for potential energy improvements.

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

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

**Use Intensity** e.g.:
- Circular economy
- Design for Re-X (recycling, reuse and remanufacturing)
- Material efficiency and substitution

### Technical Energy Savings Opportunities:

**Chemicals**
- Impractical Opportunity (2023)
- Future Opportunity (1176)
- Current Opportunity (764)

**Petroleum Refining**
- Impractical Opportunity (1793)
- Future Opportunity (793)
- Current Opportunity (420)

**Iron and Steel**
- Impractical Opportunity (228)
- Current Opportunity (239)

**Pulp and Paper**
- Current Opportunity (464)
- Impractical Opportunity (154)

**Future Opportunity** (147)

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

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

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

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

Use Intensity e.g.:
- Circular economy
- Design for Re-X (recycling, reuse and remanufacturing)
- Material efficiency and substitution

Example analysis based in part on bandwidth SOTA & PM potential, and EIA Annual Energy Outlook (AEO) forecast as baseline.
### Use Intensity

**Aluminum**

<table>
<thead>
<tr>
<th>btu/lb</th>
<th>primary</th>
<th>secondary</th>
</tr>
</thead>
<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, Biomass-based fuels, Renewables
- **Use Intensity** e.g.: Circular economy, Design for Re-X (recycling, reuse and remanufacturing), Material efficiency and substitution

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**Graph:**
- **Monthly U.S. aluminum production**
  - Thousand metric tons

  - **Primary production**
    - Jan-15 to Jan-17
  - **Secondary production**
    - Jan-15 to Jan-17

  - 23,800 btu/lb Materials shift

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15
Fuels as Feedstocks: Chemical Bandwidth Extension Analysis to understand full supply chain implications

- **Goal 1**: Supply chain analysis based on 2015 DOE chemical sector energy bandwidth study
- **Goal 2**: Determine supply chain impacts associated with bio-based chemical production

- 73 fossil-based and 3 bio-based chemical supply chains analyzed using NREL’s [MFI tool](https://www.nrel.gov/manufacturing/mfi-modeling-tool.html)*
- Fossil feedstock energy is reduced by 80-90% in bio-based scenarios
- GHG emissions may be higher for some bio-based pathways, due to higher process fuel or electricity requirements

Opportunities in process heating

• **7 Quads.** Process heating accounts for a sizable fraction of total U.S. energy use, and more direct energy use than any other energy consuming processes in manufacturing.

• **95% fossil fuel based.**

• **Potential?** What is potential to avoid the 2.5 Q of energy losses and reduce the 4.6 Q of energy demand in process heating?

• **Opportunity for electrification?** Traditional industrial (thermal) processes can be inefficient, difficult to control and result in materials and products with compromised quality and performance.

• **Timeframe?** Can adoptions of electric arc furnaces; Hall-Herault for aluminum; induction melting & heat-treating; etc. inform future technology adoption/progression?
Use of Electricity for Process Heating in Different Industries

(Source: Manufacturing Energy Consumption Survey, Energy Information Administration, 2010)

Process Heating Primary Energy Use (TBtu)
Study and Analysis Objectives

- Identify use of **current and emerging ETs** in process heating applications.

- Identify the **barriers to the large scale implementation** of ETs in the manufacturing sector.

- **Quantify the economic and other benefits** from the use of ETs or hybrid systems at manufacturing process level for major industries.

- **Estimate of the national level impact** (i.e., increase in electricity use and production requirement) with application of ETs in all major industries.

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**Preliminary - case study on NG-Fired Furnace vs Induction Furnace in a Forging Plant**
# Global Manufacturing Sector Energy Consumption by fuel type, 2015.

<table>
<thead>
<tr>
<th></th>
<th>Coal and coal products</th>
<th>Electricity</th>
<th>Natural gas</th>
<th>Oil products</th>
<th>Biofuels and waste</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>World</td>
<td>31%</td>
<td>27%</td>
<td>20%</td>
<td>10%</td>
<td>7%</td>
<td>5%</td>
</tr>
<tr>
<td>United States</td>
<td>8%</td>
<td>25%</td>
<td>48%</td>
<td>4%</td>
<td>12%</td>
<td>2%</td>
</tr>
<tr>
<td>Canada</td>
<td>6%</td>
<td>36%</td>
<td>35%</td>
<td>6%</td>
<td>15%</td>
<td>2%</td>
</tr>
<tr>
<td>France</td>
<td>9%</td>
<td>36%</td>
<td>42%</td>
<td>6%</td>
<td>6%</td>
<td>0.4%</td>
</tr>
<tr>
<td>Germany</td>
<td>12%</td>
<td>35%</td>
<td>34%</td>
<td>5%</td>
<td>7%</td>
<td>8%</td>
</tr>
<tr>
<td>Italy</td>
<td>5%</td>
<td>38%</td>
<td>32%</td>
<td>11%</td>
<td>3%</td>
<td>11%</td>
</tr>
<tr>
<td>Japan</td>
<td>29%</td>
<td>32%</td>
<td>14%</td>
<td>20%</td>
<td>4%</td>
<td>0%</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>9%</td>
<td>36%</td>
<td>32%</td>
<td>16%</td>
<td>4%</td>
<td>3%</td>
</tr>
<tr>
<td>China</td>
<td>57%</td>
<td>28%</td>
<td>4%</td>
<td>5%</td>
<td>0%</td>
<td>6%</td>
</tr>
<tr>
<td>Rest of World</td>
<td>19%</td>
<td>24%</td>
<td>25%</td>
<td>14%</td>
<td>13%</td>
<td>5%</td>
</tr>
</tbody>
</table>

Looking forward - anticipate and address tomorrow’s energy intensive materials with R&D today

CFRP composites have the highest manufacturing energy intensity, but with R&D advances could compete with incumbent materials on an energy/performance basis.

https://energy.gov/eere/amo/energy-analysis-sector

Global Steel Production
1,565 million tons/year

U.S. Steel Production
88.7 million tons/year

Aluminum: Global 45.4 million tons/year; U.S. 1.9 million tons/year
GFRP: Global 6.0 million tons/year; U.S. 1.1 million tons/year
Magnesium: Global 823 thousand tons/year; U.S. 21 thousand tons/year
Titanium: Global 146 thousand tons/year; U.S. 17 thousand tons/year
CFRP: Global 117 thousand tonnes/year; U.S. 33 thousand tonnes/year
NEMS is a simulation model of the U.S. energy system organized by energy producing, consuming, and conversion sectors.

- **The Industrial Demand Module (IDM)** estimates energy consumption by energy source (fuels and feedstocks) for 15 manufacturing and 6 non-manufacturing industries.

- **Process energy** is modeled in two different ways, either with technologies by process flow or by end uses using efficiency (TPC) curves.
The Annual Energy Outlook (AEO) is based on NEMS

Examples of constraints/concerns with the industrial model:

• The Industrial Demand Module (IDM) provides very limited opportunities to shift to certain energy sources, e.g. electricity based technologies. There are no electric boiler options in the model.

• Technology choice (in processes) is only available for 5 major industries. Cement & Lime (AEO2012), Aluminum (AEO2013), Glass (AEO2014), Steel (AEO2016), Pulp & Paper (AEO2016)

• Diagnostic cases have illustrated that for the fuel competition (among selected technologies), electricity prices have the greatest influence on technology shares, with a limited impact from the alternative-specific constants (‘forcing electricity’) and no significant impact from the cost of the technologies.
Do our current frameworks demonstrate a lack of vision?

Technology static over decades. Future structure largely based on current structure.

Pessimistic or pragmatic?

Drivers – Moving Towards High Energy & Carbon Productivity

Future looks very different.

Optimistic or delusional?
Survey of 116 firms
New product cycle times (months)

<table>
<thead>
<tr>
<th>New-to-the-world</th>
<th>53.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>New product lines</td>
<td>36.0</td>
</tr>
<tr>
<td>Next generation improvements</td>
<td>22.0</td>
</tr>
<tr>
<td>Incremental improvements</td>
<td>8.6</td>
</tr>
</tbody>
</table>


Technology Progression – Confluence of Additive/Composites Manufacturing Technologies

Big Area Additive Manufacturing (BAAM)

- **Obstacle:** Most additive processes are slow (1-4 in³/hr), use higher cost feedstocks, and have small build chambers.

- **Solution:** ORNL has worked with equipment manufacturers and the supply chain to develop large scale additive processes that are bigger, faster, cheaper, and increase the materials used.

- **Large Scale Printers**
  - Cincinnati System 8’x20’x6’ build volume

- **Fast Deposition Rates**
  - Up to 100 lbs/hr (or 1,000 ci/hr)

- **Cheaper Feedstocks: Pellet-to-Part**
  - Pelletized feed replaces filament with up to 50x reduction in material cost

- **Better Materials**
  - Higher temperature materials
  - Bio-derived materials
  - Composites Hybrids
Additive Manufacturing or Composites Manufacturing?

Shelby Cobra replica and tooling for wind turbine blade, printed via additive manufacturing at the DOE Manufacturing Demonstration Facility at ORNL
Opportunities for improved methods that can inform technology / policy options:

• Refined methods to account for technology choice and technology progression in large scale models (e.g. NEMS).

• Approaches to prioritize the next generation of industrial technologies based on life cycle energy and carbon productivity.

• Integrated analysis techniques that can assess a range of technology choices.
Aspen’s big news in 1892 was the building of the Holden Lixiviation works on the west side of town. The newspaper declared that “the sweet day dreams of those who have longed to see Aspen a great city are about to be realized.” Completed just 14 months before Congress repealed the Sherman Silver Act, the plant never cleared a profit and went bankrupt almost immediately. It was one of only eighteen plants build world-wide to utilize the experimental Russell Lixiviation process to refine low grade ore.

The Russell Lixiviation process used crushing, heat, and chemical salts to refine silver from ore as low grade as ten ounces per ton (Aspen ores averaged 400 to 600 ounces of silver per ton, but much low grade ore had to be discarded). The fumes from the plant’s Stetefeldt furnaces were
2018


2017


2016


2016 cont.


2015


2014

2013


<table>
<thead>
<tr>
<th>Sector (Year Published)</th>
<th>Visit</th>
</tr>
</thead>
</table>
Assess energy savings opportunities within manufacturing....

Energy bandwidth studies frame the range (or bandwidth) of potential energy savings in manufacturing, and technology opportunities to realize those savings.

Measures of energy intensity studied:

<table>
<thead>
<tr>
<th>Current Typical (CT)</th>
<th>State of the Art (SOA)</th>
<th>Practical Minimum (PM)</th>
<th>Thermodynamic Minimum (TM)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Basis:</strong> Literature review and stakeholder outreach, based on current typical manufacturing processes in the U.S.</td>
<td><strong>Basis:</strong> Literature review and stakeholder outreach, based on the most energy-efficient technologies and practices available worldwide</td>
<td><strong>Basis:</strong> Modeled based on plausible energy savings from identified R&amp;D technologies under development worldwide</td>
<td><strong>Basis:</strong> Calculated analytically using a Gibbs free energy approach assuming ideal conditions</td>
</tr>
</tbody>
</table>
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Note: 1 quad = 1000 TBtu
... for potential energy improvements.

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Note: 1 quad = 1000 TBtu
Technology Adoption Back-up Slides
What we have done up to now: technology adoption w./energy focus

(A) Adoption start time (when technology will be introduced into market)
- RD&D process
- Technology and manufacturing readiness

(B) Full adoption level
- Total size of potential market determined on a technology-by-technology basis
- Technology may only capture a portion of the potential market

(C) Adoption trajectory (adoption speed and shape of adoption curve)
- Linear
- Bass diffusion & variants

Factors affecting technology adoption:
- Technology
  - attributes
  - competition
- Investment
  - RD&D
  - market
- Information
  - p’s & q’s
  - behavior

Candidate Indicator?: $ Market/$ RD&D
(A) Adoption Start time

Factors influencing concept-to-commercial time

- Technology complexity
- Technical difficulty
- Project “newness”
- Development process
- Co-development w/customers, suppliers
- Financial and regulatory support

Survey of 116 firms
New product cycle times (months)

<table>
<thead>
<tr>
<th>Product Type</th>
<th>Time (months)</th>
</tr>
</thead>
<tbody>
<tr>
<td>New-to-the-world</td>
<td>53.2</td>
</tr>
<tr>
<td>New product lines</td>
<td>36.0</td>
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<td>Incremental improvements</td>
<td>8.6</td>
</tr>
</tbody>
</table>

Source: [2]

Physical science innovation timeline

<table>
<thead>
<tr>
<th>Technology Stage</th>
<th>Timing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theory</td>
<td>Decades</td>
</tr>
<tr>
<td>Fundamental research</td>
<td>Decades</td>
</tr>
<tr>
<td>Technology development</td>
<td>5–10 years</td>
</tr>
<tr>
<td>Proof of concept</td>
<td>1–2 years</td>
</tr>
<tr>
<td>Prototype</td>
<td>6 months</td>
</tr>
<tr>
<td>Alpha product</td>
<td>6–12 months</td>
</tr>
<tr>
<td>Qualification &amp; manufacturing</td>
<td>12 months</td>
</tr>
<tr>
<td>Product extensions</td>
<td>2 years +</td>
</tr>
</tbody>
</table>

Source: [3]
<table>
<thead>
<tr>
<th>Product</th>
<th>Fast Adoption Time</th>
<th>Medium Adoption Time</th>
<th>Slow Adoption Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hybrid corn</td>
<td>6.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conversion to 70% H2O2 delivery systems</td>
<td>6.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Continuous bleach ranges</td>
<td>6.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CT Head Scanner</td>
<td>7.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CT Body Scanner</td>
<td>7.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Personal computer: specific technologies</td>
<td>8.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hybrid corn</td>
<td>6.0</td>
<td></td>
<td></td>
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<tr>
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<td>6.0</td>
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<tr>
<td>Continuous bleach ranges</td>
<td>6.2</td>
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</tr>
<tr>
<td>CT Head Scanner</td>
<td>7.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CT Body Scanner</td>
<td>7.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Personal computer: specific technologies</td>
<td>8.4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Adoption times are years to reach 95% adoption, calculated based on p and q estimates from sources [7, 9-15]
Additive manufacturing (AM) of airplane parts [4]

- Determine number and weight of airplanes in market
- Evaluate airplane parts to determine applicability of AM technology based on
  - Materials used
  - Load rating
  - Shape complexity
  - Volume
- Compare with competing technologies
  - Carbon fiber
  - Lightweight metals

<table>
<thead>
<tr>
<th>Component systems</th>
<th>Component category</th>
<th>Mass fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wing</td>
<td>Structural</td>
<td>0.23</td>
</tr>
<tr>
<td>Wing</td>
<td>Auxiliary</td>
<td>0.01</td>
</tr>
<tr>
<td>Body</td>
<td>Structural</td>
<td>0.18</td>
</tr>
<tr>
<td>Body</td>
<td>Auxiliary</td>
<td>0.01</td>
</tr>
<tr>
<td>Galley &amp; Lavatory</td>
<td>Structural</td>
<td>0.03</td>
</tr>
<tr>
<td>Floor panels, other</td>
<td>Structural</td>
<td>0.02</td>
</tr>
<tr>
<td>Seats</td>
<td>Functional</td>
<td>0.07</td>
</tr>
<tr>
<td>Engine</td>
<td>Structural</td>
<td>0.02</td>
</tr>
<tr>
<td>Engine</td>
<td>Functional</td>
<td>0.09</td>
</tr>
<tr>
<td>Engine</td>
<td>Auxiliary</td>
<td>0.01</td>
</tr>
<tr>
<td>Alighting gear</td>
<td>Structural</td>
<td>0.09</td>
</tr>
<tr>
<td>Alighting gear</td>
<td>Auxiliary</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Tail systems</td>
<td>Structural</td>
<td>0.04</td>
</tr>
<tr>
<td>Tail systems</td>
<td>Auxiliary</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Propulsion systems</td>
<td>Functional</td>
<td>0.04</td>
</tr>
<tr>
<td>Nacelle systems</td>
<td>Structure</td>
<td>0.04</td>
</tr>
<tr>
<td>Nacelle systems</td>
<td>Auxiliary</td>
<td>&lt;0.01</td>
</tr>
</tbody>
</table>
### Diffusion of Innovations [5]

- Relative advantage
- Compatibility
- Complexity
- Trialability
- Observability

### Technology attributes [6] characterizing:

- Relative advantage
- Technical context
- Information context

Adoption trajectory: Bass curve

- Shape of Bass curve determined by two parameters
  - \( p \): coefficient of innovation determines early adoption speed
  - \( q \): coefficient of imitation determines speed after initial adoption

- Alternative way of specifying Bass curve: time to ‘full adoption’ vs. shape parameter \( q/p \)
  - In LIGHTEn UP, Bass adoption is implemented by allowing the user to specify the time to full adoption, and providing three options for the shape parameter \( q/p \): slow, medium, and fast
  - Slow, medium, and fast values for \( q/p \) selected based on ranges of \( q \)’s and \( p \)’s collected from the technology diffusion literature
Predicting technology adoption from limited data: using prior data from other technologies

- Prior data analysis:
  - Obtained estimates of $q$ and $p$ from variety of data sources [7, 9-15]
  - Calculated years to 95% adoption using $q$ and $p$ estimates

- Prior data informing $q$ and $p$ - match technology with similar existing technologies for which recent data are available
  - Similar technology
    - Example: variable speed drive for pumps, fans, compressors
  - Similar technology characteristics
    - Example: Distance to core process - close (reactive distillation : microwave enhanced cracking)
    - Example: Type of modification - technology substitution (composite turbine blades : permanent magnet turbine generators)

- Option: metamodel of existing studies to choose adoption speed for a new technology based on values of selected characteristics (e.g. relative advantage, distance to core process)
Bayesian approaches combine data fitting with knowledge about likely parameter ranges for predicting technology adoption from limited data: using early adoption data.

- Just fitting data, no prior
- Just prior, no fitting data
- Both fitting data and prior

Assumptions: priors drawn from
- \( p \sim N(0.011, 0.013) \)
- \( q \sim N(0.45, 0.30) \)
- \( m \sim N(0.57, 0.24) \)
- std. dev. of error in fitting data = 0.01
Notional Policy Impacts on Technology Adoption

- **Accelerate start time by 5 years**

  - 25-year benefit: 4.0
  - 40-year benefit: 4.0
  - 15 years to full adoption

- **Reduce time to full adoption by 33%**

  - 25-year benefit: 1.9
  - 40-year benefit: 1.9
  - 15 years to full adoption

- **Increase market share by 25%**

  - 25-year benefit: 1.6
  - 40-year benefit: 4.6
  - 15 years to full adoption
Technology Adoption References


Back-up Slides
AMO Strategic Goals

• Improve the productivity and energy efficiency of U.S. manufacturing.

• Reduce lifecycle energy and resource impacts of manufactured goods.

• Leverage diverse domestic energy resources in U.S. manufacturing, while strengthening environmental stewardship.

• Transition DOE supported innovative technologies and practices into U.S. manufacturing capabilities.

• Strengthen and advance the U.S. manufacturing workforce.

Multi-Year Program Plan

• Describes the Office mission, vision, and goals

• Identifies the technology, outreach, and crosscutting activities the Office plans to focus on over the next five years.

https://energy.gov/eere/amo/advanced-manufacturing-office

Public feedback and comments can be sent to AMO_MYPPIInfo@ee.doe.gov
AMO Multi-Year Program Plan (MYPP) Framework

Advanced Manufacturing Technology Areas:
- Sustainable Manufacturing – Flow of Materials through Industry
- Combined Heat and Power Systems
- Waste Heat Recovery Systems
- Advanced Sensors, Controls, Platforms and Modeling for Manufacturing
- Process Heating
- Process Intensification
- Roll-to-Roll Processing
- 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

Emerging and Crosscutting Areas:
- Clean Water
- Energy-Efficient Advanced Computing
- Motor-Driven Systems
- Technology Partnerships
- Workforce Development
- Communications and Outreach

Advanced Manufacturing for Energy Systems:
- Electric Power Delivery
- Electric Power Generation
- Fuels Production
- Buildings
- Transportation
Sustainable Manufacturing TA describes systems framework, methodologies, tools used elsewhere....

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

- Energy reductions
- Emissions reductions
- Use and re-use energy/emissions reductions
- Increased value-added
- Improved quality / Improved service
Potential use intensity improvements from additive – in aerospace

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>New Aircraft</th>
<th>New Parts</th>
<th>Accelerated Replacement</th>
</tr>
</thead>
<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>

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


Note: 1 quad = 1,000 TBtu
NEMS is a simulation model of the U.S. energy system organized by energy producing, consuming, and conversion sectors.

- The Industrial Demand Module (IDM) estimates energy consumption by energy source (fuels and feedstocks) for 15 manufacturing and 6 non-manufacturing industries.
- Process energy is modeled in two different ways, either with technologies by process flow or by end uses using efficiency (TPC) curves.
Use Intensity Improvements

**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.

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

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

**Use Intensity** e.g.:
- Circular economy
- Design for Re-X (recycling, reuse and remanufacturing)
- Material efficiency and substitution

**Aluminum Materials Flows** – U.S. and Canada, 2009 Billions of Pounds
Energy savings for carbon fibers could be realized through, for example, lower-energy-intensity precursor materials

Energy intensity comparison* for carbon fibers produced from PAN, polyolefin, and lignin precursors

(Onsite manufacturing energy; feedstocks excluded)

PAN

Polymerization 316,080 Btu/lb

Oxidation/Carbonization

Spinning

Finishing

Polyolefin

Polymerization 72,270 Btu/lb

Oxidation/Carbonization

Spinning

Finishing

Lignin

Polymerization 102,910 Btu/lb

Oxidation/Carbonization

Spinning

Finishing

Carbon fiber production from novel precursors (including materials that may not be in use as precursors today) represents a key technology development opportunity for R&D.

* Energy data provided by Sujit Das, Oak Ridge National Laboratory

Results presented are draft data; studies are currently being peer reviewed.
The **Current Opportunity** and **R&D Opportunity** for energy savings were both sizable for carbon fiber composites.

### Current Opportunity

Energy savings if the best technologies and practices available were used to upgrade production.

### R&D Opportunity

Additional energy savings if applied R&D technologies under development worldwide were successfully deployed.

**SOA Technology Examples:**
- motor re-sizing and/or variable speed drives
- waste heat recovery
- moderate carbon fiber recycling or down-cycling

**R&D Technology Examples:**
- alternative precursor processes
- selective heating for carbon fiber conversion
- recovery/recycling of the polymer matrix
- advanced carbon fiber recycling enabling increased recovery

Results presented are draft data; studies are currently being peer reviewed.
### Integrating analyses leverage tools and analytical capabilities at the National Laboratories, through the DOE AMO Strategic Analysis Team

<table>
<thead>
<tr>
<th>National Renewable Energy Laboratory</th>
<th>Lawrence Berkeley National Laboratory</th>
<th>Oak Ridge National Laboratory</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Materials Flow through Industry (MFI) Tool</strong>: a tool for analytically tracking the energy and GHG impacts of shifts in material flows, and to quantify supply chain impacts of current and next-generation technologies.</td>
<td><em><em>LIGHTEn-UP</em> Tool</em>*: a scenario framework for assessing prospective net energy and GHG impacts of a technology/product, accounting for both manufacturing and end-use life cycle phases.</td>
<td><strong>Additive Manufacturing Life Cycle Energy Tool</strong>: a user-friendly tool that manufacturers can use to evaluate additive vs. conventional manufacturing processes on a life cycle energy basis.</td>
</tr>
</tbody>
</table>

* LIGHTEn-UP: Lifecycle GH gas, Technology, and Energy through the Use Phase*
Material Flows Through Industry (MFI)

Linear network model of U.S. industrial and manufacturing sectors

Based on a database of 1,365 recipes

Mass/energy balance for each material → Input-output model of a manufacturing process

Database contains:

639 products with recipes
670 products without recipes

Additional products and recipes are added as data gaps are identified

Network diagram of the MFI database. A connection between nodes indicates that a product is used to produce another product.
## Defining Manufacturing Scenarios

### Product and Steps
- Choose end product(s)
- Choose number of supply chain steps
- Default is 10 steps, which captures about 95% of the total supply chain

### Technology Mix
- Specify the combinations of technologies used to produce a product
- Change for end products and for products upstream in the supply chain

### Material Substitution
- Replace existing materials or chemicals with next-generation alternatives
- Make the substitution in product demand or upstream in the supply chain

### Sector Efficiency Potential
- Improve energy efficiency by replacing existing process equipment with best available
- Implement at the recipe, sector or economy scale

### Manufacturing Scenario Parameters

<table>
<thead>
<tr>
<th>Product and Steps</th>
<th>Technology Mix</th>
</tr>
</thead>
<tbody>
<tr>
<td>Choose end product(s)</td>
<td>Specify the combinations of technologies used to produce a product</td>
</tr>
<tr>
<td>Choose number of supply chain steps</td>
<td>Change for end products and for products upstream in the supply chain</td>
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<td>Make the substitution in product demand or upstream in the supply chain</td>
<td>Implement at the recipe, sector or economy scale</td>
</tr>
</tbody>
</table>
Material Flows Through Industry (MFI)

Define Manufacturing Scenario

- Product and Steps
- Technology Mix
- Material Substitution
- Sector Efficiency Potential

Run MFI Model

- Fossil fuel consumption
- GHG emissions
- Material inventories
- Water use

Interpret Outputs

- Track consumption throughout the supply chain
- Quantify “What”, “Where” and “How Much”
- Identify hot spot processes and important inputs
Caveats and MFI Limitations

MFI system boundary is cradle-to-gate

• Results represent commodity production only
• Use phase, end-of-life is not captured

Some potentially significant effects are not captured

• Vehicle lightweighting leads to reduced fuel use, emissions
• Advanced smelting technologies are more difficult, less safe to operate
• Increased recycling decreases landfilling, bauxite imports

......So, how do we look at broader life cycle impacts.....?
Cross-sectoral Impacts Assessment Tool – Lifecycle GHgas, Technology and Energy through the Use Phase (LIGHTEn-Up)

### Examples of Sectors and Complexity

<table>
<thead>
<tr>
<th>Increasing Complexity</th>
<th>Example</th>
<th>Industrial</th>
<th>Residential</th>
<th>Commercial</th>
<th>Transportation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Combustion Air Preheating In Steel Hot Rolling</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>Light-Weighting Airplanes with “Additive Manufacturing” Parts</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>LED lighting in Buildings</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>Wide-Band Gap Materials</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Objectives:

- A substantive, transparent, and intuitive scenario framework
- Prospective net energy and GHG impacts of technologies utilized in both manufacturing and end-use-phases across the U.S. economy

About the Data:

- Benchmarked to publically available DOE datasets
- Annual Energy Outlook – U.S. economy-wide energy consumption forecast out to 2040
- Includes EIA’s Manufacturing Energy Consumption Survey (MECS) 2010 detailed energy consumption by end-uses

For examples of LIGHTEn-UP analysis output, see the Composites and Sustainable Manufacturing Technology Assessments, available at: http://energy.gov/quadrennial-technology-review-2015-omnibus#chap6ta
Publically Available U.S. Energy Consumption Data

<table>
<thead>
<tr>
<th>Year</th>
<th>Data Source Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>12 AEO† Tables covering 3 Building Types, 6 Energy Sources x 14 End-Use Types</td>
</tr>
<tr>
<td>2015</td>
<td>2 AEO† Tables covering 11 Building Types, 5 Energy Sources x 10 End-Use Types</td>
</tr>
<tr>
<td>2020</td>
<td>20 AEO† Tables covering 17 Modes x 13 Energy Sources</td>
</tr>
<tr>
<td>2025</td>
<td>12 AEO† Tables</td>
</tr>
<tr>
<td>2030</td>
<td>83 MECS†† Manufacturing Classifications, 6 Energy Sources x 22 End-Use Types</td>
</tr>
<tr>
<td>2035</td>
<td></td>
</tr>
<tr>
<td>2040</td>
<td></td>
</tr>
<tr>
<td>2045</td>
<td></td>
</tr>
<tr>
<td>2050</td>
<td></td>
</tr>
</tbody>
</table>

**About the Data**

† Annual Energy Outlook (AEO) Tables – U.S. economy-wide energy consumption forecast to 2040

†† Manufacturing Energy Consumption Survey (MECS) 2010 – Detailed energy consumption by end-uses
## LIGHTEn-UP Tool User Interface
### Where? What? When?

<table>
<thead>
<tr>
<th>What Sector &amp; End-Use?</th>
<th>What Impact at End Year</th>
<th>When?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Industrial Commercial</td>
<td>Technical Adoption Potential %</td>
<td>Start Year</td>
</tr>
<tr>
<td>Residential Transportation</td>
<td>Relative Energy Savings %</td>
<td>End Year</td>
</tr>
</tbody>
</table>

### Equations:
1) \( E_{t=Y_2} = E_{t=0} \times GR \)
2) \( E_{(TP)}_{t=Y_2} = E_{t=Y_2} \times \% \, (TP) \)
3) \( E_{(RS)}_{t=Y_2} = E_{(TP)} \times \% \, (RS) \)

Energy Impact = green area
LIGHTEn-UP Analysis - Net Energy Impact with utilization of recycled Carbon Fiber Reinforced Plastic Composites (CFRP) in vehicles
LIGHTEn-UP Analysis - Net Energy Impact with utilization of recycled Carbon Fiber Reinforced Plastic Composites (CFRP) in vehicles

- High embodied energy CFRP from Composites TA
- Low embodied energy CFRP from Composites TA
- Total (Net) Energy
LIGHTEn-UP Analysis - Net Energy Impact with utilization of recycled Carbon Fiber Reinforced Plastic Composites (CFRP) in vehicles

High embodied energy CFRP from Composites TA

Recycling RD&D opportunity timeline

Will Recycling Be Possible?

Low embodied energy CFRP from Composites TA

Total (Net) Energy
For net energy benefits from CFRP lightweighting, fuel savings must fully offset the increased manufacturing energy

- Policymakers and automotive manufacturers are looking to lightweight materials such as CFRP* composites, and viable manufacturing processes, to reduce vehicle mass and meet fuel economy standards.

- However, it may take many years of vehicle use for accumulated fuel savings to fully offset the manufacturing energy for these materials.

- Example at right shows a payback period of 20 years from initial adoption of a CFRP component in the vehicle fleet.

- In some cases, energy payback may never be reached at all! Important opportunity to reduce the life cycle energy impacts by improving the manufacturing operations, and developing a circular economy for CRFPs.

* CFRP = Carbon Fiber Reinforced Polymer
Energy Productivity Drivers

a. **Less Energy to Produce** – Decrease energy intensity (i.e. energy/mass) of existing commodities/materials by developing new pathways towards practically achievable minimum energy requirements.

b. **Improved Service** – Increase life cycle performance of materials and manufactured products (i.e. service/mass) via approaches such as hyper-utilizing existing commodities and materials that result in significantly greater service for the amount of material used.

c. **Higher Value Products** - Increase the value-add of manufactured products (i.e. value-add/service) by developing new, high-value commodities and materials substitutes that can be manufactured at scale with energy and emissions that are lower than the practical limits of existing commodities and materials.

d. **Transformational Productivity** – Grow a hyper-efficient advanced manufacturing sector
   • with a particular focus on new greenfield development of low energy, low-carbon high value-add materials and products;
   • target those technologies and processes that can exceed current practical limits of energy and carbon productivity; and
   • anticipate and develop technologies that optimize life cycle resource efficiency to prevent the possible future rebound of energy & carbon intensive production.