Panel on Advanced Manufacturing Technology Analysis:
Session 1- Impacts at the Unit Operations & Plant/Facility Levels
Session 2 - Analysis Methodology & Tools

AMO Peer Review Meeting
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Advanced Manufacturing - Impacts at the Unit Operations & Plant/Facility Levels

- PH accounts for about 70% of all process energy\(^1\)
- Overall, process heating systems lose more than 2,500 TBtu annually of on-site energy\(^2\)

- A significant amount of WH is not currently recovered across all temperature ranges
- An expanded need for R&D in two temperature ranges: ultra-low (<250°F) and ultra-high (>1,600°F).

- Rapid developments in recent years and expanded to a broader range of industry applications
- Is the use of AM more sustainable than CM for manufacturing certain consumer parts?

Industrial Process Heating - Goal

- Characterize the potential to reduce energy intensity for thermal processing of materials in manufacturing operations. If able to attain practical minimum through proper design and operation of PH equipment, can 50% improvement be attained?
- What is the opportunity for advanced PH unit operations to provide improved properties, quality, and/or product value at cost parity to conventional techniques?
Example Process Heating Research Questions

- How to better assess the improvement potential of the installed process heating system base, source of energy (i.e. electrical vs. fuel fired), operations (batch vs. continuous) or geographical locations?

- What is the impact (energy, emissions, productivity, quality, etc.) of Smart & Digital Manufacturing Technologies in process heating applications?

- What is the potential of electrotechnologies or hybrid technologies (fuel + electricity) to optimize production value? New vs. conversion? Cost?

- What is needed to scale up alternative heating methods for large scale industrial applications?

- How much can enabling technologies (heat transfer, materials of construction, combustion equipment, material handling systems, sensors, instrumentation and controls etc.) improve thermal efficiency?

- What are the emerging technologies to extend equipment service life while maintaining their functional integrity?

- What are the opportunities for high temperature waste exhaust gas filtering? - (particles, corrosive gases, condensable material vapors, etc.) to enable WHR using presently available systems.
Optimized Process Heating System Options

What is the potential of electrotechnologies or hybrid technologies to optimize production value? New vs. conversion? Cost?
Electrotechnologies Opportunities

Example: Iron and Steel Industry

Iron and steel industry
Process Heating Application Areas

1. Coke making
2. Iron making
3. Steel making - BOF process
4. EAF steel production
5. Ladle and tundish heating
6. Steel reheating furnace
7. Annealing furnaces
8. Coating (galvanizing etc.) process
9. Heat treating (other)

1. Fluid heating
2. Steam generation
3. Metal heating
4. Metal melting
5. Metal heat treating
6. Smelting, agglomeration etc.
7. Non-metal heating, heat treating
8. Non-metal melting
9. Calcining
10. Drying
11. Curing and thermal forming
12. Thermal reactors
13. Other heating

Note: Applicable thermal processes

Possible Applicable Electrotechnologies

- Resistance heating
- Microwave
- Induction heating
- Resistance heating
- Induction heating
- Electric arc
- Plasma
- Induction
- Electric arc ??
- Plasma ??
- Resistance ??
- Infrared
- UV
- EB
- Resistance
- Resistance heating
- Microwave
- RF ??

Development of a calculator to compare total heating cost between fuel fired and electric heating systems
Industrial Waste Heat Recovery - Goal

Can an overall reduction of waste heat discharged from heating be minimized to 25% of the current value of waste heat via?

- Reducing production or emission of waste heat from heating systems,
- Recycling the waste heat within the system itself, and
- Recovery of the waste heat.

1. Reduction
   - Reduce infiltration/exfiltration of ambient air
   - Effective insulation of walls
   - Appropriate air-to-fuel ratio
   - Reduce fixture/cooling/heat storage losses

2. Recycling (within the same heating system)
   - Combustion air preheating
   - Load-charge preheating
   - Internal heat recycling - cascading

3a. Recovery (for other systems within the same plant)
   - Steam generation
   - Cascading to lower temp. heating operations
   - Space heating
   - Reaction heat for endothermic process

3b. Waste Heat to Power
   - Conventional steam generation (Rankine Cycle)
   - Organic Rankine Cycle (ORC)
   - Kalina Cycles
   - Superheat Cycles
Example WHR Research Questions

- What’s the potential for industrial WHR in the U.S. (specifically in the high and low temperature regimes)? What methods we could use to estimate the potential? What data already available? What’s the economically feasible potential?

- What are the advanced and emerging technologies available to recover high and low temperature waste heat? What are the R&D needs? What material issues? Design Issues?

- Are there high efficiency (>20%) WHP conversion systems (such as Steam Rankine Cycle) in high temperature (>1400°F) applications for low mass flow waste heat streams from relatively small fired systems (firing rate <5 to 10 MM Btu/hr.)?

- What are the innovative technologies for relatively high efficiency (>15%) WHR or WHP systems that can be used for variable mass flow and variable temperature waste heat sources?

- What are the advanced and emerging technologies available to extend equipment service life while maintaining their functional integrity?
## Waste Heat Recovery Opportunity in Different Temp. Regimes

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</tr>
</thead>
<tbody>
<tr>
<td>1) The Exhaust Gases or Vapors</td>
<td>Low to Ultra-high</td>
<td>High to Ultra-high</td>
<td>High to Ultra-high</td>
<td>Low to Medium</td>
<td>Low to high</td>
<td>Low to high</td>
<td>Low to high</td>
<td>Low to medium</td>
<td>High to ultra-high</td>
<td>Low to medium</td>
<td>Low to medium</td>
<td>Low to medium</td>
</tr>
<tr>
<td>3) Hot Products</td>
<td>High to Ultra-high</td>
<td>Low to Medium</td>
<td>High to Ultra-high</td>
<td>Ultra-low to Low</td>
<td>Ultra-low to Medium</td>
<td>Ultra-low to Medium</td>
<td>Ultra-low to Medium</td>
<td>High to Ultra-high</td>
<td>Low to Medium</td>
<td>Low to Medium</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4) High Temperature Surfaces</td>
<td>Ultra-low to Low</td>
<td>Ultra-low to Low</td>
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**Temperature Code:**
- Ultra high >1600°F, High – 1200 to 1600°F, Medium – 450 to 1200°F, Low – 250 to 450°F, Ultra-low <250°F.

- **High & ultra-high temperature & harsh environment** → greater than 400 TBTU/year\(^1\)
- **Low/Ultra-low temperature waste heat** → between 1,084 to 1,637 TBtu/year\(^2\)
- **The largest source of waste heat** for most manufacturing industries is exhaust / flue gases or heated air from heating systems.
- **This table does not give additional details on composition or other characteristics of the waste stream.**

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\(^1\) ORNL/TM-2014/622, January 2014.
\(^2\) Technology Assessment on Low-Temperature Waste Heat Recovery in Industry, Arvind Thekdi, Sachin Nimballkar, ORNL/TM-2016/xxx
# Practices Used by Industry for Managing or Dealing with Exhaust Gases Classified as Harsh Environments:

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Practice</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>No heat recovery but treating exhaust gases (scrubbing, cooling by blending with cold air or mist cooling) to meet regulatory requirements</td>
<td>EAF and BOF exhaust gases</td>
</tr>
<tr>
<td>2</td>
<td>Partial WHR due to materials limitations, design issues and space considerations</td>
<td>Regenerators used on glass melting furnaces</td>
</tr>
<tr>
<td>3</td>
<td>Partial heat recovery due to other limitations such as safety, maintenance, lifetime</td>
<td>Scrap preheaters for EAFs HRSGs on BOF installations</td>
</tr>
<tr>
<td>4</td>
<td>Partial or no heat recovery due to high capital cost, limited operating hours, or other operating and economic reasons</td>
<td>Small glass, aluminum melting furnaces, cement and lime kilns</td>
</tr>
<tr>
<td>5</td>
<td>Loss of sensible heat and certain condensable organic materials during treatment of exhaust gases, and use of chemical heat after drying the gases as fuels</td>
<td>Blast furnaces and coke ovens</td>
</tr>
</tbody>
</table>
Agglomerated Cost-size Data for Different Types of WHP Systems -
- At present, ORC offers both the widest range of electricity outputs and lowest established cost.
- Maximum electrical output has at least as large an effect on the normalized price ($/kW) as does the type of system.
- The hollow triangle represents expected cost decrease of the PCM system in the near future.

Economic Landscape -
- Main factors of economic viability: initial payment, electricity cost, and O&M costs
- Given average US industrial electricity prices, $0.06-0.08/kWh, and typical system costs, further drop in payback period is needed for widespread industrial use
- Economic viability of WHP projects are also heavily dependent on local factor, such as electricity prices and governmental policies
Spark spread for selected regions of higher electricity costs

Component Cost Breakdown of an ORC Heat Recovery System

**Notes -**
- Electricity price varies significantly across the country.
- Recognition as a **renewable equivalent** energy source - recognition can provide companies incentives ranging from tax breaks to rebates.
- Potential savings from emissions cost.
- The single largest cost of these systems is the **electricity producing component, turbine or engine**, followed by heat exchanging devices, from heat exchangers to boilers and condensers.
Additive Manufacturing - Goal

- Provide a fundamental and comprehensive understanding of additive manufacturing’s current state, future trends, and potential implications relative to conventional manufacturing.

<table>
<thead>
<tr>
<th>AM Attributes compared to traditional manufacturing</th>
<th>Impact on product offerings</th>
<th>Impact on supply chains</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturing of complex-design products</td>
<td>🟢</td>
<td>🟢</td>
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<tr>
<td>New products that break existing design and manufacturing limitations</td>
<td>🟢</td>
<td>🟢</td>
</tr>
<tr>
<td>Customization to customer requirements</td>
<td>🟢</td>
<td>🟢</td>
</tr>
<tr>
<td>Ease and flexibility of design iteration</td>
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<td>🟢</td>
</tr>
<tr>
<td>Part simplification/sub-parts reduction</td>
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<td>🟢</td>
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<tr>
<td>Reduced time to market</td>
<td>🟢</td>
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<tr>
<td>Waste Minimization</td>
<td>🟢</td>
<td>🟢</td>
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<tr>
<td>Weight reduction</td>
<td>🟢</td>
<td>🟢</td>
</tr>
<tr>
<td>Production near/at point of use</td>
<td>🟢</td>
<td>🟢</td>
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<tr>
<td>On-demand manufacturing</td>
<td>🟢</td>
<td>🟢</td>
</tr>
</tbody>
</table>

Key: Very High 🟢 High 🟢 Medium 🟢 Low 🟢

Source – QTR 2015.
Additive manufacturing – Extensive state-of-the-art review

**Objective:** assess current performance and potential future trends of AM technologies from review of >400 machines and >600 materials

- Comparing properties of AM and conventionally manufactured parts, we find:
  - Metal AM parts – some evidence for higher strength
  - Polymeric AM parts – mostly similar properties
  - Composite AM parts – mostly lower strength and elasticity

- Other findings:
  - AM envelope volume trending higher
  - AM precision trending to smaller feature size
  - AM price per envelope volume trending down

Reported properties of AM parts overlaid on Ashby materials selection chart

Analysis Methodology & Tools Development – across the manufacturing systems levels

**Analysis Methodology & Tools Development**

**Strategic question:** How is energy being used and where are the energy savings opportunities within manufacturing, and across other energy supply and use sectors?

- **Additive Manufacturing LCA tool ORNL**
  - Energy impacts of conventional vs. AM technologies

- **Life cycle GH gas, Technology & Energy through the Use-Phase (LIGHTEn-UP) Tool LBNL**
  - Evaluate cross sectoral impacts of implementing next gen technologies

- **Market Penetration Tool ANL, LBNL**
  - Generate technology adoption projections for life cycle analysis.

- **Bandwidth Analysis NREL, Energetics**
  - Evaluate energy use and energy savings opportunities within industrial sectors

- **Materials Flow through Industry (MFI) Tool NREL**
  - Evaluate energy, carbon and resource impacts of the industrial supply chain
Prospective Life Cycle Sustainability Analysis

The strategic analysis team is developing tools to support **prospective life cycle sustainability analysis** of advanced manufacturing technologies

- **Prospective** = forecasts sustainability benefits from technology adoption into the future
- **Life cycle** = encompasses entire value chain from materials extraction and refining, to intermediate and end-use product manufacture, and through use, reuse, and recycling of materials and end-use products
- **Sustainability** = assesses energy use, emissions, materials flows, water use, and costs
### Energy Bandwidth Studies

#### Bandwidth Studies: Recently Completed and In-Progress

<table>
<thead>
<tr>
<th>2015 (published)</th>
<th>Manufacturing sector studies:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>• Chemicals</td>
</tr>
<tr>
<td></td>
<td>• Iron &amp; Steel</td>
</tr>
<tr>
<td></td>
<td>• Pulp &amp; Paper</td>
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<tr>
<td></td>
<td>• Petroleum Refining</td>
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<table>
<thead>
<tr>
<th>2016 (drafts)</th>
<th>Lightweight materials manufacturing studies:</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>• Aluminum</td>
</tr>
<tr>
<td></td>
<td>• Advanced High Strength Steel</td>
</tr>
<tr>
<td></td>
<td>• Titanium</td>
</tr>
<tr>
<td></td>
<td>• Magnesium</td>
</tr>
<tr>
<td></td>
<td>• Carbon Fiber Reinforced Polymer Composites</td>
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<tr>
<td></td>
<td>• Glass Fiber Reinforced Polymer Composites</td>
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#### Current Analysis

<table>
<thead>
<tr>
<th>Water/energy studies:</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Desalination</td>
</tr>
</tbody>
</table>

**Manufacturing sector studies:**

- Plastics & Rubber Products
- Cement
- Glass
- Food & Beverage

**Follow-on analysis:**

- Lightweight Materials Integrating Analysis

Collaborators: Energetics; NREL; LBNL

**Energy bandwidth studies** frame the range (or bandwidth) of potential energy savings in manufacturing, and technology opportunities to realize those savings.
Energy Bandwidth Example of Results – Iron & Steel
The energy bandwidth methodology is currently being extended to explore energy saving opportunities for lightweight materials manufacturing.

Lightweight Materials energy bandwidth analyses conducted in 2015-2016:
- Advanced High Strength Steel
- Titanium
- Aluminum
- Magnesium
- Carbon Fiber Composites
- Glass Fiber Composites

Phase II analysis underway in 2016 will enable comparisons across materials on a performance-adjusted basis.
Lifecycle GHgas, Technology and Energy through the Use Phase (LIGHTEn-Up) Tool & Analysis Framework

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
Materials Flows through Industry (MFI) Tool

Strategic need: ability to analytically track the energy and GHG impacts of the supply chain and evaluate changes from adopting next generation technologies. Be able to answer:

• Where are the supply chain hotspots for energy and emissions?
• What are the most significant material inputs?
• Which materials are most energy intensive?
• Which products or processes offer the greatest potential energy use reduction?
Evaluating next-generation materials

- Steel
- Aluminum, Hall-Heroult
- Aluminum, Carbothermic
- Aluminum, Clay Carbochlorination
- Carbon Fiber Reinforced Plastic
- Glass Fiber Reinforced Plastic

Greenhouse Gas Emissions (kg CO2-eq/kg steel eq.)

Energy Consumption (GJ/kg steel eq.)

Steel Baseline

Efficiency

- Baseline Efficiency
- Efficient Process
- Efficient Economy
Name: Acetylene Scenario
Product Category Type: Industrial Gases
Product: ACETYLENE
Demand: 1000
Include Byproduct: true
Include Interim Result: true

Electricity by Step (kWh)

Fuel Materials Used as Feedstocks

Feedstock Material

Primary

Avoided

Net

Fuel Use Type

Fuel Use Type

Fuel Use Type
Market Penetration Calculator

- Strategic need: systematic method for projecting future market penetration of manufacturing technologies for prospective life cycle analysis
- Calculator captures adoption dependencies on technology readiness and stock turnover

**Inputs**
- Demand or supply trajectories
- Adoption years
- Diffusion parameters
- Retirement rates
- Initial age distribution

**Scenario analysis** ➔ **Sensitivity analysis** ➔ **Calculation modules**

**Outputs (for each scenario)**
- Production breakdowns
- In use stock breakdowns
- End of life breakdowns

**Calculation modules**

**Production**
- From demand
- From supply

**Technology adoption**
- Linear
- Bass diffusion
- Production capacity

**Stock turnover**
- Constant retirement rates
- Age-dependent retirement rates

**Examples of outputs**
- Parts produced, scenario 1
- Parts in use, scenario 1
- Parts retired, scenario 1
Reduced Product Life Cycle Energy Consumption through Additive Manufacturing (The AM Energy Impacts Tool)

- The tool provides a **consistent methodology** to calculate life cycle energy impacts from AM vs. conventional manufacturing.

- **MFI and the LIGHTEnUP Tools** are a foundation for methodology used in the AM tool.

- The tool **defines and calculates the energy requirements at each step of the AM process** - drawing in part from the wide range of primary data available from subject matter experts.

- The tool and the user guide are currently published on America Makes member only webpage.
Example: Topologically Optimized Aerospace Bracket - EBM vs. Conventional Machining

<table>
<thead>
<tr>
<th>Life Cycle Phases</th>
<th>Unit</th>
<th>Conventional Manufacturing</th>
<th>Additive Manufacturing</th>
<th>Energy Savings per Part</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw Material Energy</td>
<td>Btu/part</td>
<td>2,021,120</td>
<td>263,900</td>
<td>1,757,221</td>
</tr>
<tr>
<td>Manufacturing Energy</td>
<td>Btu/part</td>
<td>65,485</td>
<td>65,872</td>
<td>(387)</td>
</tr>
<tr>
<td>Freight and Distribution Energy</td>
<td>Btu/part</td>
<td>40,462</td>
<td>14,161</td>
<td>26,301</td>
</tr>
<tr>
<td>Use Phase Energy</td>
<td>Btu/part</td>
<td>99,583,158</td>
<td>34,854,105</td>
<td>64,729,052</td>
</tr>
<tr>
<td>Disposal Energy Use</td>
<td>Btu/part</td>
<td>(433,775)</td>
<td>(151,821)</td>
<td>(281,954)</td>
</tr>
<tr>
<td>Total Energy Use per Part</td>
<td>Btu/part</td>
<td>101,276,449</td>
<td>35,046,216</td>
<td>66,230,233</td>
</tr>
</tbody>
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Red team reviews

Peer review of Strategic Analysis Team’s Tools:

• Material Flows through Industry (MFI)
• Lifecycle GHgas, Technology and Energy through the Use Phase (LIGHTEn-Up)
• Additive Manufacturing Tool

Review Format:

• Selection of reviewer based on their expertise
• Introductory webinar review of tools & User’s Guides
• Reviewer’s formal (written) comments incorporated into the tools and Reports
IMI Project evaluations

Evaluation of Innovative Manufacturing Initiative (IMI) projects

• 18 IMI projects ranging from materials (CFRP, GaN), to processes (chemicals, additive manufacturing), to smart technologies (milling machine optimization)

• Scenarios developed in the LIGHTEnUP tool - Energy impact forecasts out to 2050

• Scenarios based on: validity of IMI application statements, and Independent engineering principles.

• Magnitude of energy impacts range between manufacturing (smaller) & multisector (larger)

• IMI LIGHTEnUP compendium to be released in 2016