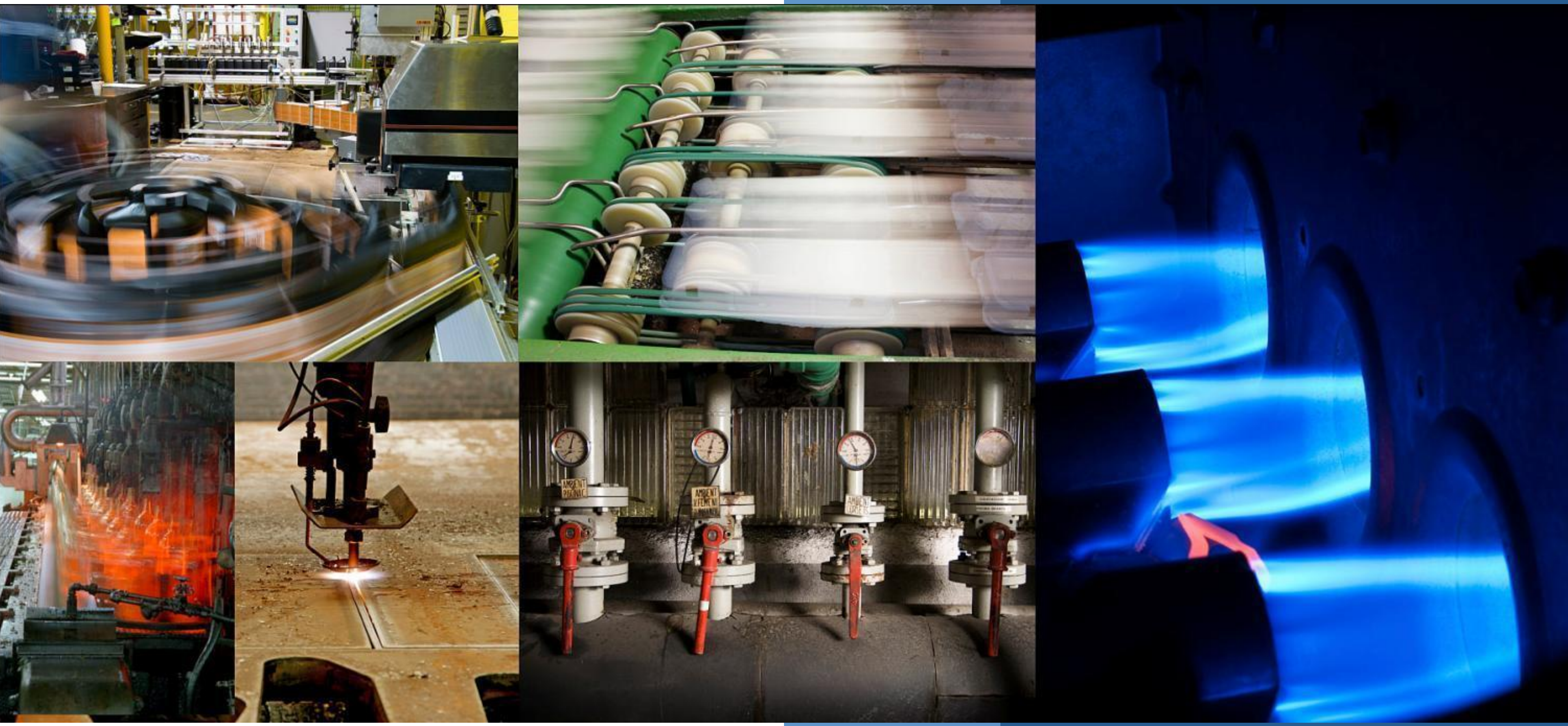
Office of Energy Efficiency & Renewable Energy
Advanced Manufacturing Office

U.S. DEPARTMENT OF ENERGY



Quadrennial Technology Review (QTR):

Technology Assessment - Sustainable Manufacturing/Flow of Materials Through Industry

Joe Cresko - joe.cresko@ee.doe.gov

Sustainable Manufacturing Workshop

Portland, OR
January 6, 2016

Quadrennial Technology Review-2015

http://www.energy.gov/quadrennial-technology-review-2015

QUADRENNIAL TECHNOLOGY REVIEW

AN ASSESSMENT OF ENERGY TECHNOLOGIES AND RESEARCH OPPORTUNITIES

Chapter 6: Innovating Clean Energy Technologies in Advanced Manufacturing
September 2015

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

- **<u>The Climate Action Plan</u>** (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

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

- **<u>Quadrennial Technology Review (QTR)</u>**: 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

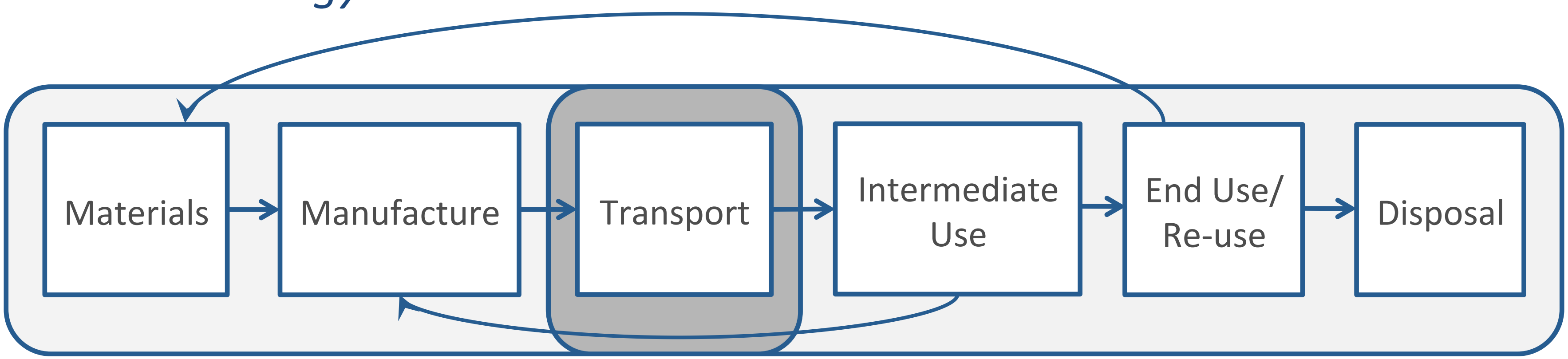
REPORT AND CHAPTERS	TECHNOLOGY ASSESSMENTS	SUPPLEMENTAL INFORMATION
[PDF] Quadrennial Technology Review 2015		
[PDF] Executive Summary		
[PDF] Chapter 1 — Energy Challenges		Supplemental Information
[PDF] Chapter 2 — Energy Sectors and Systems		
[PDF] Chapter 3 — Enabling Modernization of the Electric Power System	Technology Assessments	
[PDF] Chapter 4 — Advancing Clean Electric Power Technologies	Technology Assessments	
[PDF] Chapter 5 — Increasing Efficiency of Buildings Systems and Technologies		Supplemental Information
[PDF] Chapter 6 — Innovating Clean Energy Technologies in Advanced Manufacturing	Technology Assessments	Supplemental Information
[PDF] Chapter 7 — Advancing Systems and Technologies to Produce Cleaner Fuels	Technology Assessments	Supplemental Information
[PDF] Chapter 8 — Advancing Clean Transportation and Vehicle Systems and Technologies	Technology Assessments	
[PDF] Chapter 9 — Enabling Capabilities for Science and Energy		Supplemental Information
[PDF] Chapter 10 — Concepts in Integrated Analysis		Supplemental Information
[PDF] Chapter 11 — Summary and Conclusions		

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*



- Energy reductions
- Emissions reductions

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

Sustainable Manufacturing Technology Assessment

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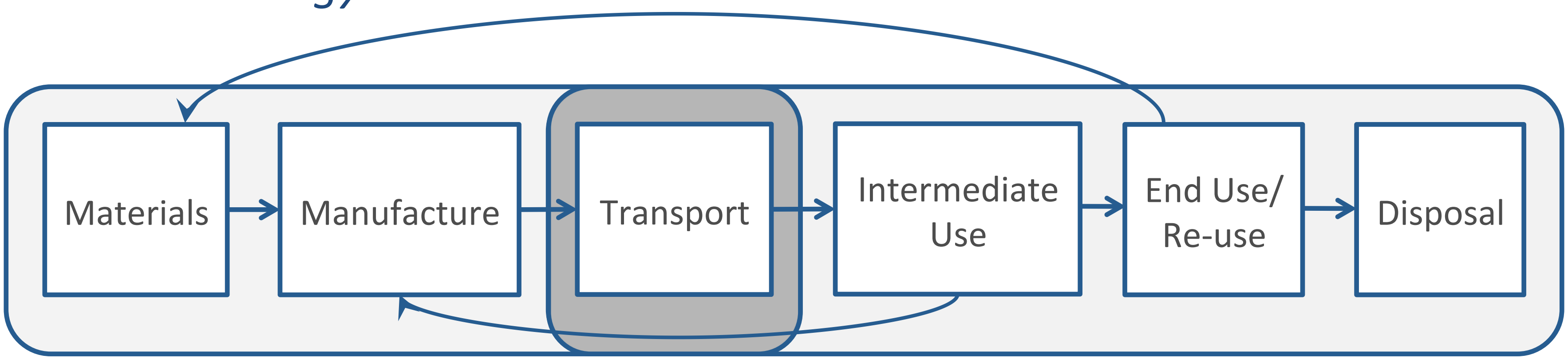


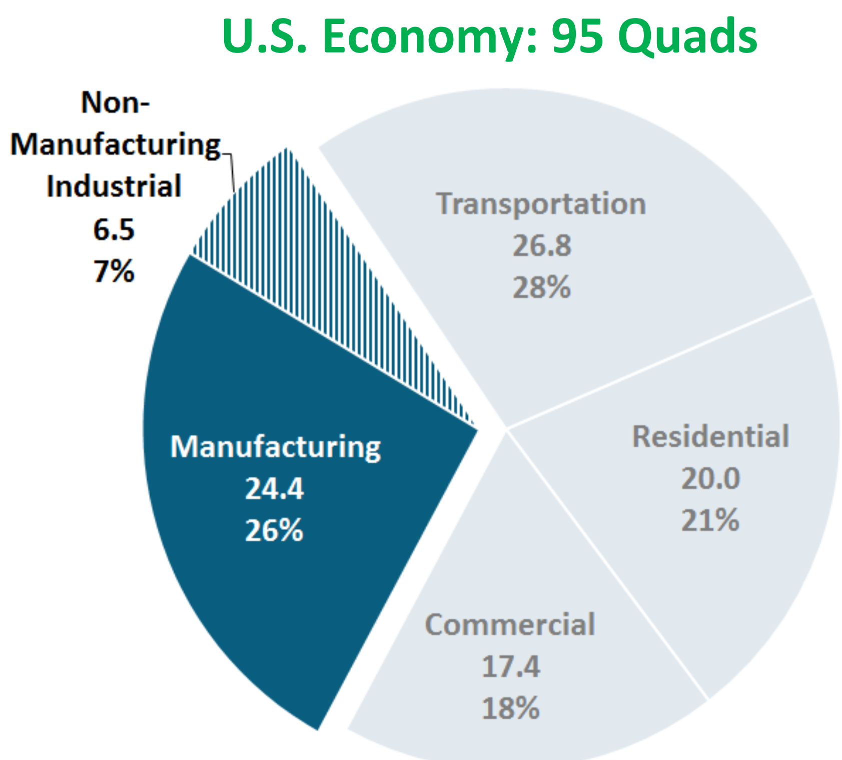
- Energy reductions
- Emissions reductions

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

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

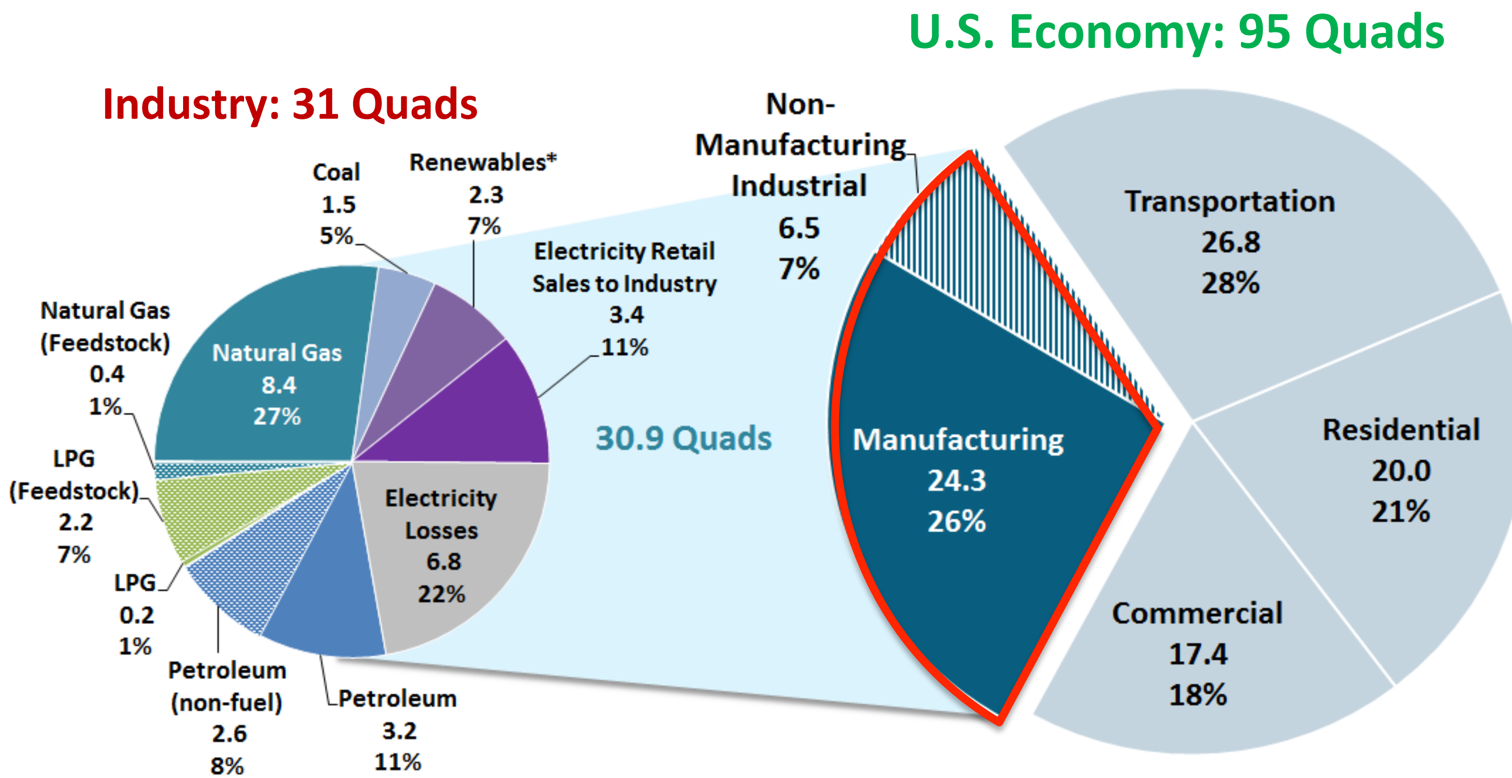


2012 Data

Source: EIA Monthly Energy Review, Aug 2014; AEO 2014

Industry and Manufacturing Energy Use

Fuel mix shows diverse nature of industry energy use



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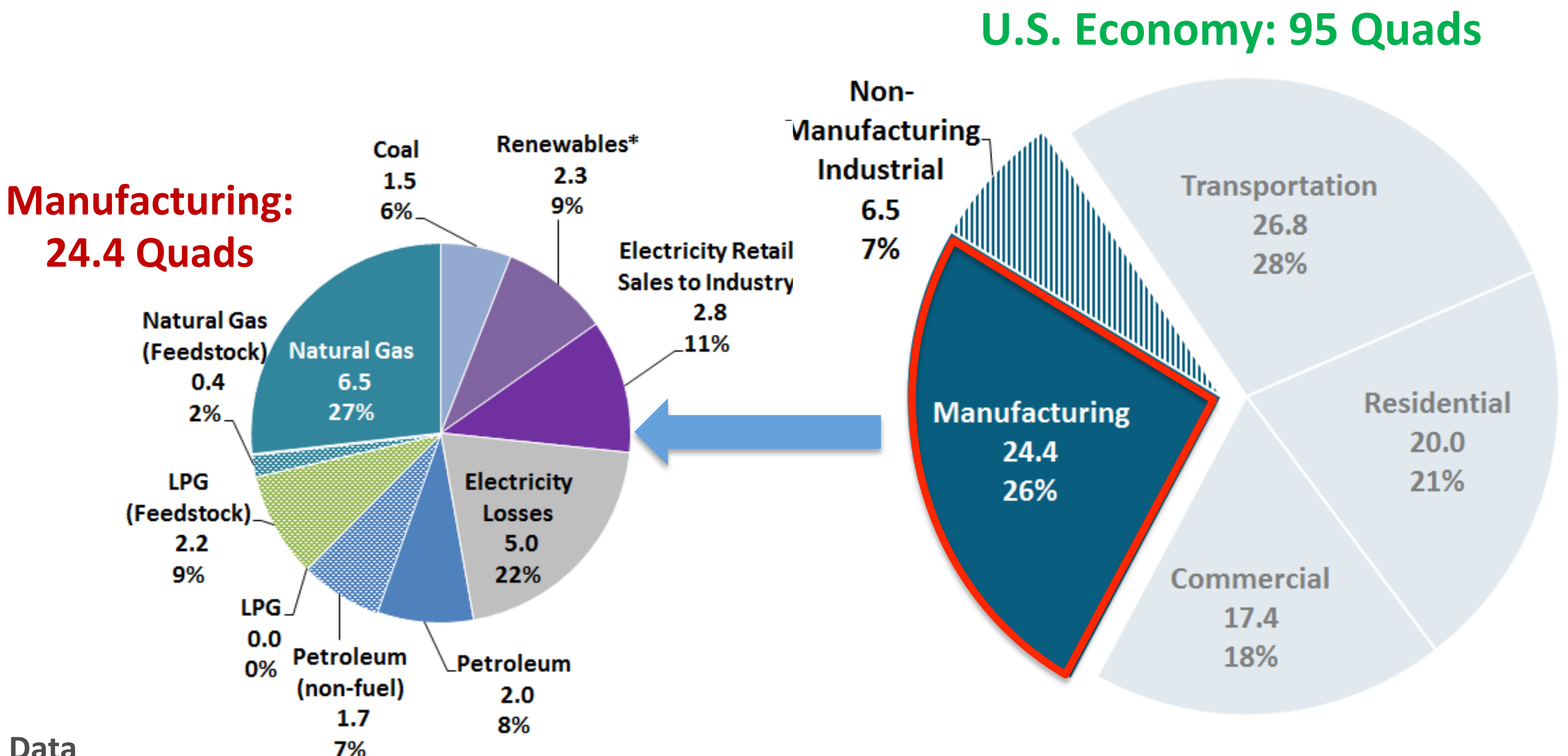
* Renewables consist primarily of biomass energy (2.2 Quads), with the remainder from onsite hydroelectric, geothermal, wind and solar energy.

Industry and Manufacturing Energy Use

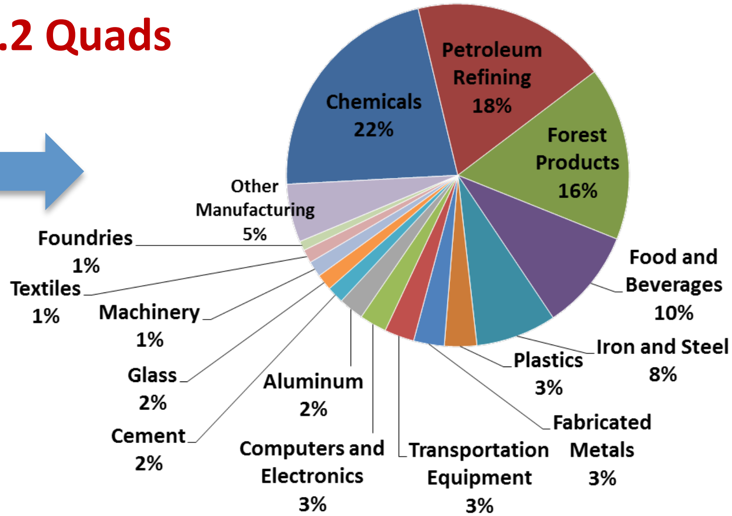


2012 Data

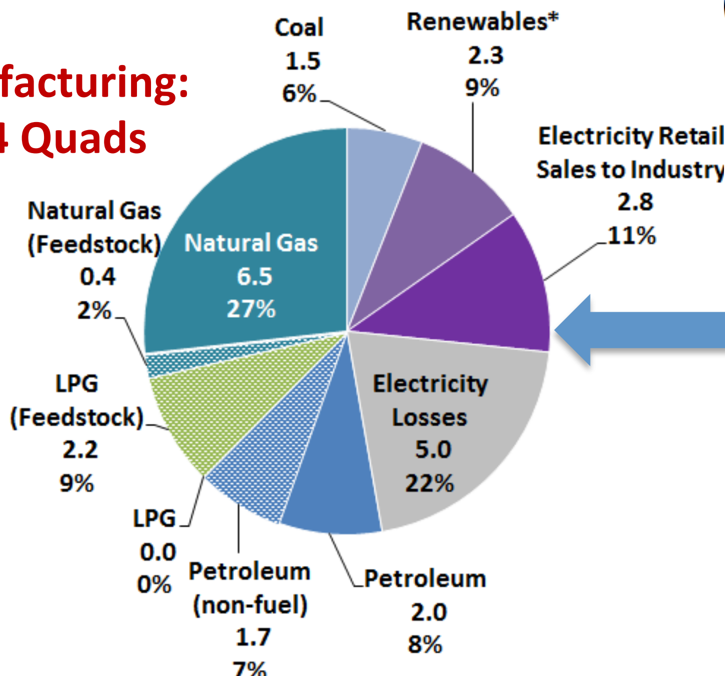
Source: EIA Monthly Energy Review, Aug 2014; AEO 2014

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

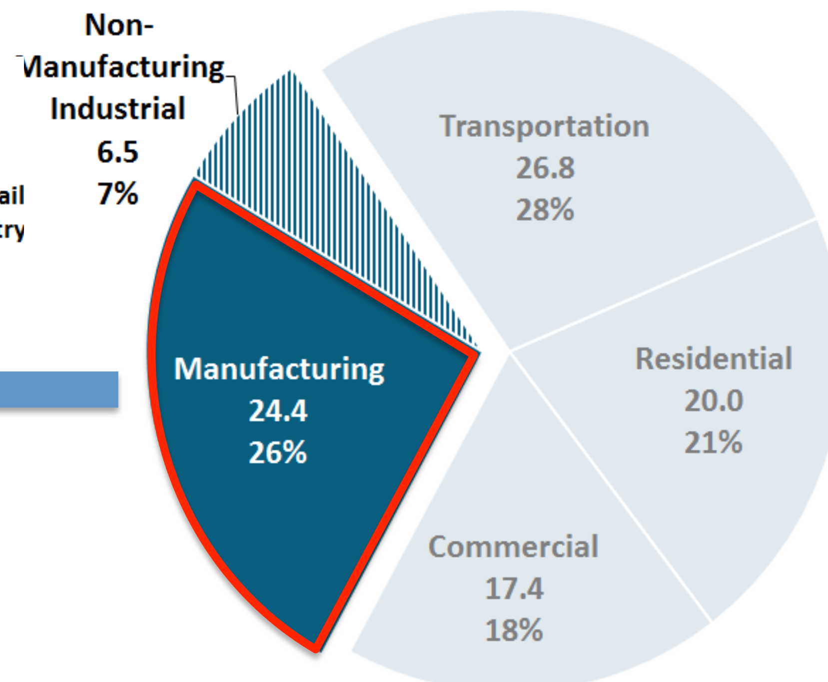
Minus feedstocks = 19.2 Quads



Manufacturing: 24.4 Quads



U.S. Economy: 95 Quads



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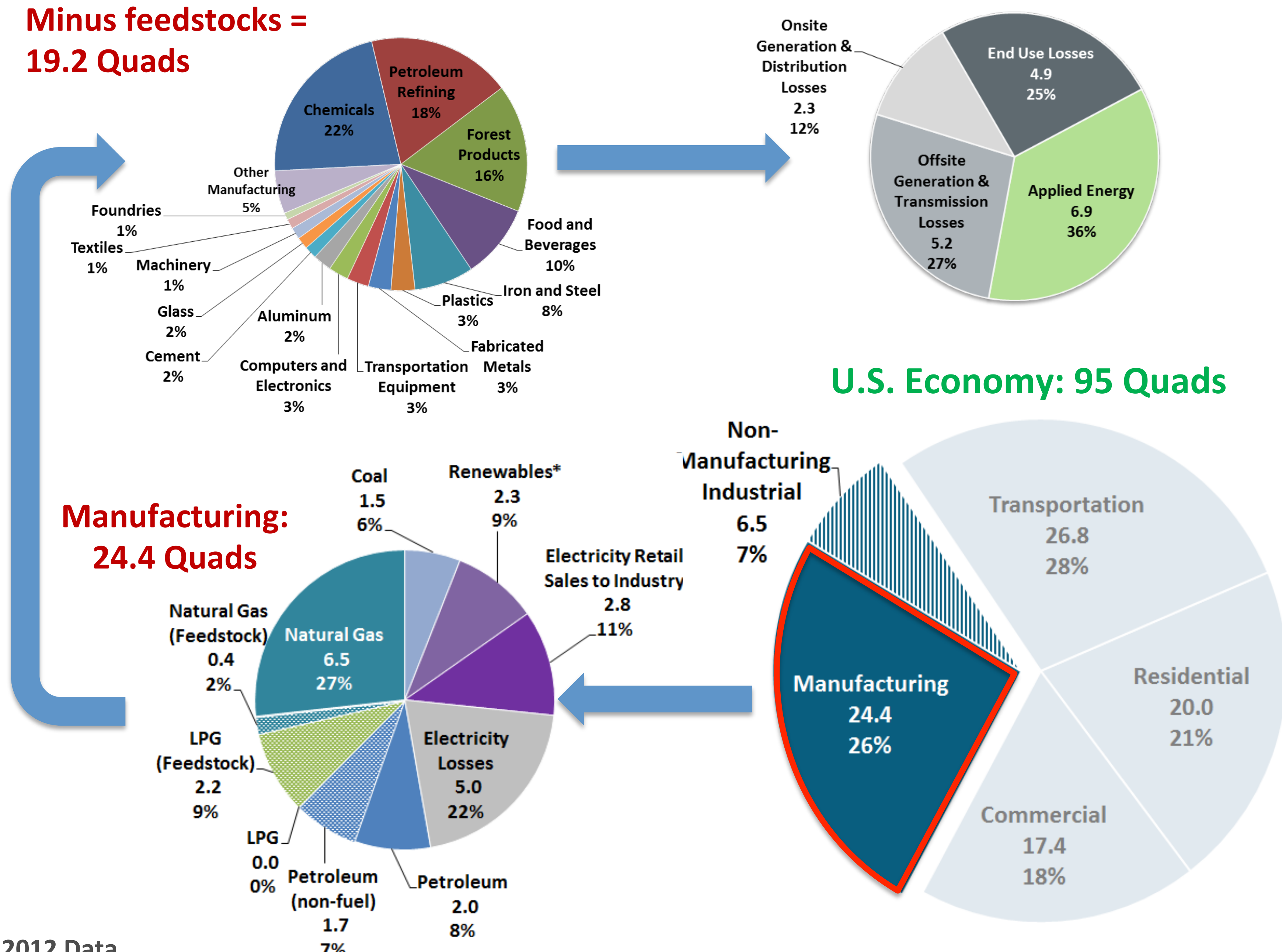

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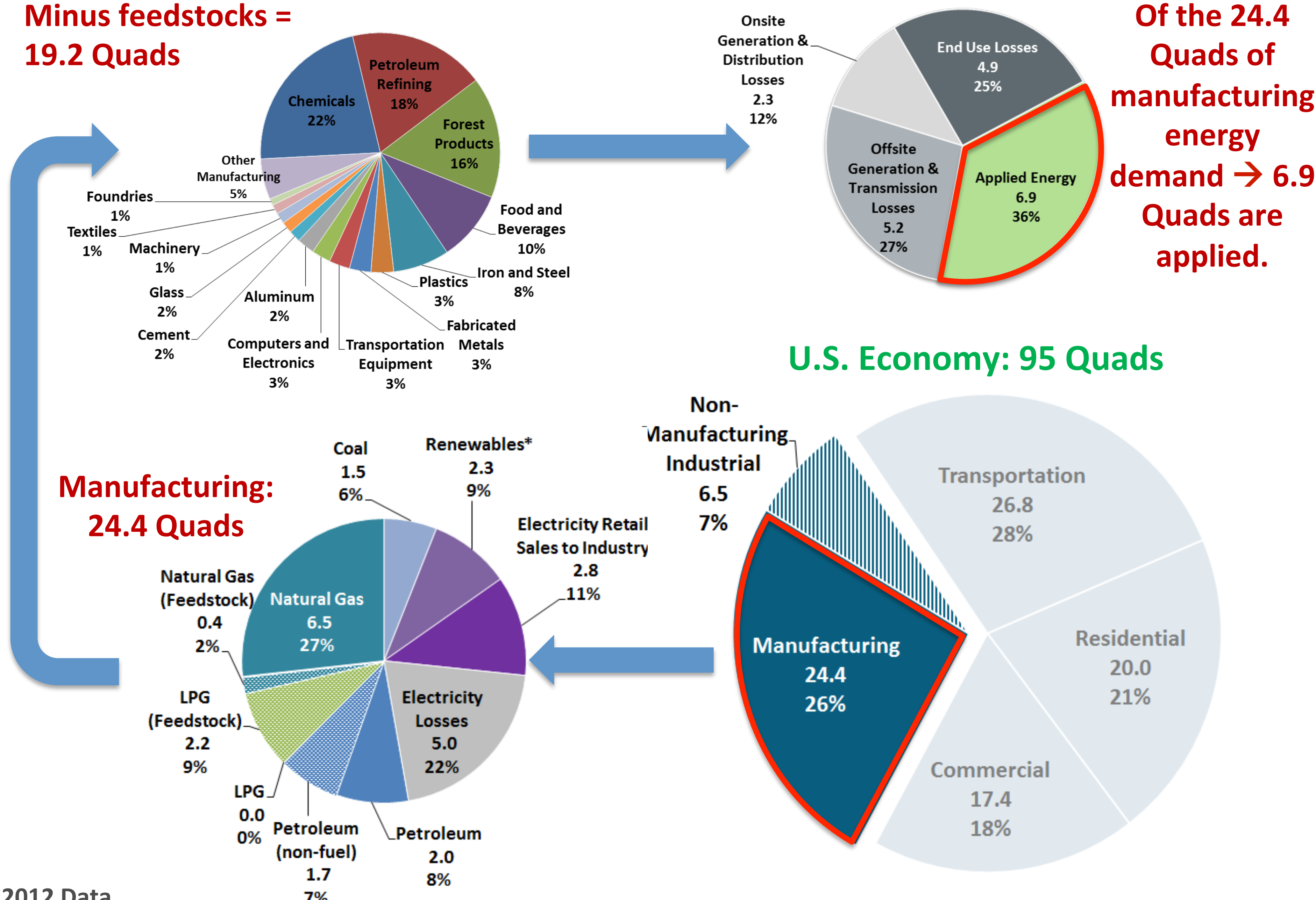

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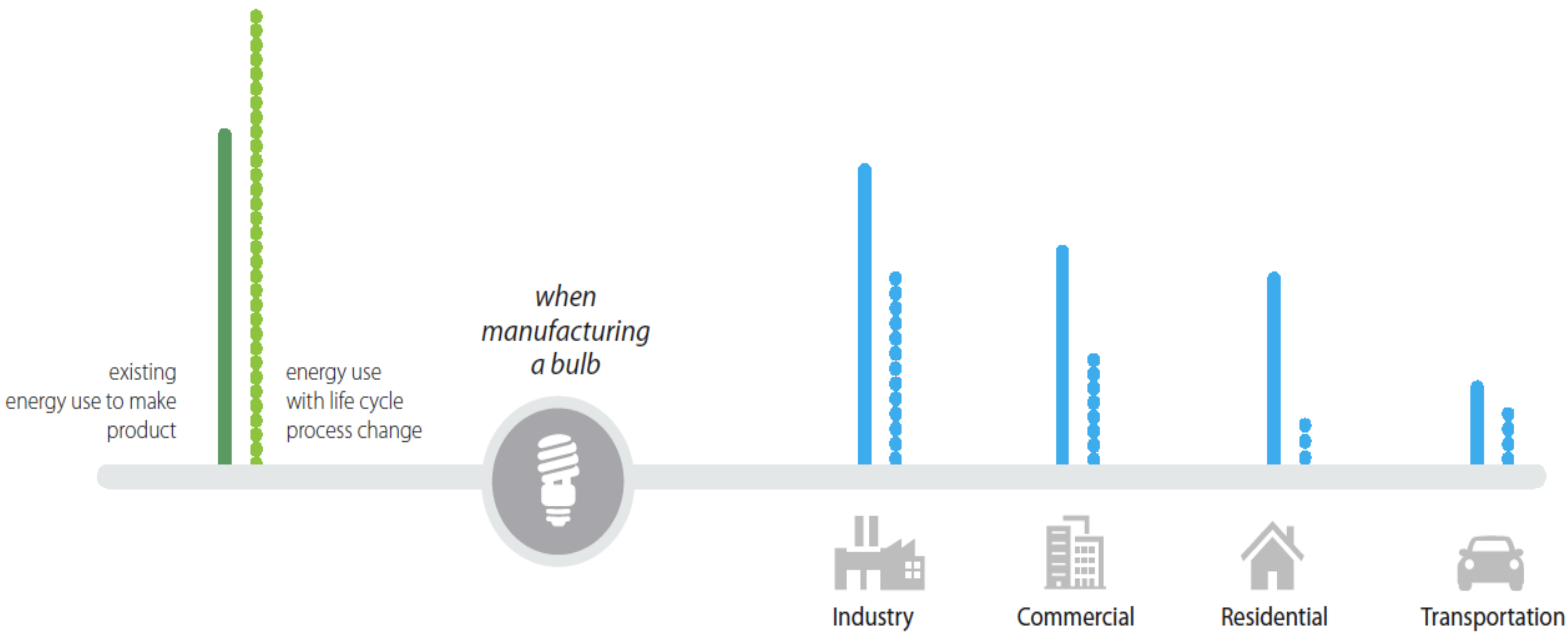
Systems approach to industrial & manufacturing analysis



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

Energy Production

Energy Delivery

U.S. Energy Economy
95 quads*

Transportation Sector 27 quads	Industrial Sector 31 quads
Residential Sector 20 quads	Commercial Sector 17 quads

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

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

Industrial Systems
31 quads

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

Production/Facility Systems

Equipment, process flow, and energy strategies that comprise a goods-producing facility

Petroleum Refinery ~26 TBtu

Facility Steam ~5 TBtu

Manufacturing Systems/ Unit Operations

Equipment used for manufacturing process and nonprocess unit operations

Atmospheric Distillation Unit ~4 TBtu

Hydro-cracker ~2 TBtu

Catalytic Reformer ~3 TBtu

Note: 1 quad = 1,000 TBtu

- *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*

*2012, EIA

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

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Process efficiency
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Waste heat recovery

Carbon Intensity, e.g.:
Process efficiency
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Process changes
Renewables

Use Intensity e.g.:
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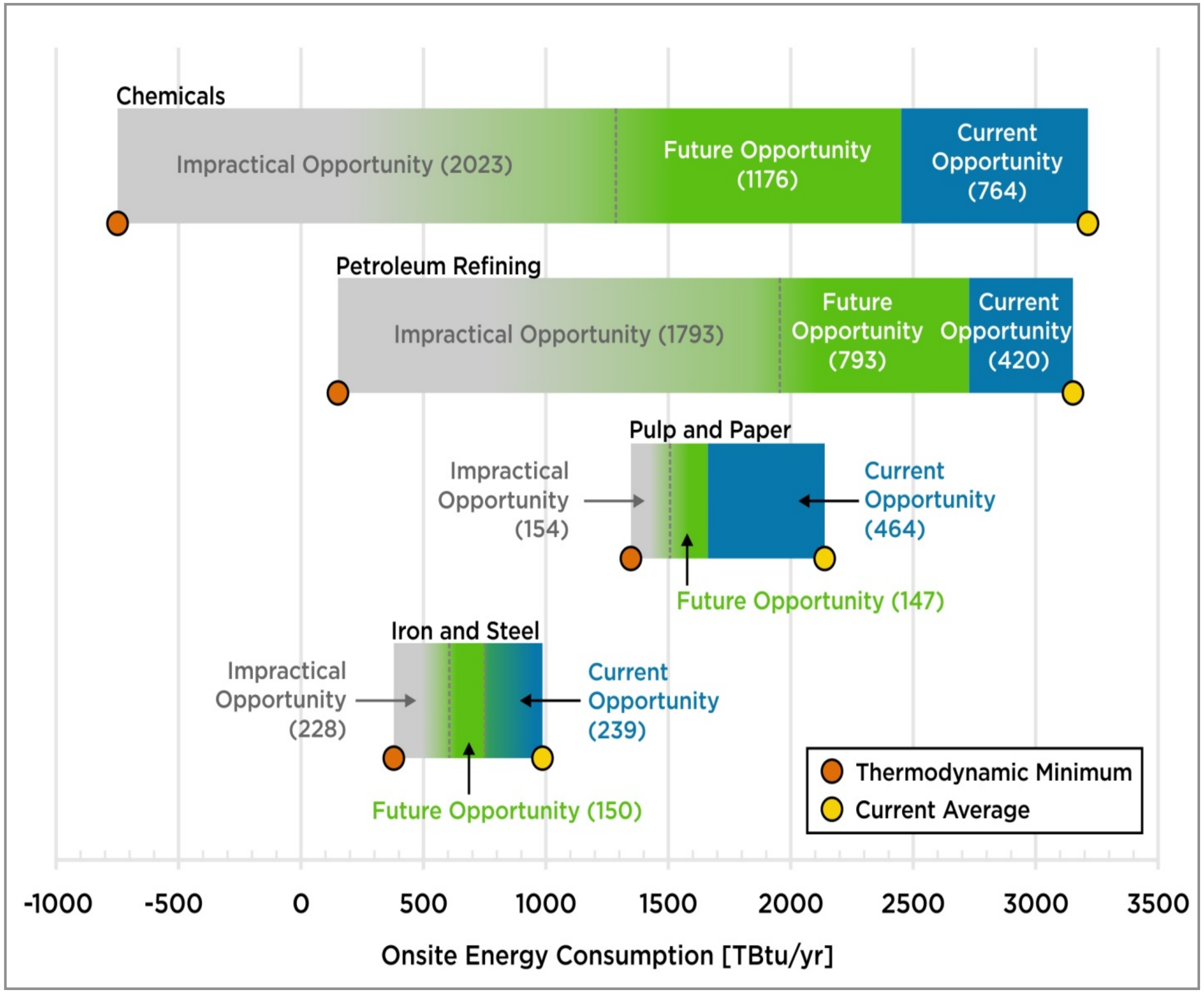
Technical Energy Savings Opportunities:



Source: DOE/AMO, Energy Bandwidth Studies (2015)
Note: 1 quad = 1000 TBtu

Carbon Intensity Improvements

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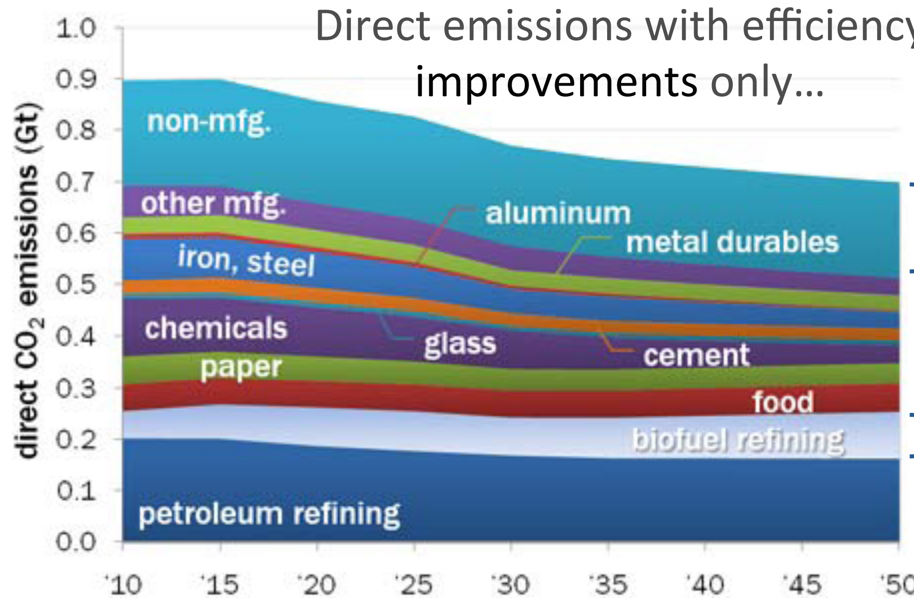
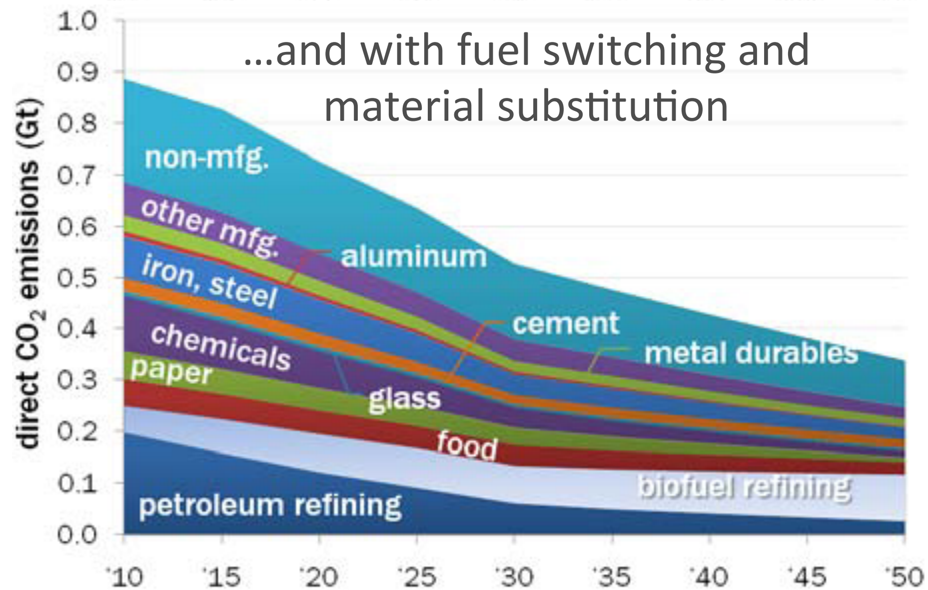


Agriculture, mining, construction: Opportunities for advanced engines, biofuels, etc.

Carbon capture and sequestration (CCS) technologies offer additional opportunities



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

Use Intensity Improvements

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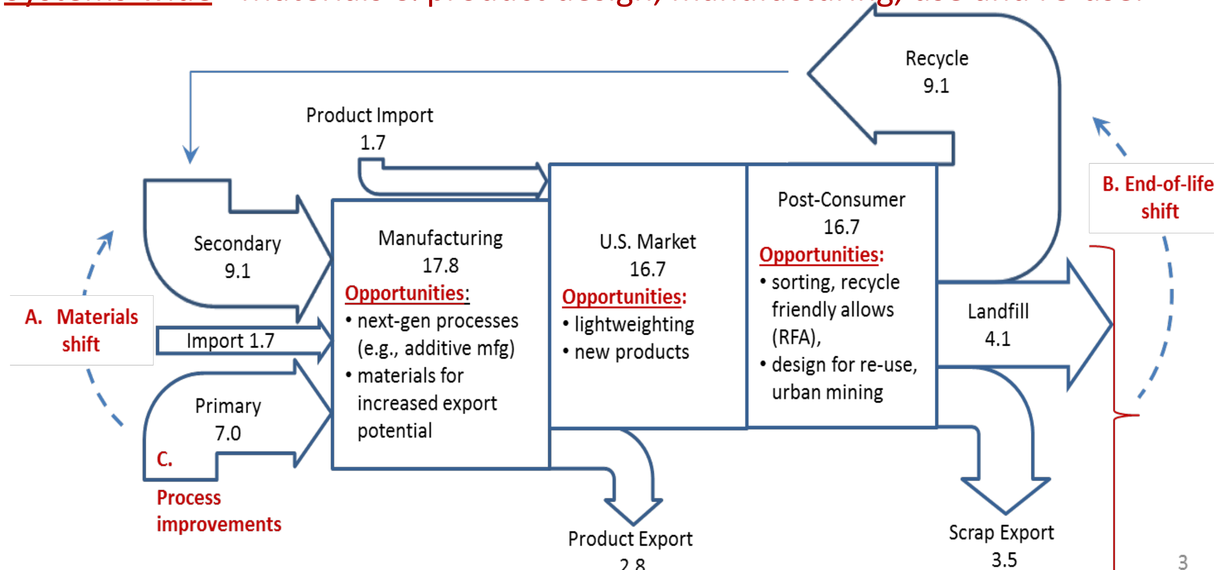
btu/lb	primary	secondary
Current average	26,000	2,200
Practically achievable	20,000	925
Current savings potential	6,000 btu/lb Process improvement	1,275
Theoretical minimum	10,200	510

23,800 btu/lb Materials shift

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

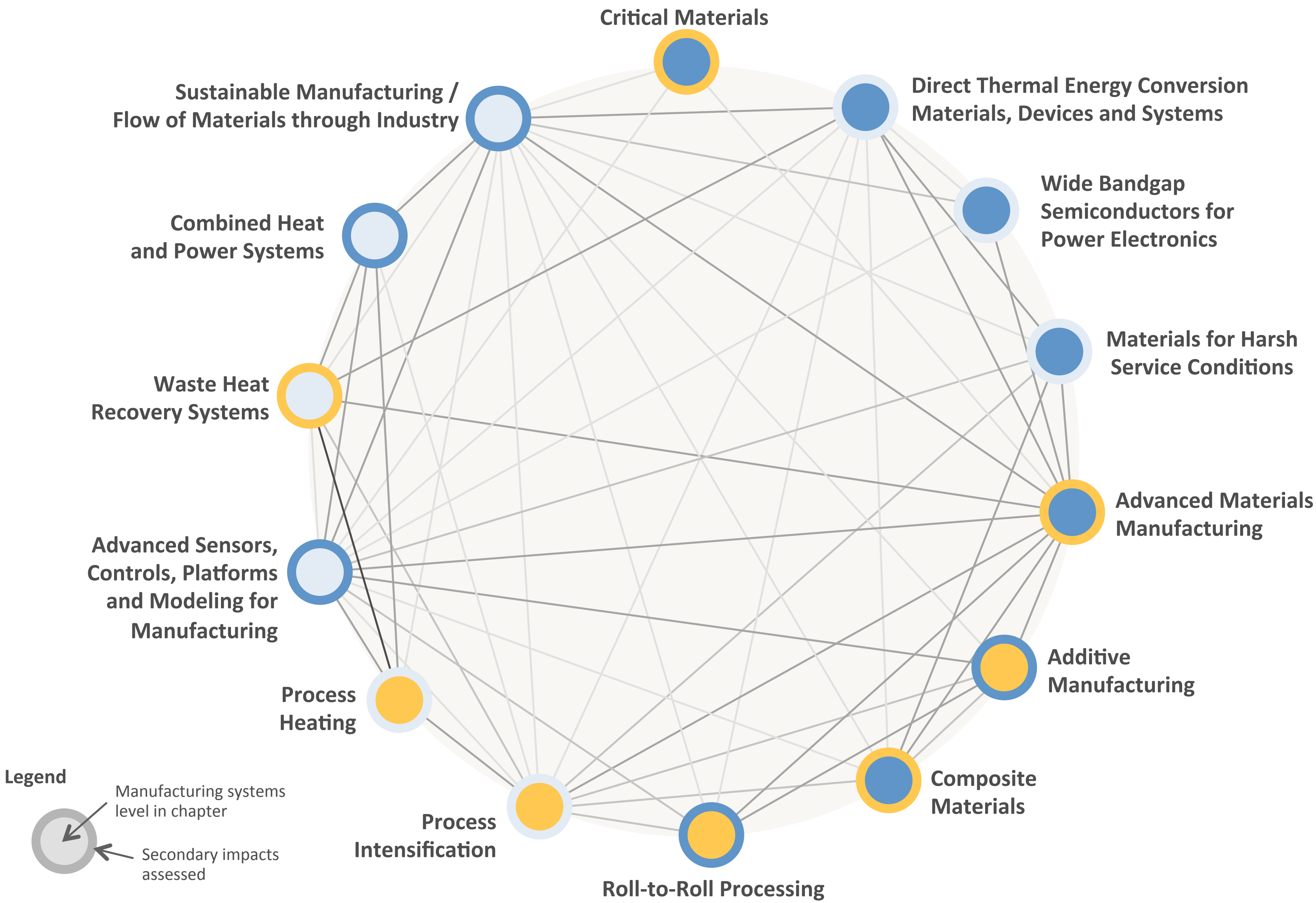
Systems approach in the QTR Industry & Manufacturing chapter:

System Level	As defined in the QTR
Manufacturing Systems/Unit Operations	*Technology and equipment used for manufacturing process and nonprocess unit operations*
Production/Facility Systems	*Equipment, process flow, and energy strategies that comprise a goods-producing facility*
Supply-Chain Systems	*Facilities and operations involved in moving materials through an industry, from the extraction of raw materials to the production of finished goods.*

Technology opportunities exist at each systems level

System Level	Examples	R&D Opportunity Examples
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

QTR Industry & Manufacturing Technology Assessments



Manufacturing Systems – Unit Operations	Production / Facility Systems – Energy and Resource Utilization	Beyond the Plant Boundaries – Supply Chain and Life Cycle

Technology Assessments at their principal manufacturing systems level:

System Level	QTR Manufacturing Technology Assessments
Manufacturing Systems/ Unit Operations *Existing Processes; New Approaches*	• *Process Heating* • *Process Intensification* • *Roll-to-Roll Processing* • *Additive Manufacturing*
Production/Facility Systems *Fuel Flexibility and Waste Energy; Data and Automation*	• *Combined Heat and Power Systems* • *Waste Heat Recovery Systems* • *Adv. Sensors, Controls, Platforms and Modeling for Mfg.*
Supply-Chain Systems *Increasing Sustainability; Manufacturing Energy-Efficient Products*	• *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
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Waste heat recovery

Carbon Intensity, e.g.:
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Biomass-based fuels
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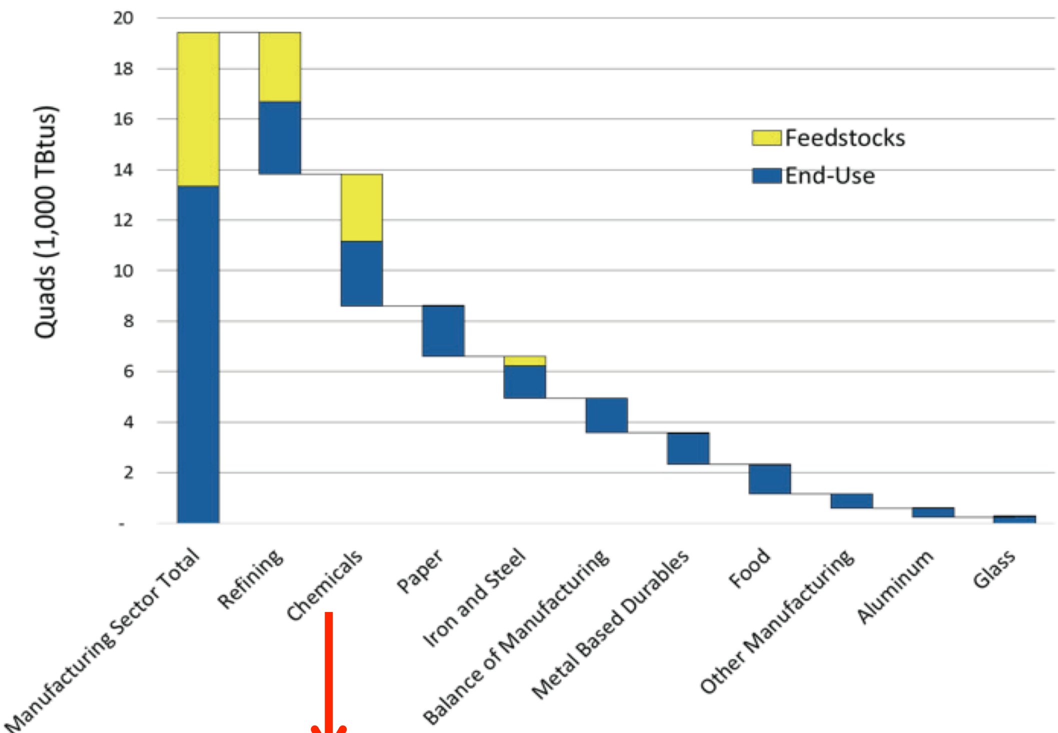

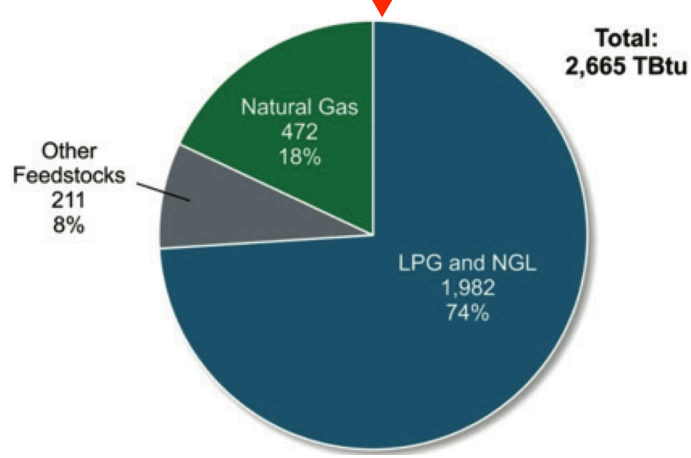

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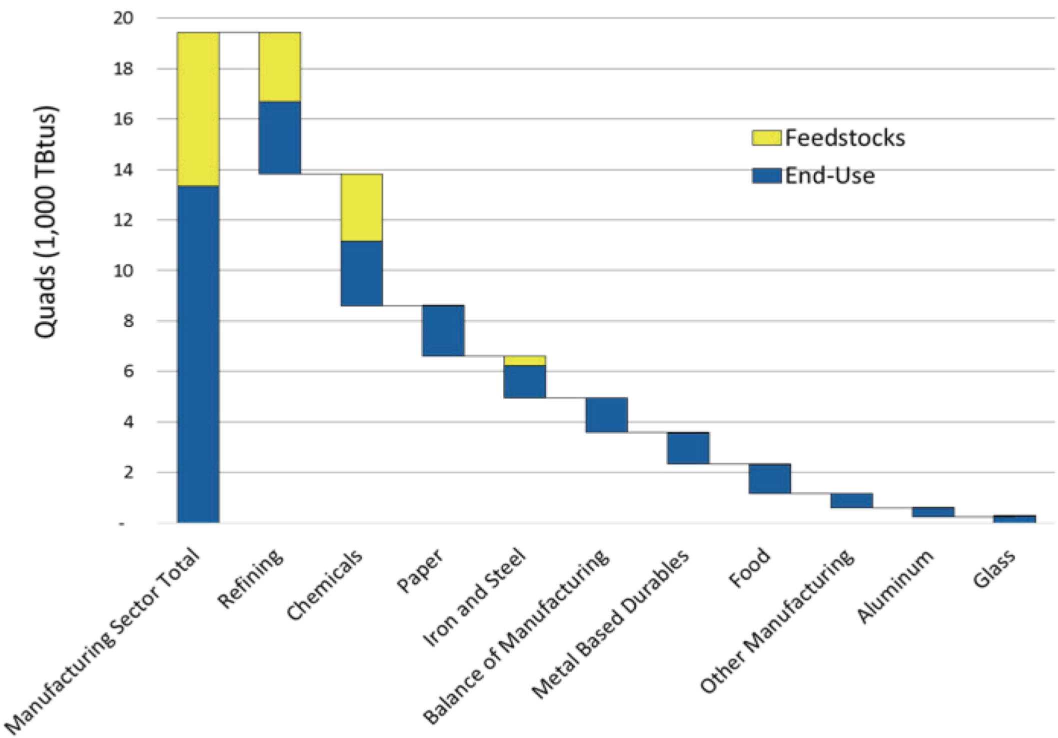
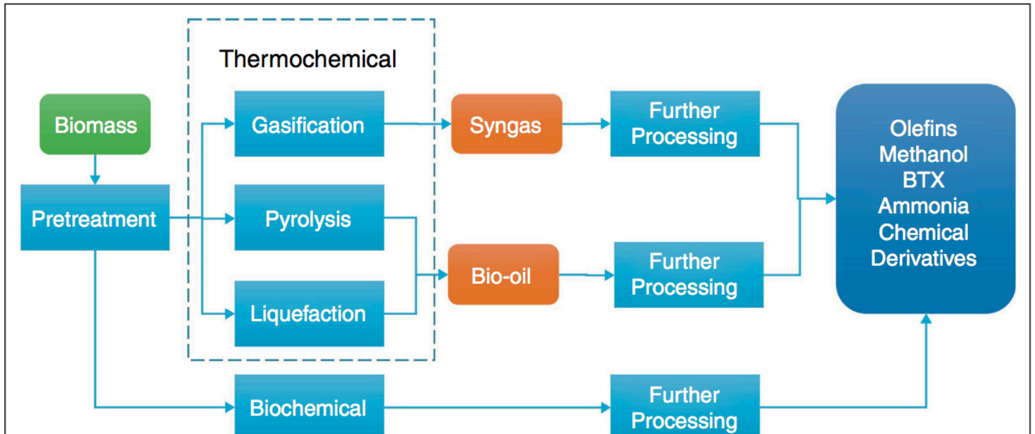




Current Opinion in Chemical Engineering

Energy, Carbon and Use Intensity Improvements

Table 2

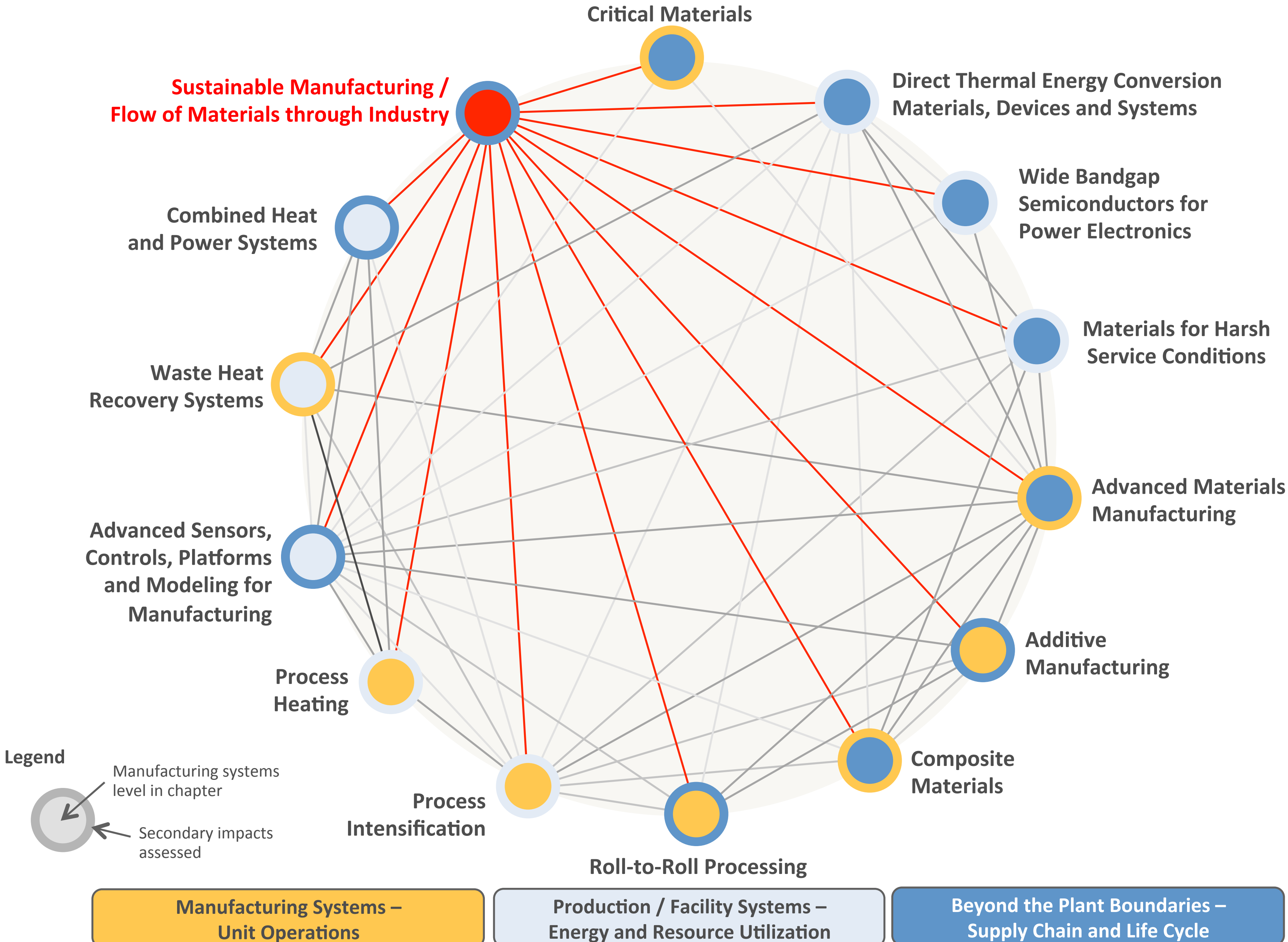
Published LCA results for biomass and CO_2 pathways associated with the EICCs and their derivatives

Chemical [references]	Conventional process	Feedstock[a]	Conversion pathway	Life cycle energy reduction GJ/t product (%)	Life cycle GHG reduction t CO_2-eq/t product (%)	Development stage	Cost ratio (bio-/fossil-based)
Bio-adipic acid [69,75] (benzene derivative)	Petroleum-based, benzene building block	Glucose from sugar beet	Bio-chemical & Thermal-chemical	30.4–58.9 GJ/t (29–57%)	9.8–17.4 tCO_2-eq/t (NA)	Pilot plant, commercialization in 1–2 years	0.8–0.7
Bio-polylactic acid PLA [76,77] (substitute)	50% PE, 50% polypropylene (PP) from ethylene, propylene (PLA replace PP and PE as plastics)	Corn starch	Bio-chemical	22–50 GJ/t (29–66%)	0.8–3.0 tCO_2-eq/t (17–63%)	Commercialized	0.9–1.3
Bio-polyethylene terephthalate PET [78] (ethylene, xylene derivative)	Petroleum based PET produced from ethylene glycol and purified terephthalic acid/ dimethyl terephthalate	Maize and sugarcane	Bio-chemical & thermo-chemical	13–22 GJ/t (24–32%)	1–2 tCO_2-eq/t PET (41–43%)	Commercialized	Comparable price with petroleum-based PET
Bio-ethylene [67,71]	Steam cracking of NGL/ naphtha/gas oil	Sugarcane, lignocelluloses, maize starch	Bio-chemical	40–100%	40%	Commercialized	1.1–2.3
Bio-polyethylene [8••] (ethylene derivative)	Polyethylene (PE) from ethylene	Corn starch or sugar cane	Bio-chemical	29.3–67.6 GJ/t (40–88%)	2.1–4.2 tCO_2-eq/t (120–200%)	Commercialized	Depends on bio-ethylene production
Bio-polyhydroxyalk-anoate (PHA) [8••,67,77] (substitute)	Polyethylene (PE) from ethylene (PHA replace PE as biodegradable plastics)	Agriculture residues, corn starch, sugar cane, lignocelluloses	Bio-chemical	−35 to 58.9 GJ/t (−47% to 77%)	−2.6 to 2.8 tCO_2-eq/t (−160% to 175%)[b]	Commercialized	4.9–5.4
Methanol [79]	Methane	CO_2 captured from power plant; CO generated by thermochemical splitting of CO_2 using solar thermal energy; H_2 generated by water gas shift of H_2O and CO	Methanol synthesis from CO/H_2	10 kWh/kg (98%)	2.4 tCO_2-eq/t (350%)[c]	Commercialized	2.7
Methanol [80]	Methane	CO_2 captured from power plant; H_2 generated by electrolysis supplied by wind farm	Direct methanol synthesis from CO_2/H_2	NA	1.1 tCO_2-eq/t (59%)		

Current Opinion in Chemical Engineering 2014, **6**:90–98

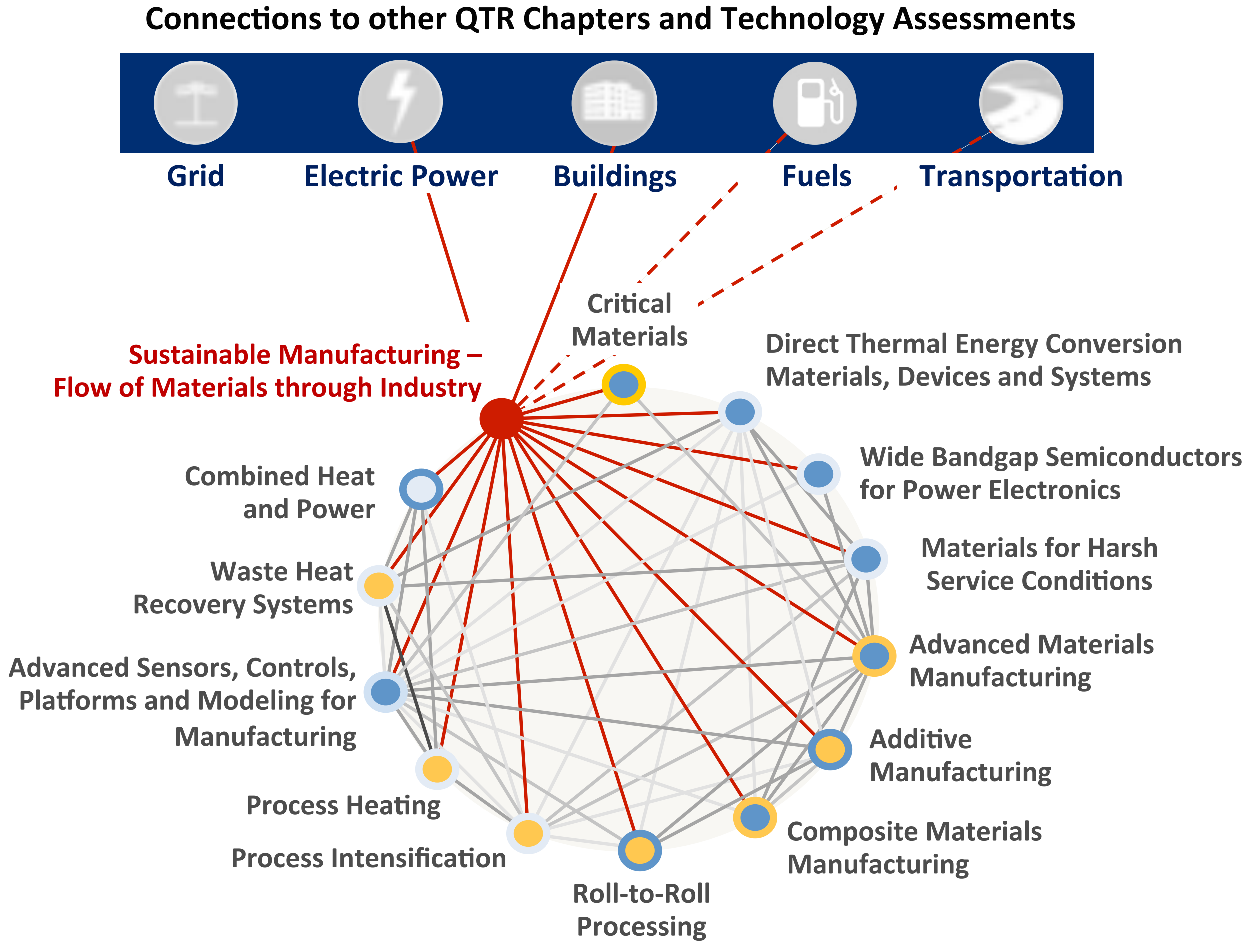
[a] As reported in the source study.
[b] Negative values indicate emerging pathway is more energy and/or GHG intensive than the conventional pathway; percent savings greater than 100% are attributable to avoided emissions.
[c] Large GHG emissions reductions are attributable to carbon capture and renewable energy.

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



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

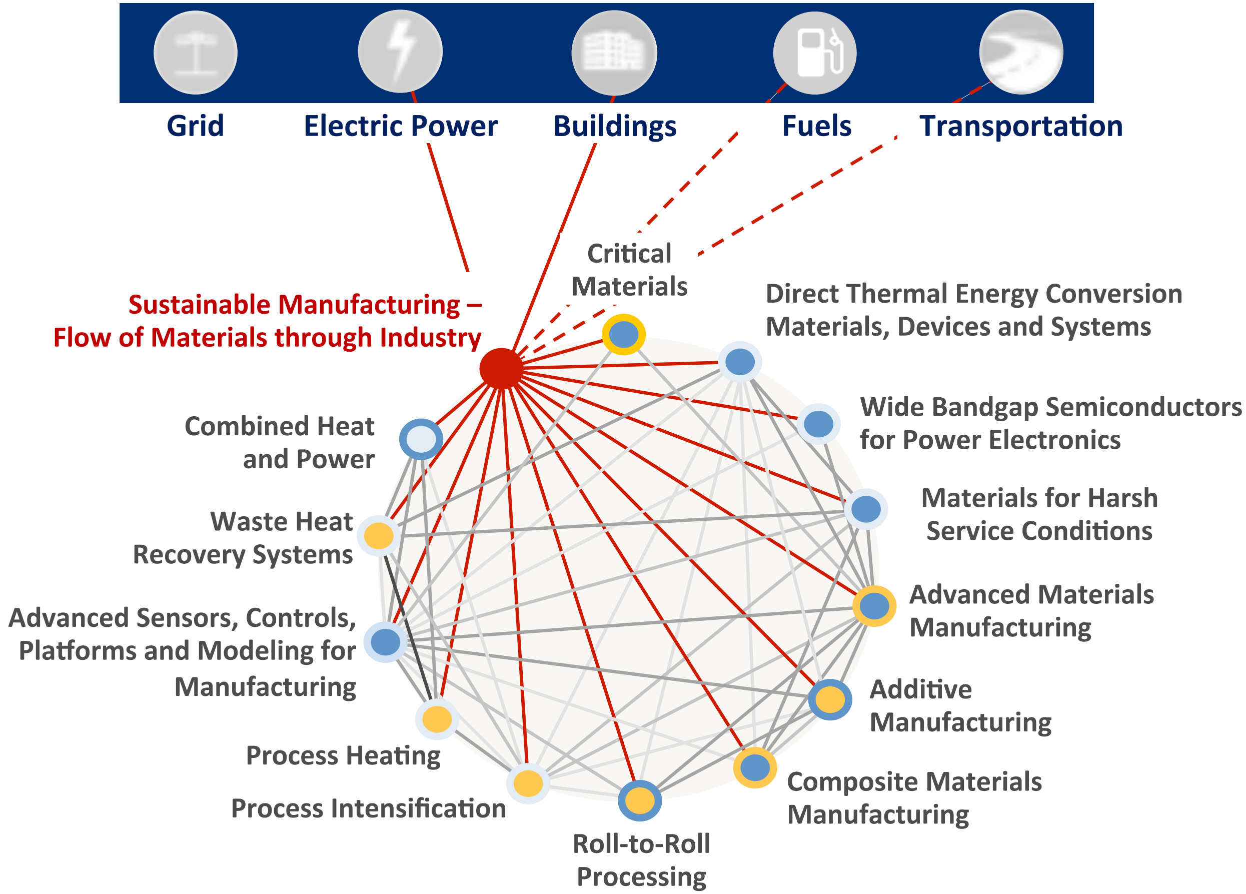


Sustainable Manufacturing Technology Assessment- Connections

Cross-Energy Connections

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

Connections to other QTR Chapters and Technology Assessments



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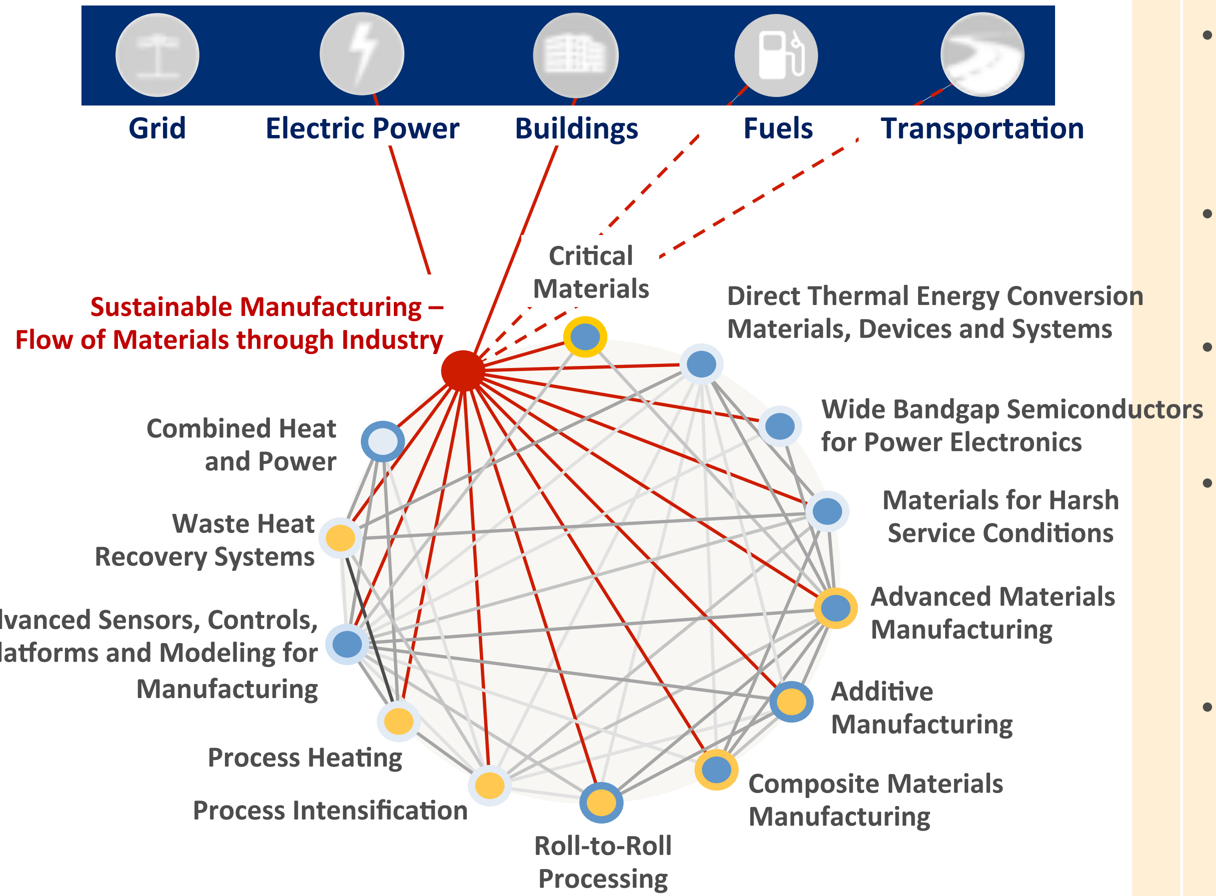

Intra-Manufacturing Connections

- **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*

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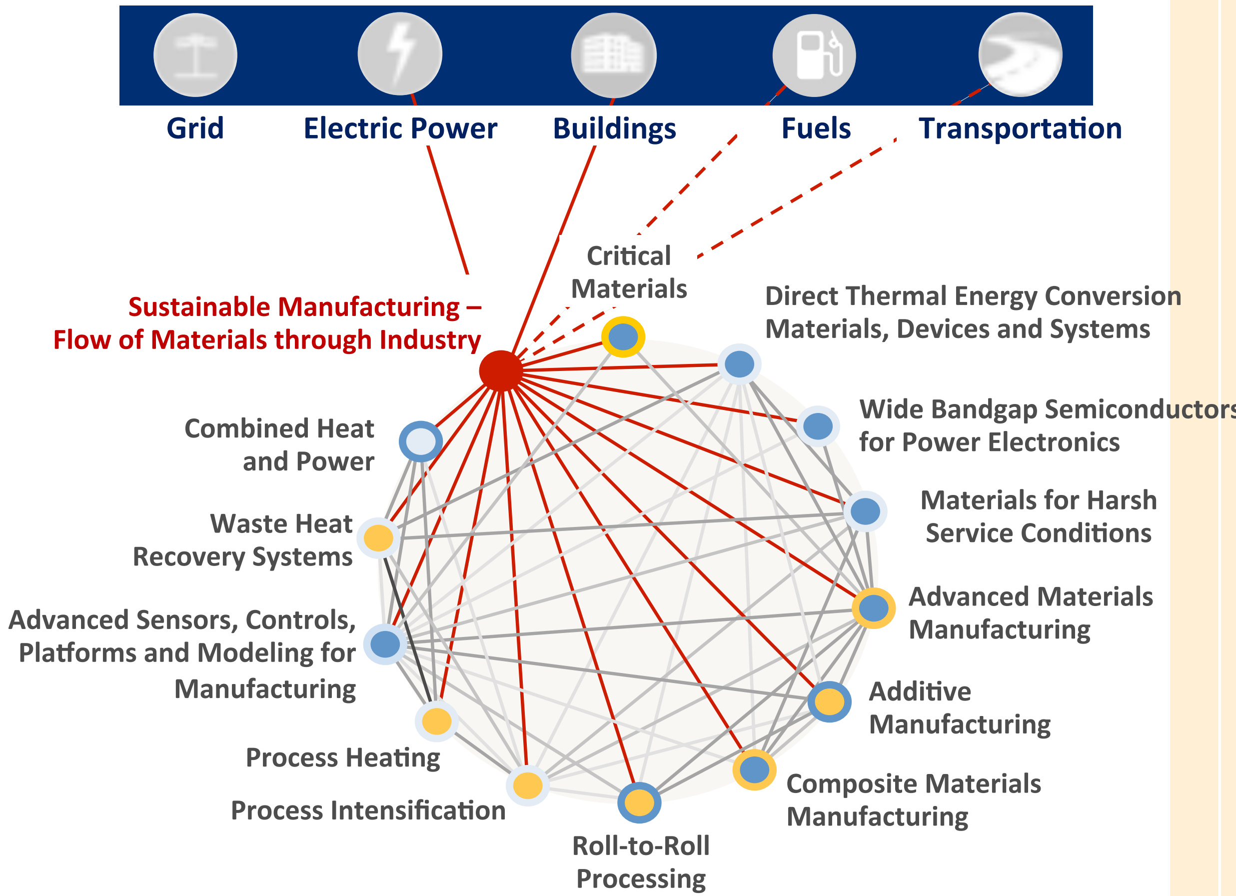

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Technology Highlights – Use Intensity Improvements

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**

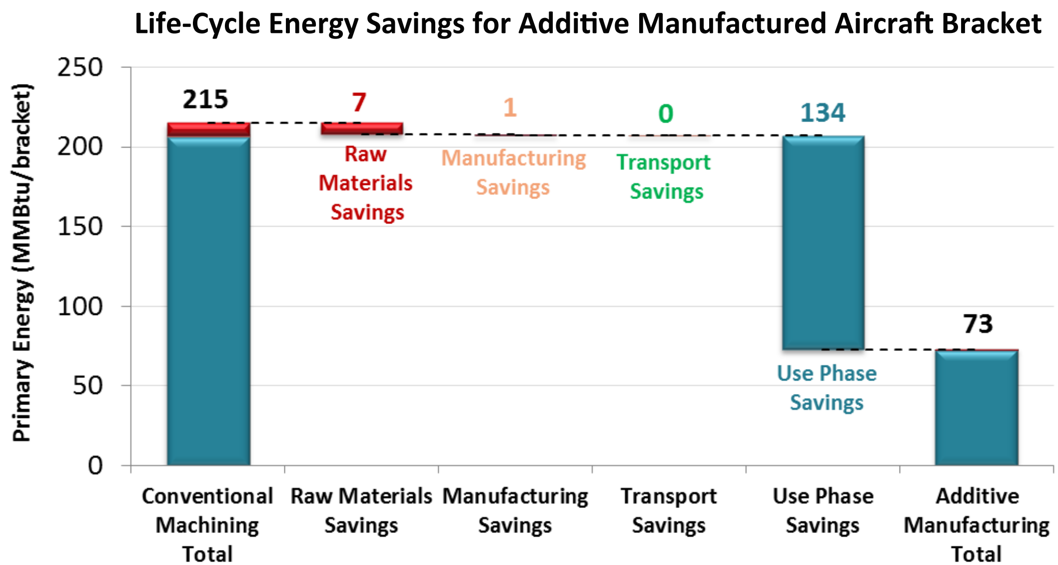
Energy, cost, and environmental impacts (throughout life cycle) are application dependent.

Case Study: Optimized Aircraft Bracket

1.09 kg

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

0.38 kg



Source: *MFI and LIGHTEnUP Analysis*
Note: 1 quad = 1 × 10^9 MMBtu

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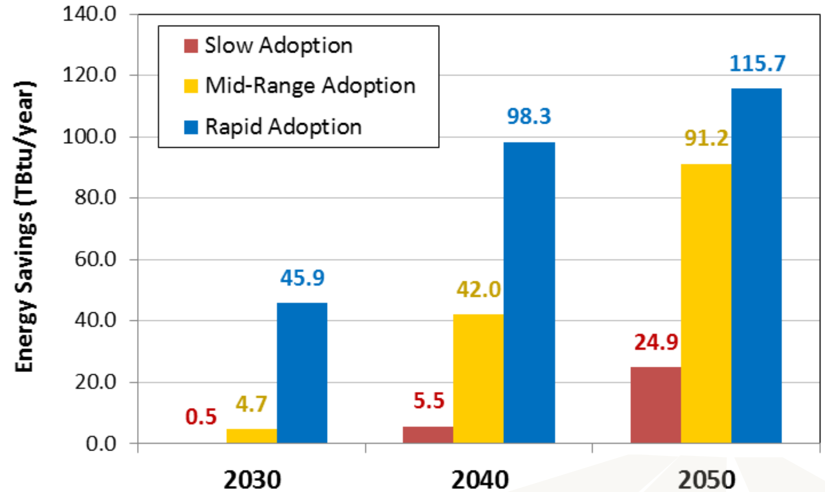
- **Time-quality** optimization
- Materials **efficiency**

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

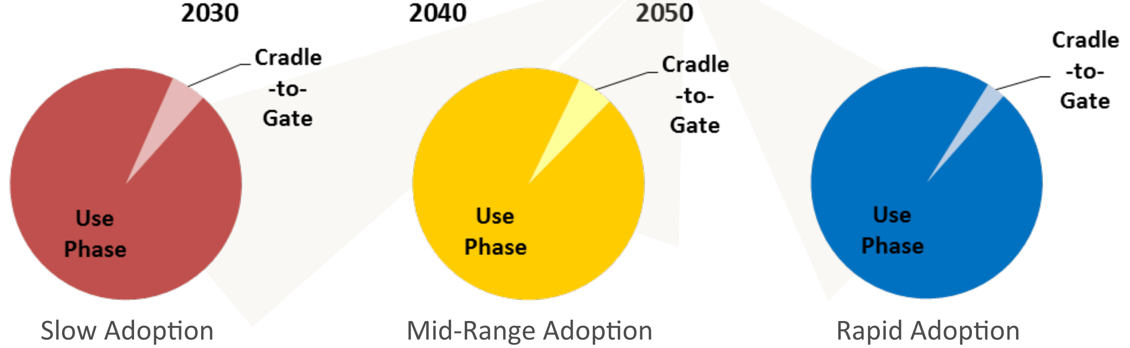


Scenario

Slow Adoption
new aircraft only

Mid-Range Adoption
new aircraft and new parts

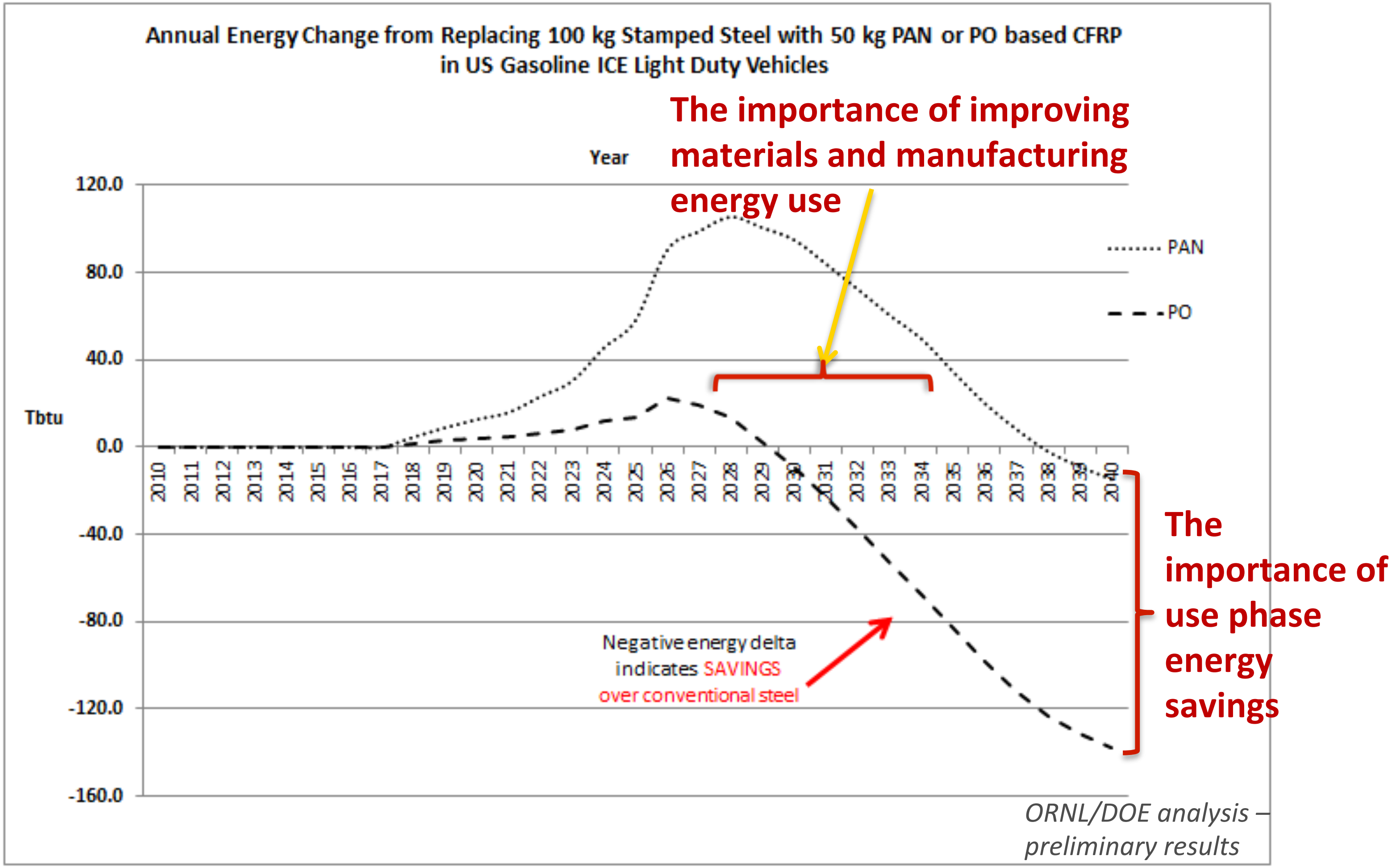
Rapid Adoption
new aircraft, new parts, and accelerated replacement



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

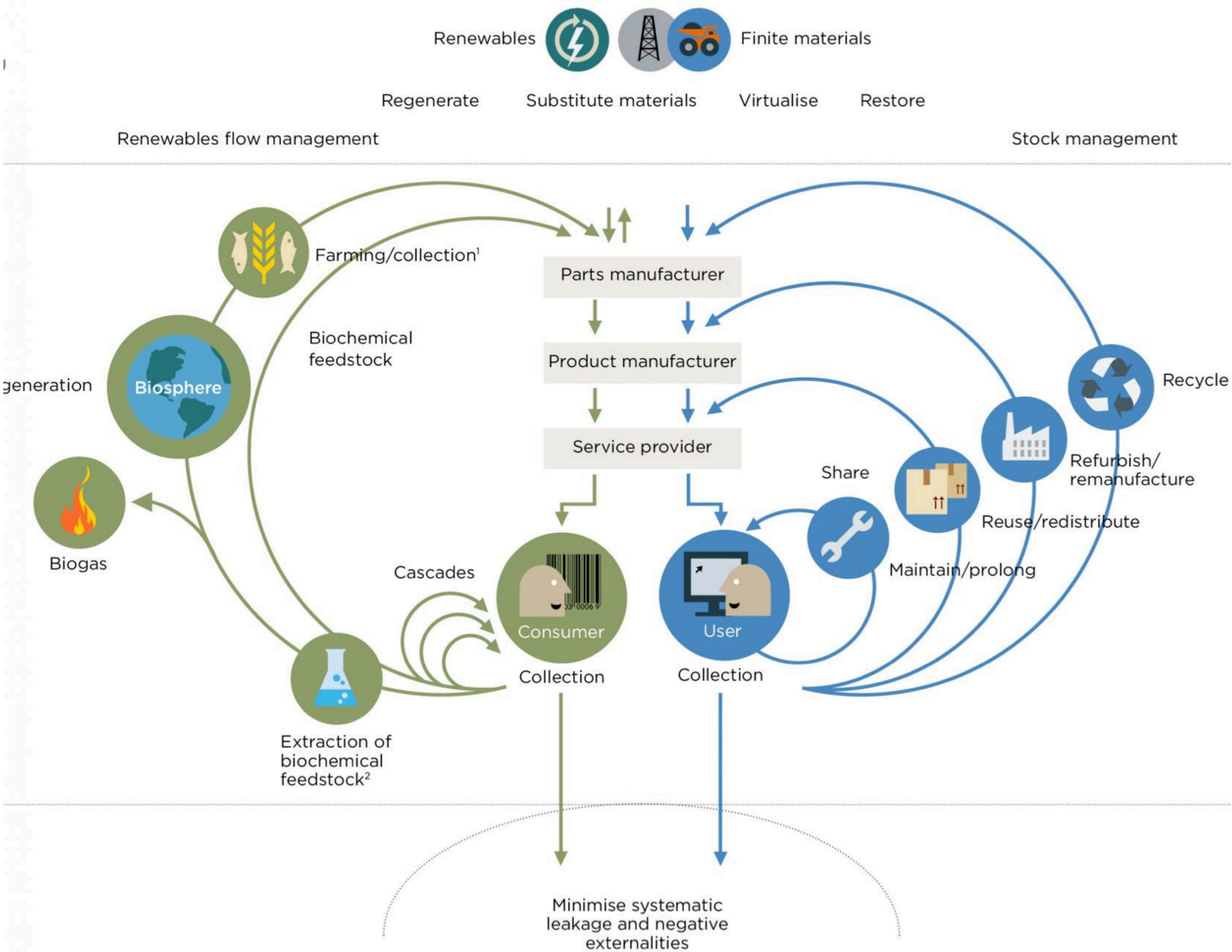
Source: *R. Huang, et al.*, "The Energy and Emissions Saving Potential of Additive Manufacturing: The Case of Lightweight Aircraft Components." (Analysis In Progress). ***Note:*** 1 quad = 1,000 TBtu

Technology Assessment – Life Cycle Energy Savings from Light-weighting Carbon Fiber Reinforced Plastics vs. Steel



- 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



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

Source: Ellen MacArthur Foundation, SUN, and McKinsey Center for Business and Environment; Drawing from Braungart & McDonough, Cradle to Cradle (C2C).

EUROPEAN
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Brussels, XXX
COM(2015) 614/2

COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS

Closing the loop - An EU action plan for the Circular Economy

Circular Economy – In December 2015, the European Commission 2030 targets for recycling municipal waste (65%) and packaging waste (75%).

1. **Production**
    - 1.1. Product design
    - 1.2. Production processes
2. **Consumption**
3. **Waste management**
4. **From waste to resources: boosting the market for secondary raw materials and water reuse**
5. **Priority areas**
    - 5.1. Plastics
    - 5.2. Food waste
    - 5.3. Critical raw materials
    - 5.4. Construction and demolition
    - 5.5. Biomass and bio-based products
6. **Innovation, investment, and other horizontal measures**
7. **Monitoring progress towards a circular economy**

"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 2: Strategies for material efficiency around different actors, and examples of enabling technologies.

Strategy	Scenario examples	Examples of enabling technologies	2015 QTR, Technology Assessment References	Actors
Substitution[4]	Non-critical material in place of critical material	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]	*Advanced Materials Manufacturing; Composite Materials Manufacturing; Wide Band Gap Semiconductors for Power Electronics; Critical Materials; Process Intensification; QTR Chapter 5*	Designers
Property improvement[4]	Improving the properties of materials and products to facilitate re-use or increase durability	Improving heat transfer to increase WHR; improving properties to make some materials suitable for AM	*Materials for Harsh Service Conditions; Waste Heat Recovery Systems; Additive Manufacturing; Direct Thermal Energy Conversion Materials, Devices and Systems*	Producers
Yield improvement[4]	Reducing material loss during processing; tessellation	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	*Additive Manufacturing; Process Intensification; Roll to Roll Processing; Advanced Materials Manufacturing*	Producers

[1]DOE Innovative Manufacturing Initiative (www.energy.gov/eere/amo/innovative-process-and-materials-technologies-0). [2]Arpa-E projects (arpa-e.energy.gov). [3]Google Project Ara (www.projectara.com). [4](Allwood 2011). [5](Allwood 2012). [6](Bernstein 2007)
AM – Additive Manufacturing; WBG – Wide band gap; WHR – Waste heat recovery.

Considerations as we start this workshop….

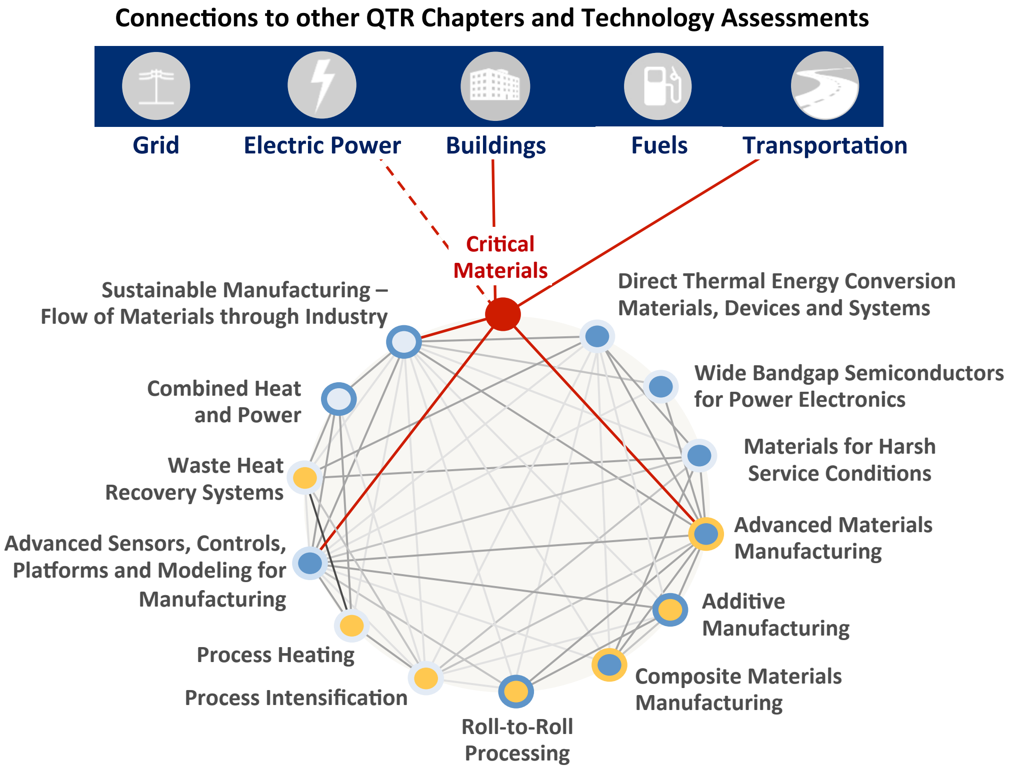
- What sustainable manufacturing technologies and system improvements* could yield the greatest economy-wide impacts?
- How can we sustainably leverage domestic energy resources (e.g., NG)?
- What timely investments could potentially enable U.S. leadership and open markets?

*<u>for example:</u>

- 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

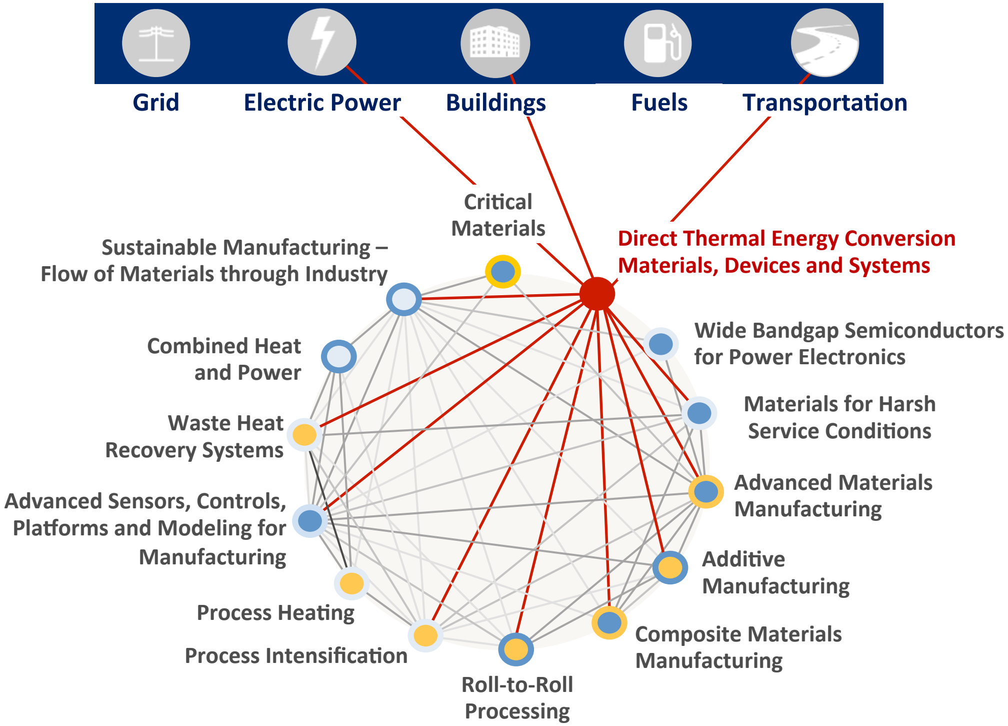
- **Electric Power:** *permanent magnets for wind turbines*
- **Buildings:** *phosphors for LED lighting*
- **Transportation:** *dysprosium and other rare earths for motors; platinum for fuel cell catalysts*

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

Connections to other QTR Chapters and Technology Assessments



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*

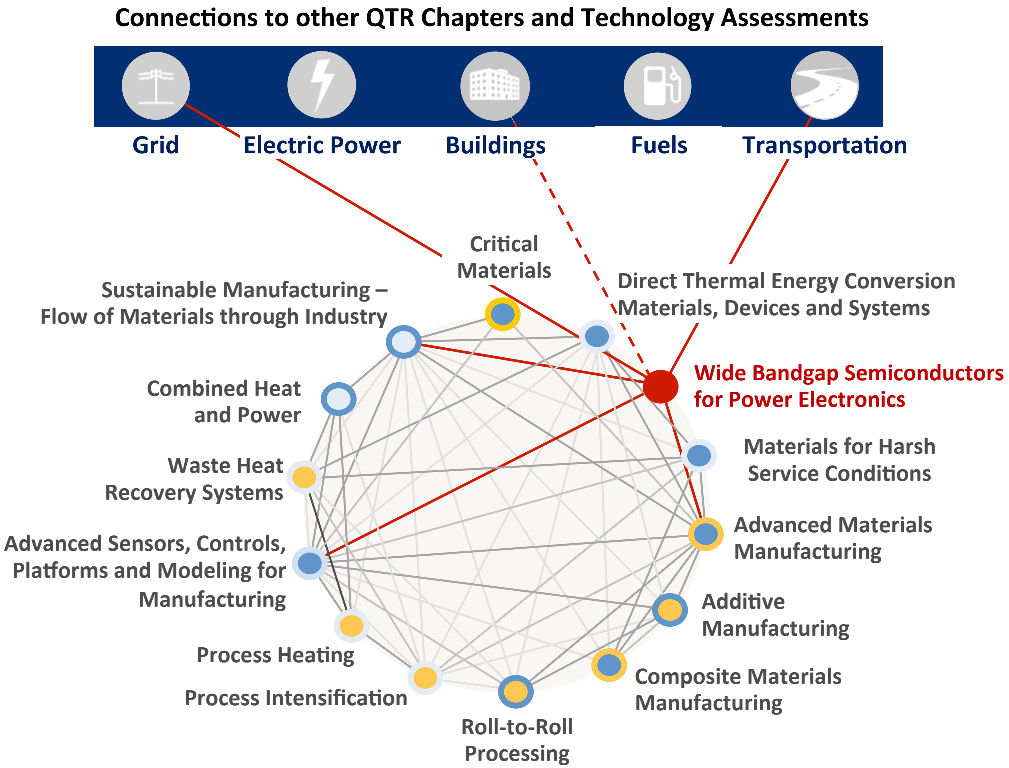
Cross-Energy Connections

- **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)

Wide Bandgap Semiconductors for Power Electronics



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*

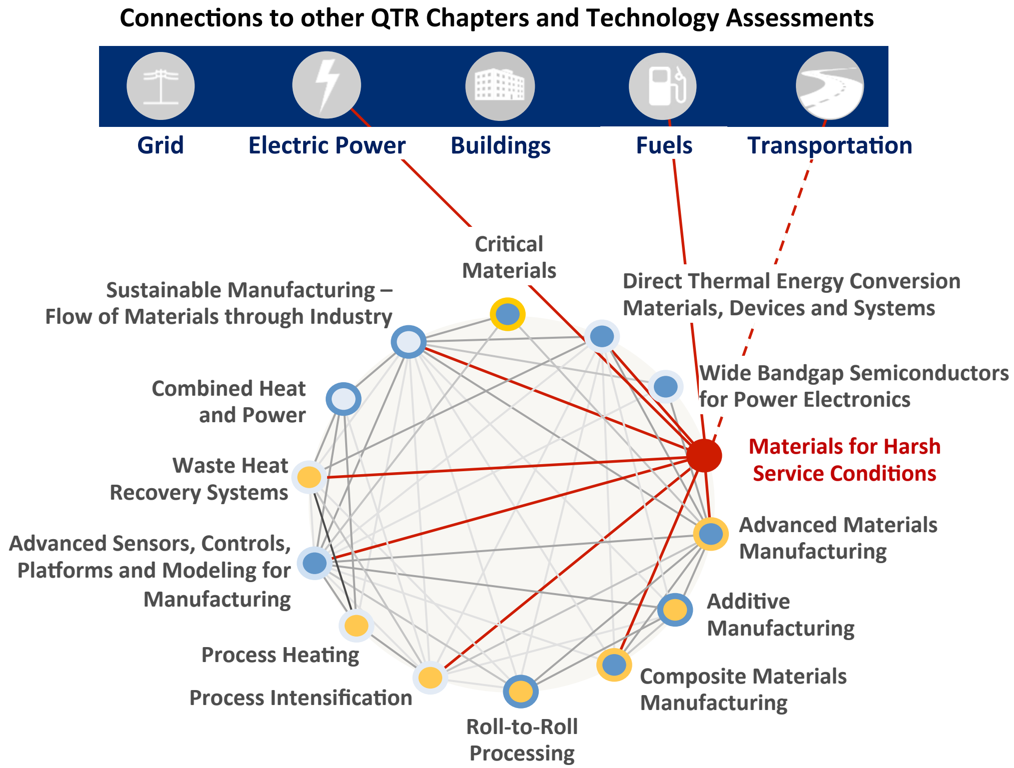
Cross-Energy Connections

- **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



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;*

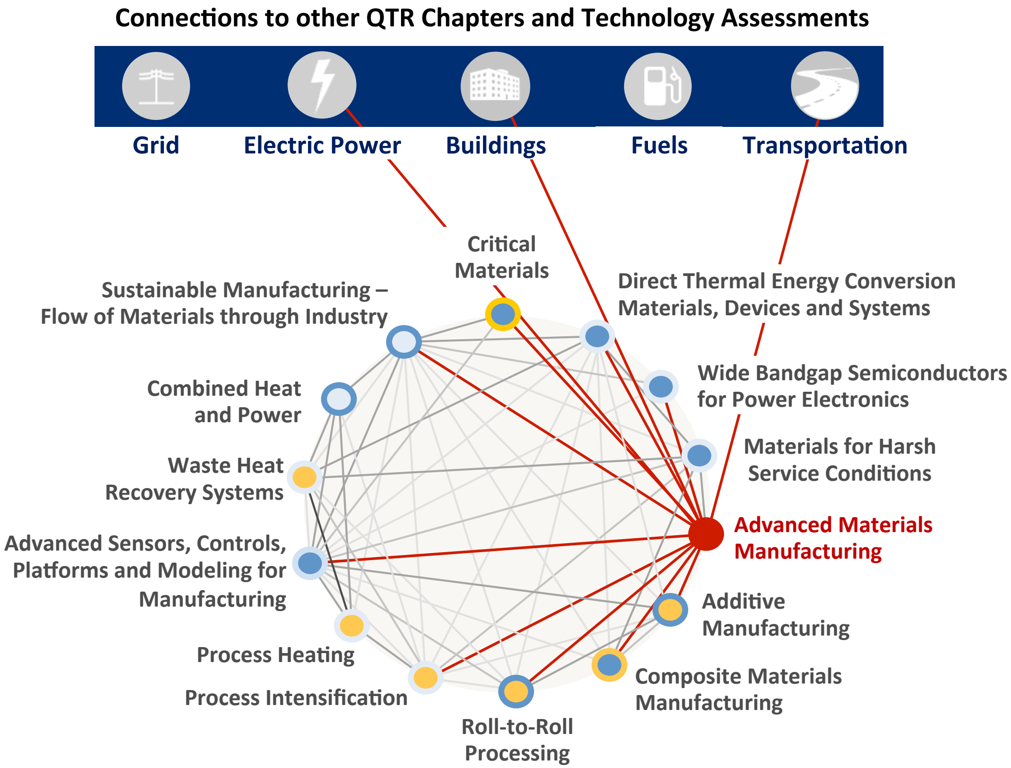
Cross-Energy Connections

- **Fuels:** *corrosion in offshore drilling equipment; ash fouling in biomass conversion equipment; hydrogen embrittlement in H_2 pipelines*
- **Electric Power:** *radiation-resistant fuel cladding; high-temperature alloys for nuclear reactors and gas and steam turbines*
- **Transportation:** *corrosion-resistant lightweight materials*

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*

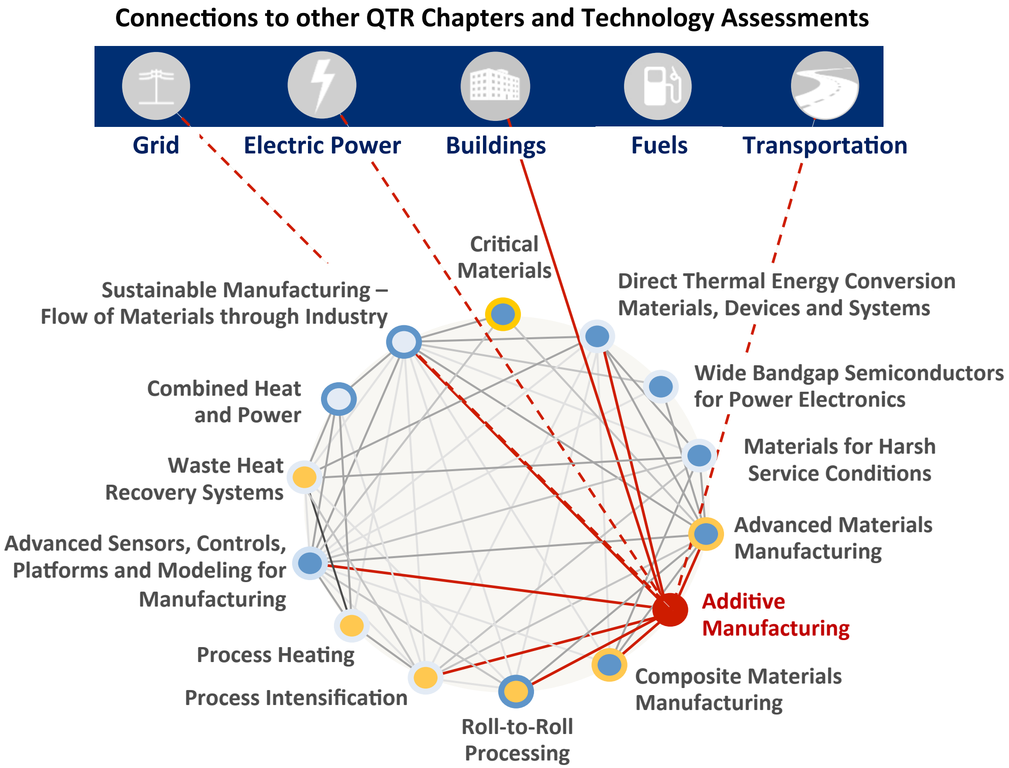
Cross-Energy Connections

- **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

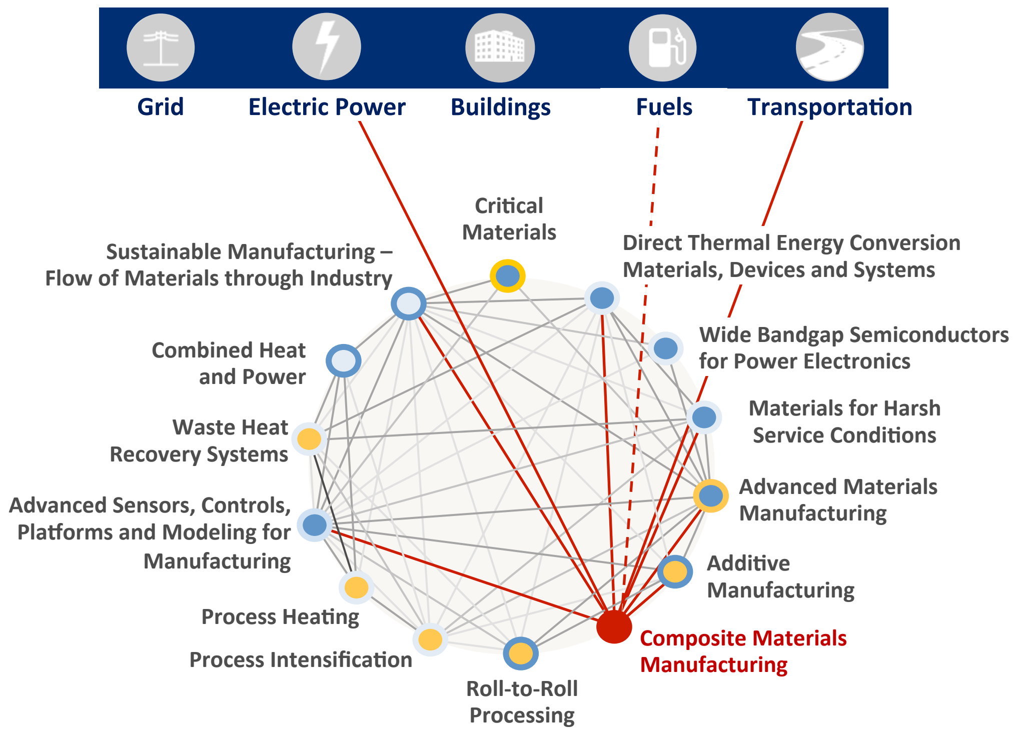
- **Fuels:** *fuel cells*
- **Electric Power:** *custom electrical components in substations; complex parts for power plants; tooling for large castings for power plants*
- **Buildings:** *heat exchangers for HVAC systems; window frames*
- **Transportation:** *Prototyping and tooling in automotive applications;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

Connections to other QTR Chapters and Technology Assessments



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*

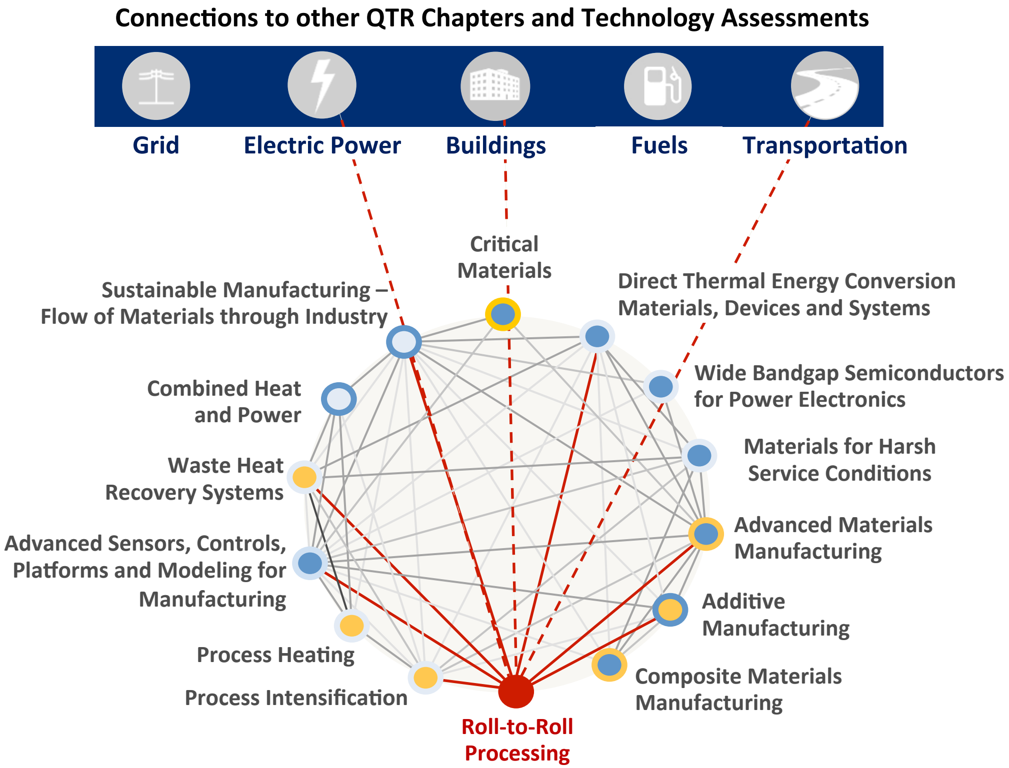
Cross-Energy Connections

- **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

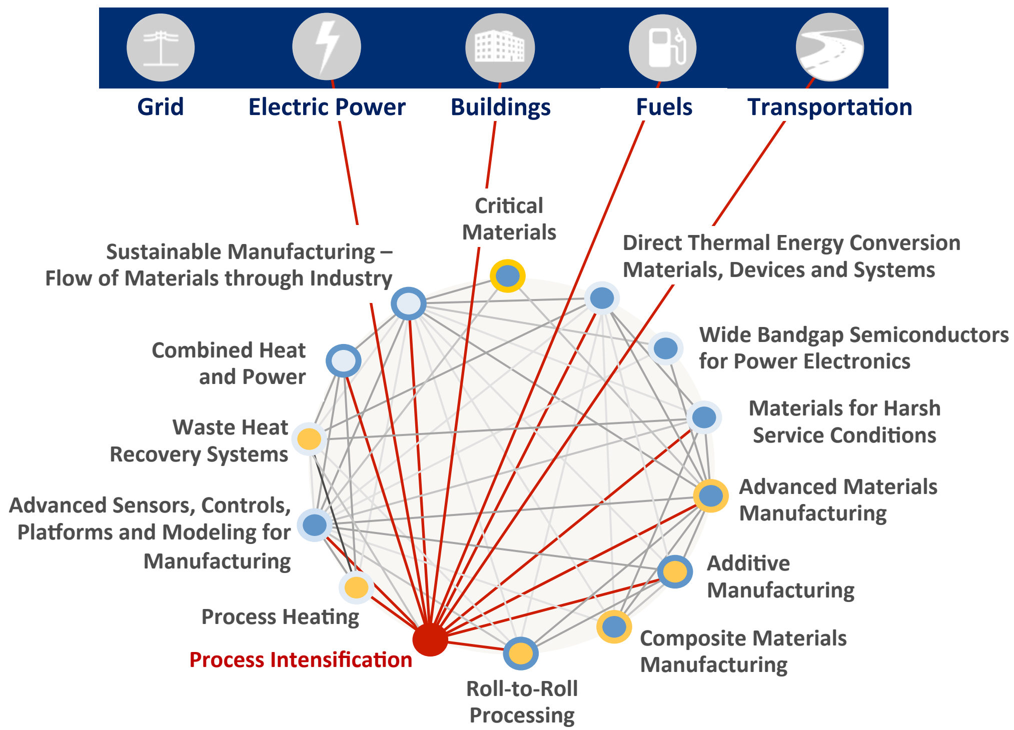
- **Electric Power:** *flexible solar panels*
- **Buildings:** *window insulation films*
- **Transportation:** *battery electrodes*

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

Connections to other QTR Chapters and Technology Assessments



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

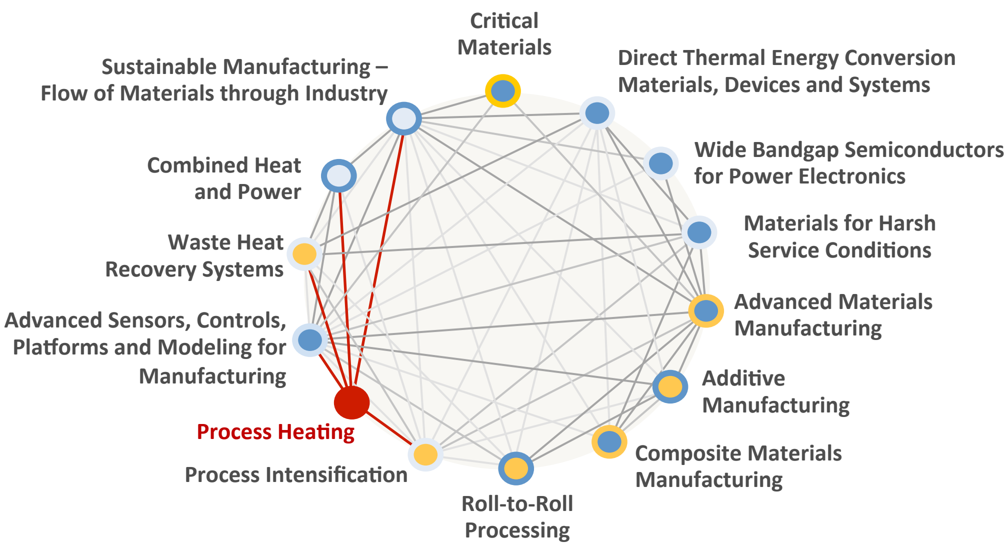
- **Fuels:** *natural gas and modular production*
- **Electric Power:** *chemical conversion of biofeedstocks; separations for CCS*
- **Buildings:** *membranes for dehumidification*
- **Transportation:** *adsorbent systems for compressed gas storage*

Scope

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

Process Heating Systems

Connections to other QTR Chapters and Technology Assessments



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*

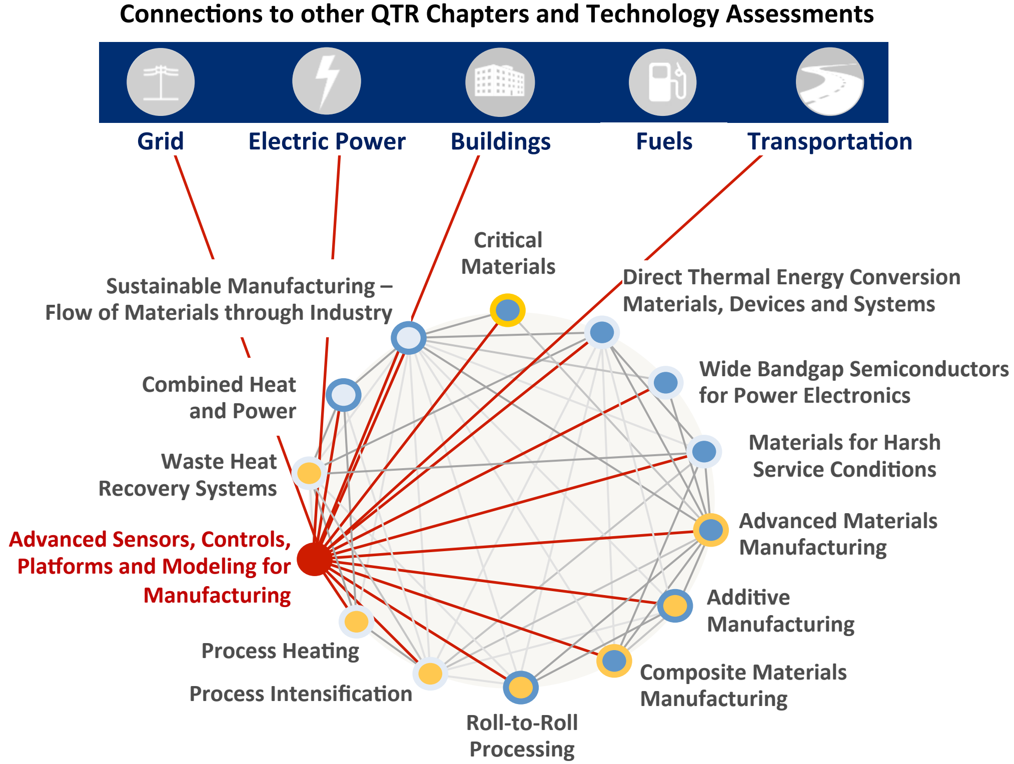
Cross-Energy Connections

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

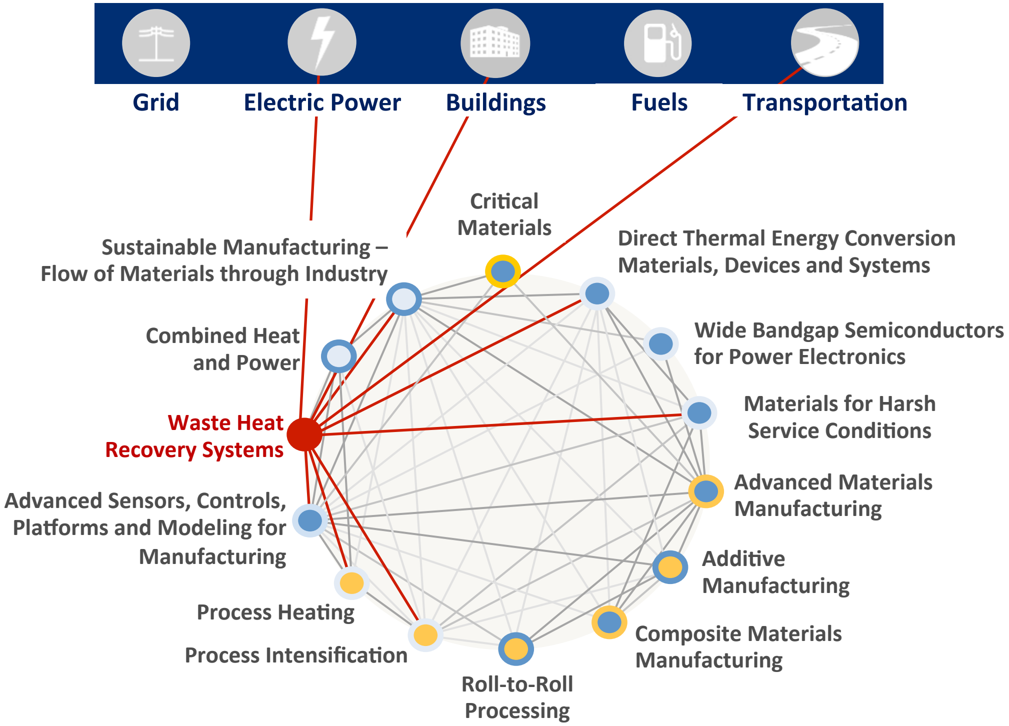
- **Grid:** *advanced metering; sensors for power flow*
- **Electric Power:** *grid integration*
- **Buildings:** *advanced sensors for lighting and HVAC*
- **Transportation:** *vehicles engine control systems*

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*

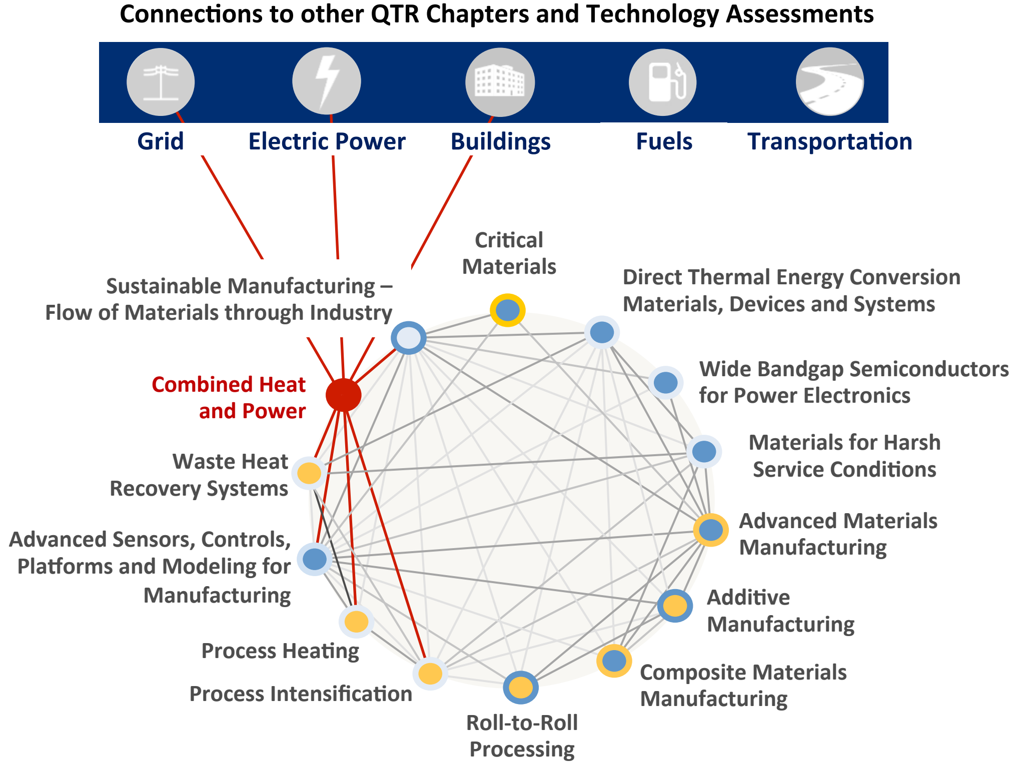
Cross-Energy Connections

- **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

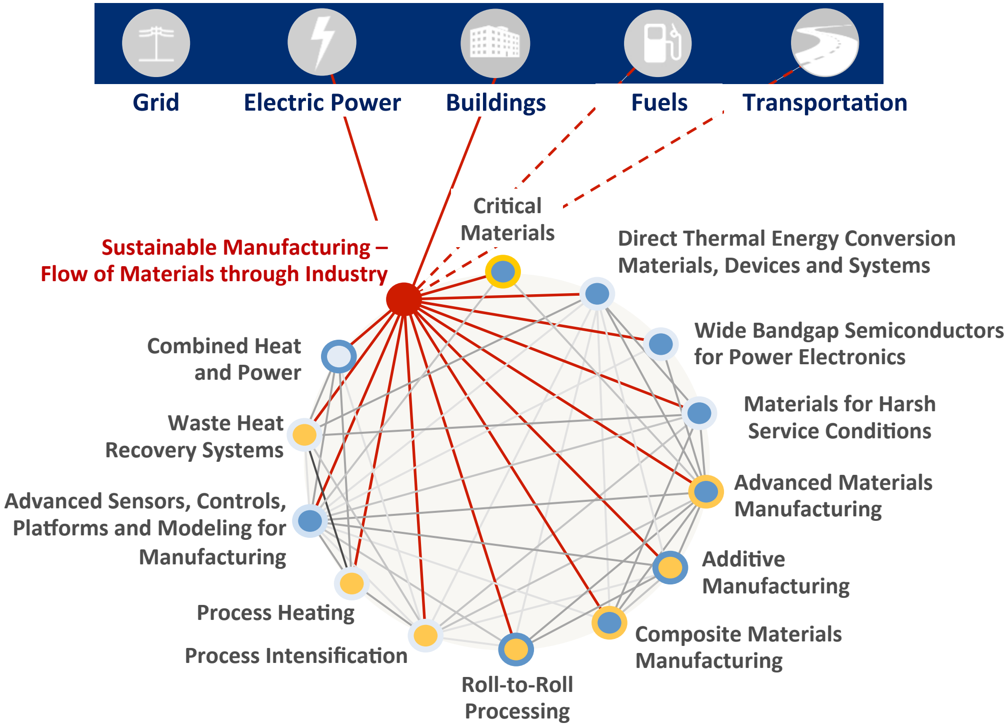
- **Grid:** *CHP for distributed generation*
- **Electric Power:** *CHP for distributed generation*

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

Connections to other QTR Chapters and Technology Assessments



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*

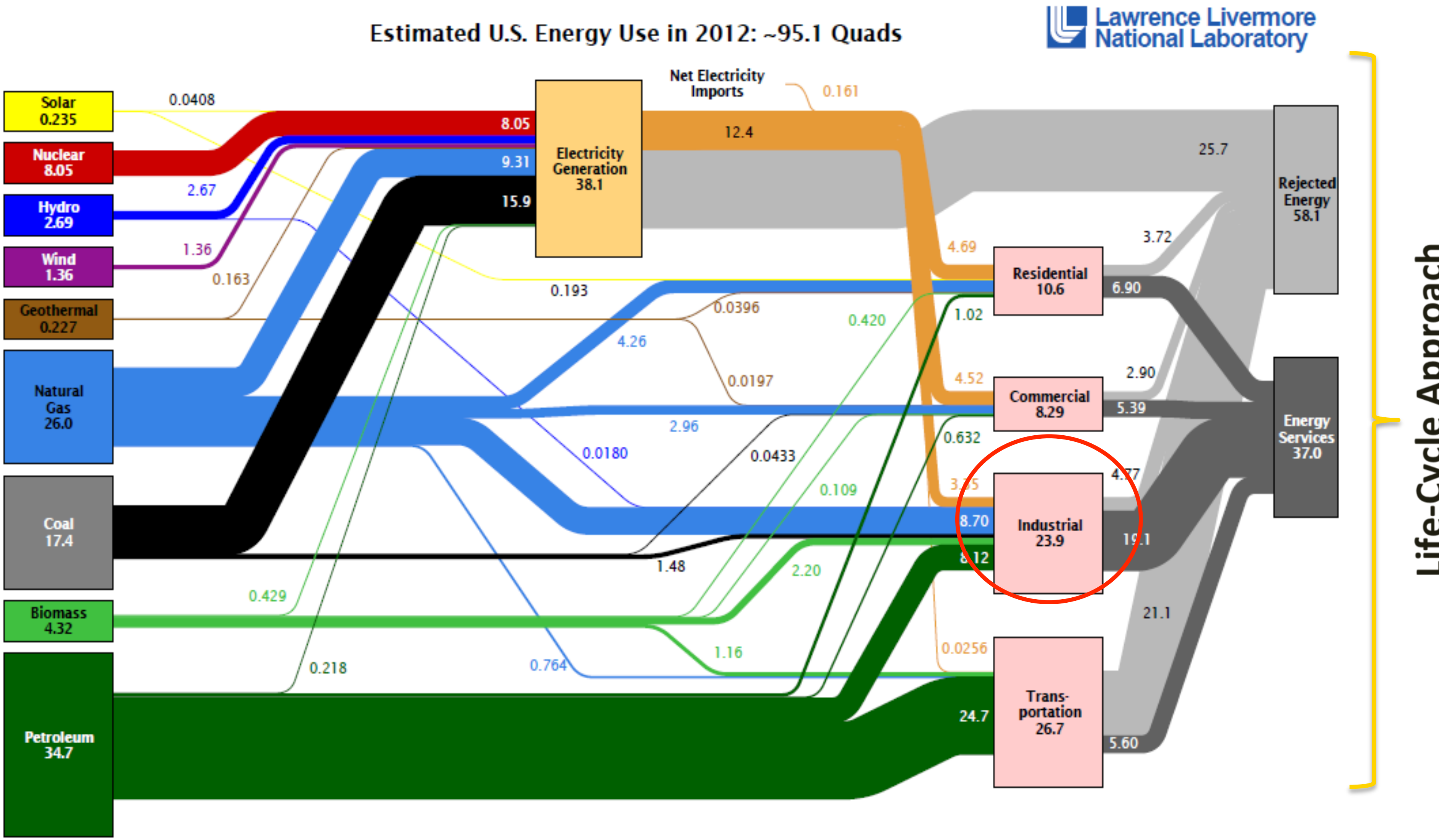
Cross-Energy Connections

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

Scope

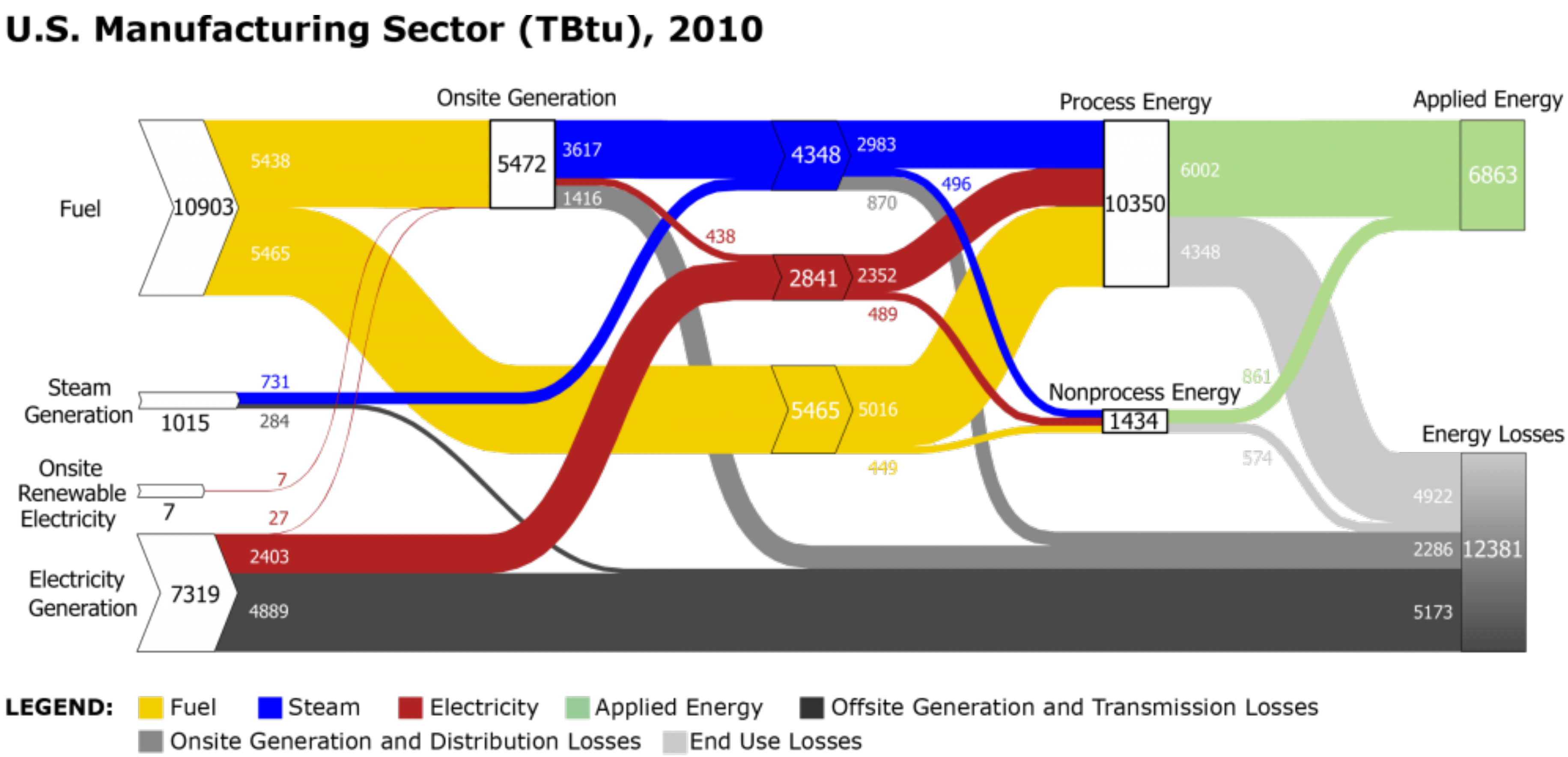
- Supply chain issues, from resource extraction to end of life (Life Cycle Analysis)
- Flow diagrams to demonstrate supply chain issues Material efficiency: mechanisms for reducing demand for materials (e.g., lightweighting, scrap reduction, increased material longevity)
- Design for Re-use / Recycling

Introduction - Flow of Energy through the U.S. Economy



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 65% 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-MI-410527

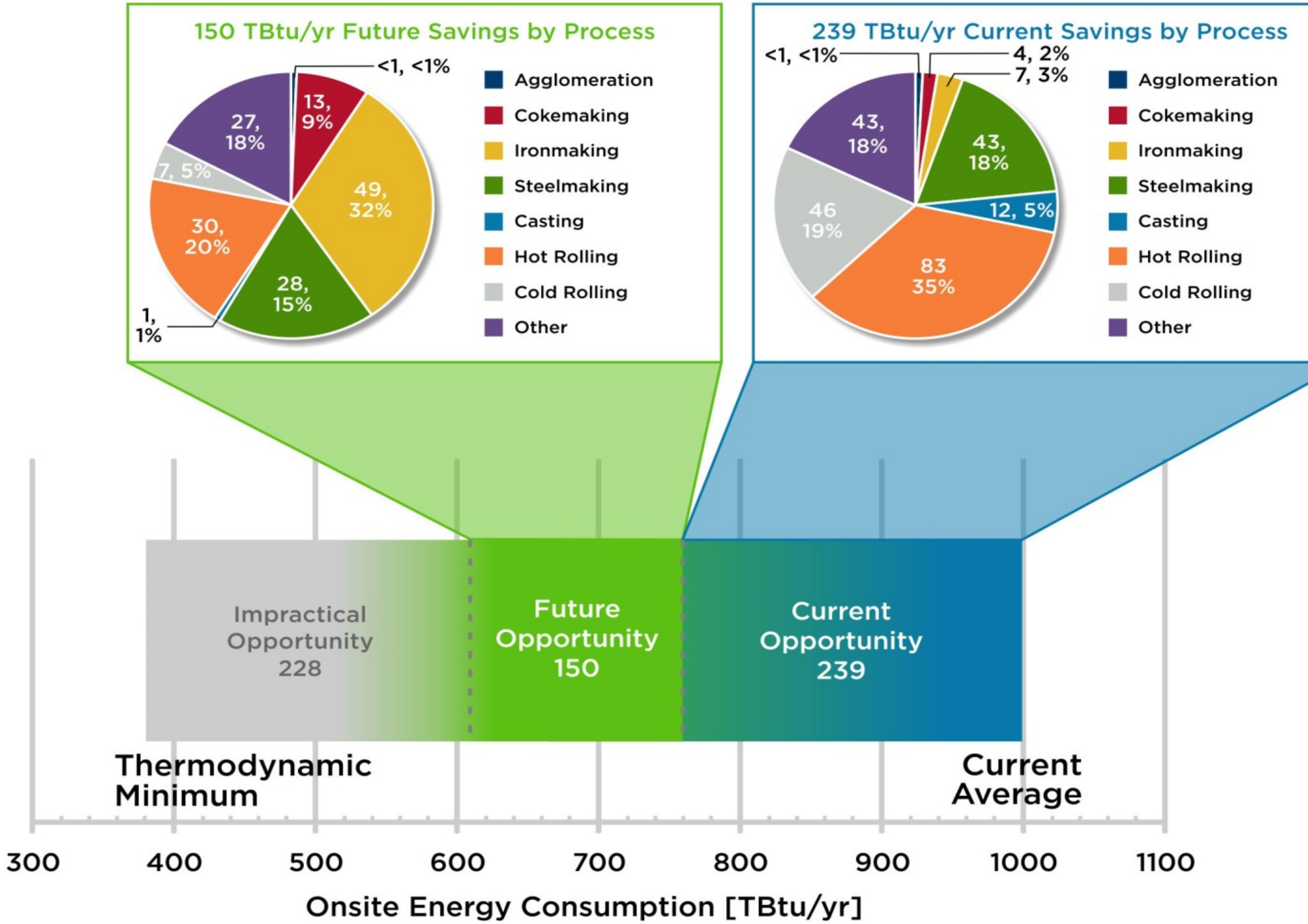
Introduction – Flow of Energy Through Manufacturing



Note: 1 quad = 1,000 TBtu

Driver – Energy Intensity Improvements

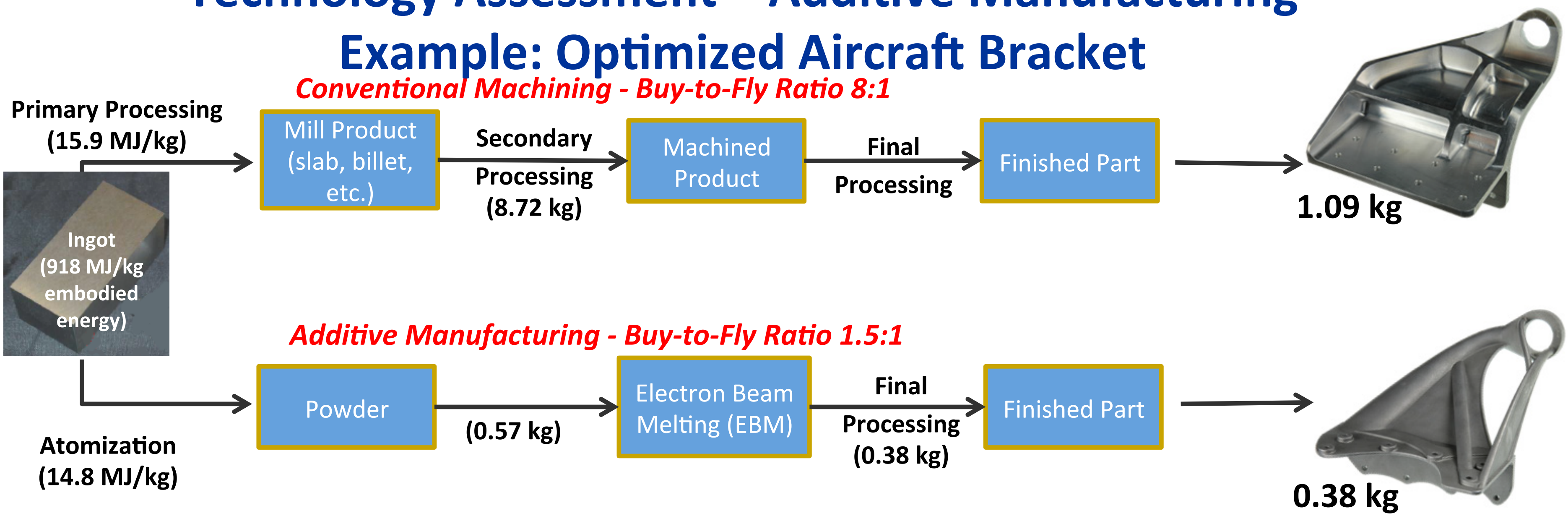
Technical Energy Savings Opportunities: Iron & Steel Industry 2015 Bandwidth Study – potential by major process area



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

Note: 1 quad = 1000 TBtu

Technology Assessment – Additive Manufacturing Example: Optimized Aircraft Bracket



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

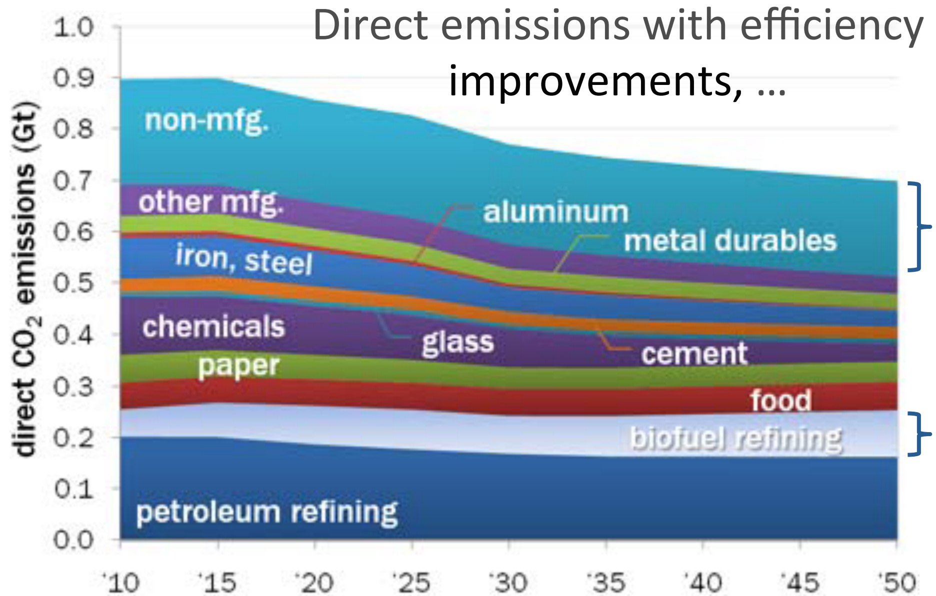
Process	Final part kg	Ingot consumed kg		Raw mat’l MJ	Manuf MJ	Transport MJ	Use phase MJ	End of life	Total energy per bracket MJ	Total energy per (120 brackets) MJ
Machining	1.09	8.72		8,003	952	41	217,949	Not considered	226,945	27.3 MM
EBM (Optimized)	0.38	0.57		525	115	14	76,282	Not considered	76,937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

Source: MFI and LIGHTEnUP Analysis

Key assumptions:

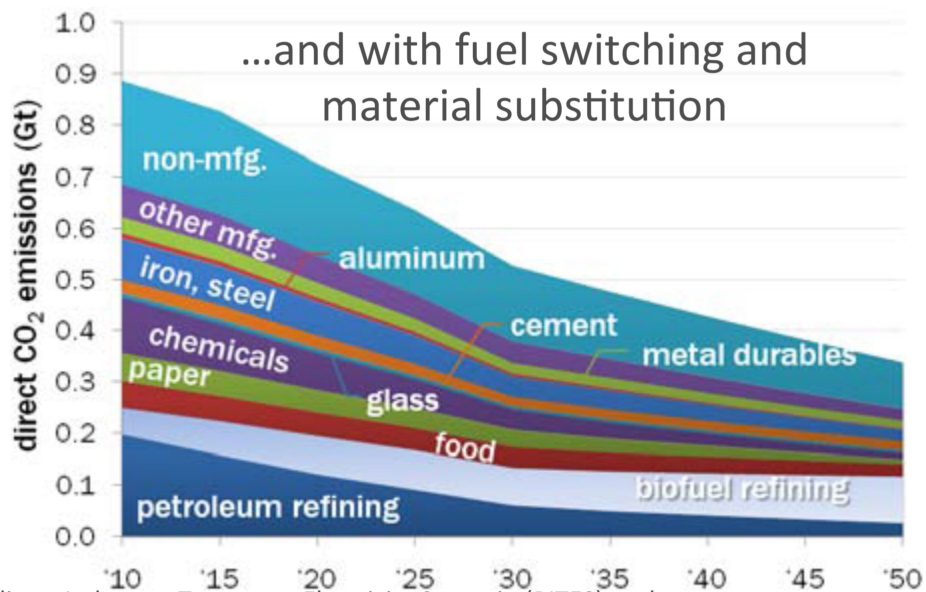
- Ingot embodied (source) energy 918 MJ/kg (255 kWh/kg)[5]
- Forging 1.446 kWh/kg[5] , Atomization 1.343 kWh/kg[6,7,8], Machining 9.9 kWh/kg removed[9], SLM 29 kWh/kg[10, 11], EBM 17 kWh/kg[10]
- 11 MJ primary energy per kWh electricity
- Machining pathway buy-to-fly 33:1[15], supply chain buy point = 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

Driver – Carbon Intensity



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

Carbon capture and sequestration (CCS) technologies offer additional opportunities

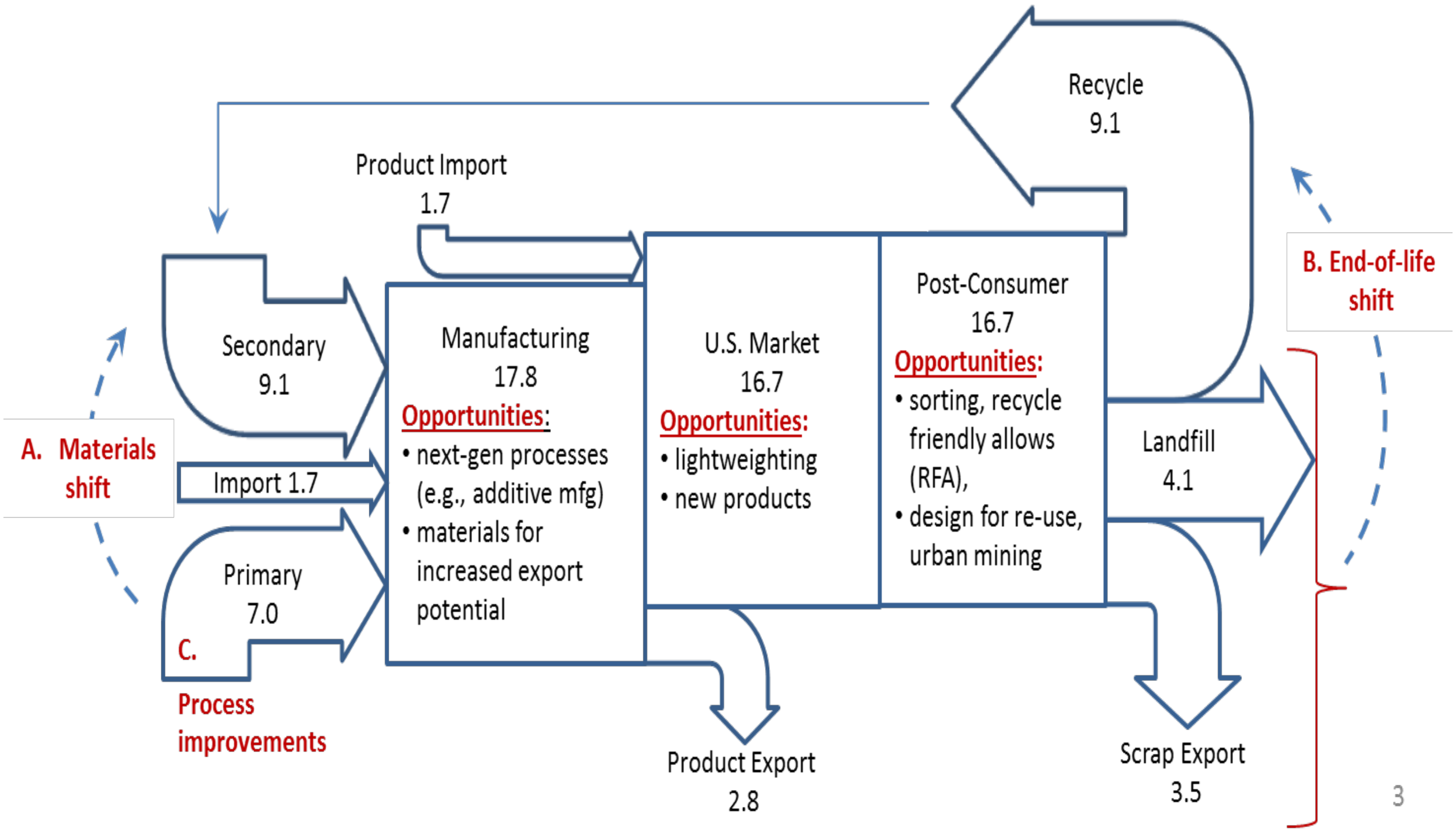


Example analysis using the Buildings, Industry, Transport, Electricity Scenario (BITES) tool

60

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.



Aluminum Materials Flows – U.S. and Canada, 2009 Billions of Pounds