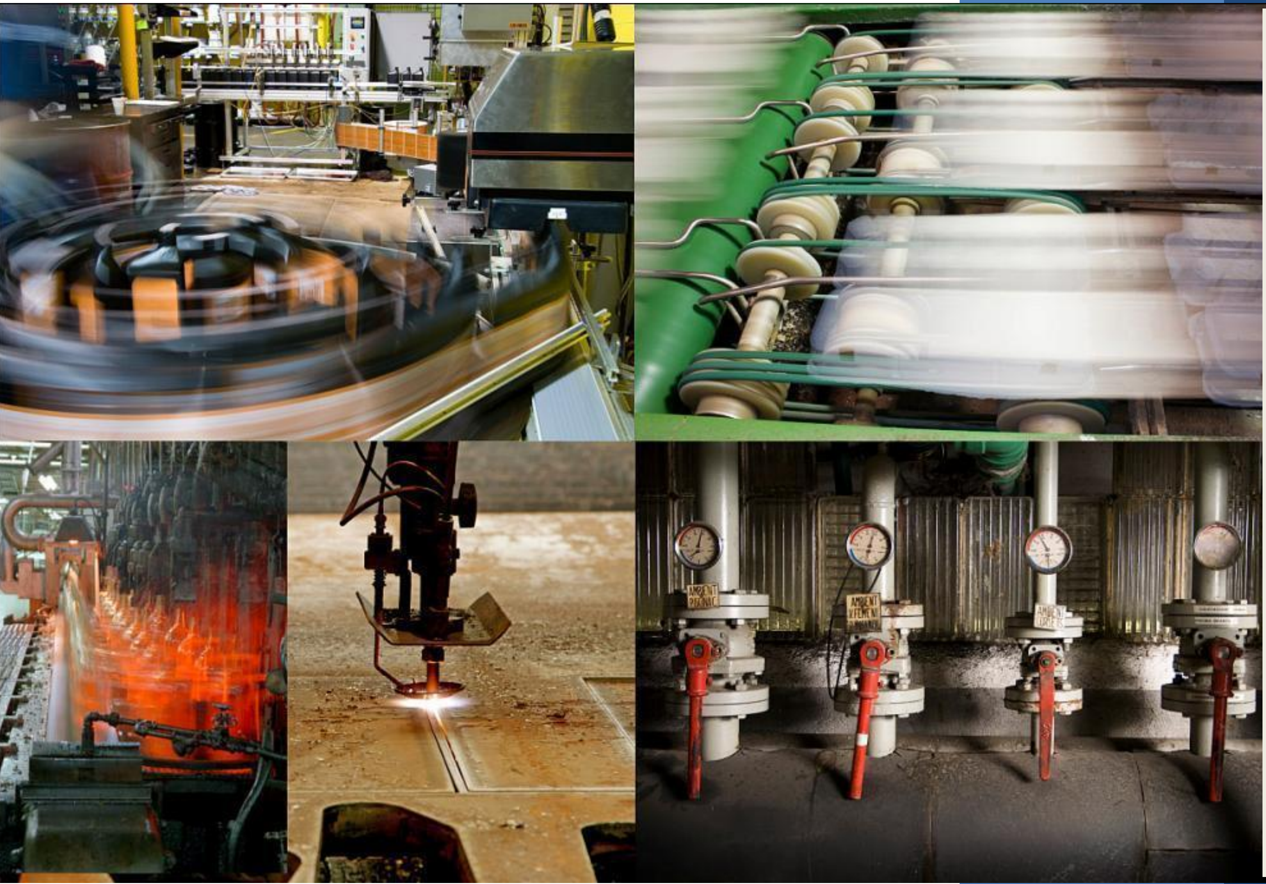
Office of Energy Efficiency & Renewable Energy
Advanced Manufacturing Office

U.S. DEPARTMENT OF ENERGY



ANL – Diane Graziano, Matt Riddle

LBNL – Arman Shehabi, William Morrow, Sarah Smith

ORNL – Sujit Das, Sachin Nimbalkar, Pablo Cassorla

NREL – Alberta Carpenter, Maggie Mann, Rebecca Hanes

Energetics – Sabine Brueske, Heather Liddell

An Overview of Strategic Analysis Efforts

Joe Cresko - Advanced Manufacturing Office, DOE

IACMI Annual Meeting

February 2, 2016

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

- Sets forth 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_MYPPInfo@ee.doe.gov by **March 15, 2017**.

Setting and Quantifying Goals

Success Indicators

- Demonstrate selected advanced manufacturing technologies and deploy practices that increase the rate of **energy intensity** improvement from business as usual (~1 % per year) to 2.5% per year.
- Develop advanced materials, manufacturing technologies, and targeted end use products with the potential to reduce **lifecycle energy impact** by 50% by 2025 compared to the 2015 state-of-the-art.

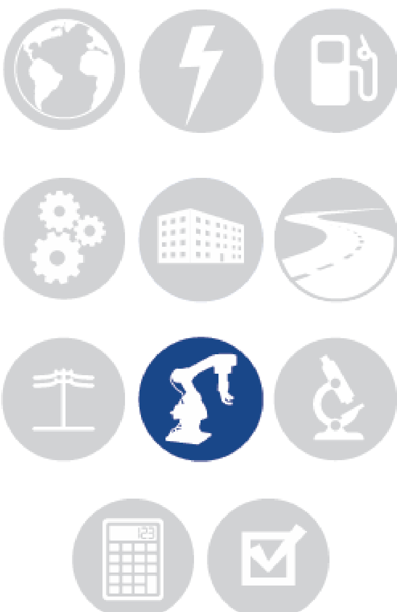
How do advances in composites manufacturing contribute?

DOE Quadrennial Technology Review (QTR) and AMO Multi-Year Program Planning (MYPP)

Quadrennial Technology Review 2015

Chapter 6: Innovating Clean Energy Technologies in Advanced Manufacturing

Technology Assessments



Additive Manufacturing

Advanced Materials Manufacturing

Advanced Sensors, Controls, Platforms and Modeling for Manufacturing

Combined Heat and Power Systems

Composite Materials

Critical Materials

Direct Thermal Energy Conversion Materials, Devices, and Systems

Materials for Harsh Service Conditions

Process Heating

Process Intensification

Roll-to-Roll Processing

Sustainable Manufacturing - Flow of Materials through Industry

Waste Heat Recovery Systems

Wide Bandgap Semiconductors for Power Electronics

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

Composite Materials– MYPP Targets

Supply-Chain Systems

Develop technologies that reduce embodied energy and manufacturing GHG emissions of carbon fiber reinforced polymer (CFRP) by 75% compared to 2015 current typical technology.

Production/Facility Systems

Reduce production cost of finished CFRP components for targeted clean energy applications by 50% compared to 2015 state-of-the-art technology.

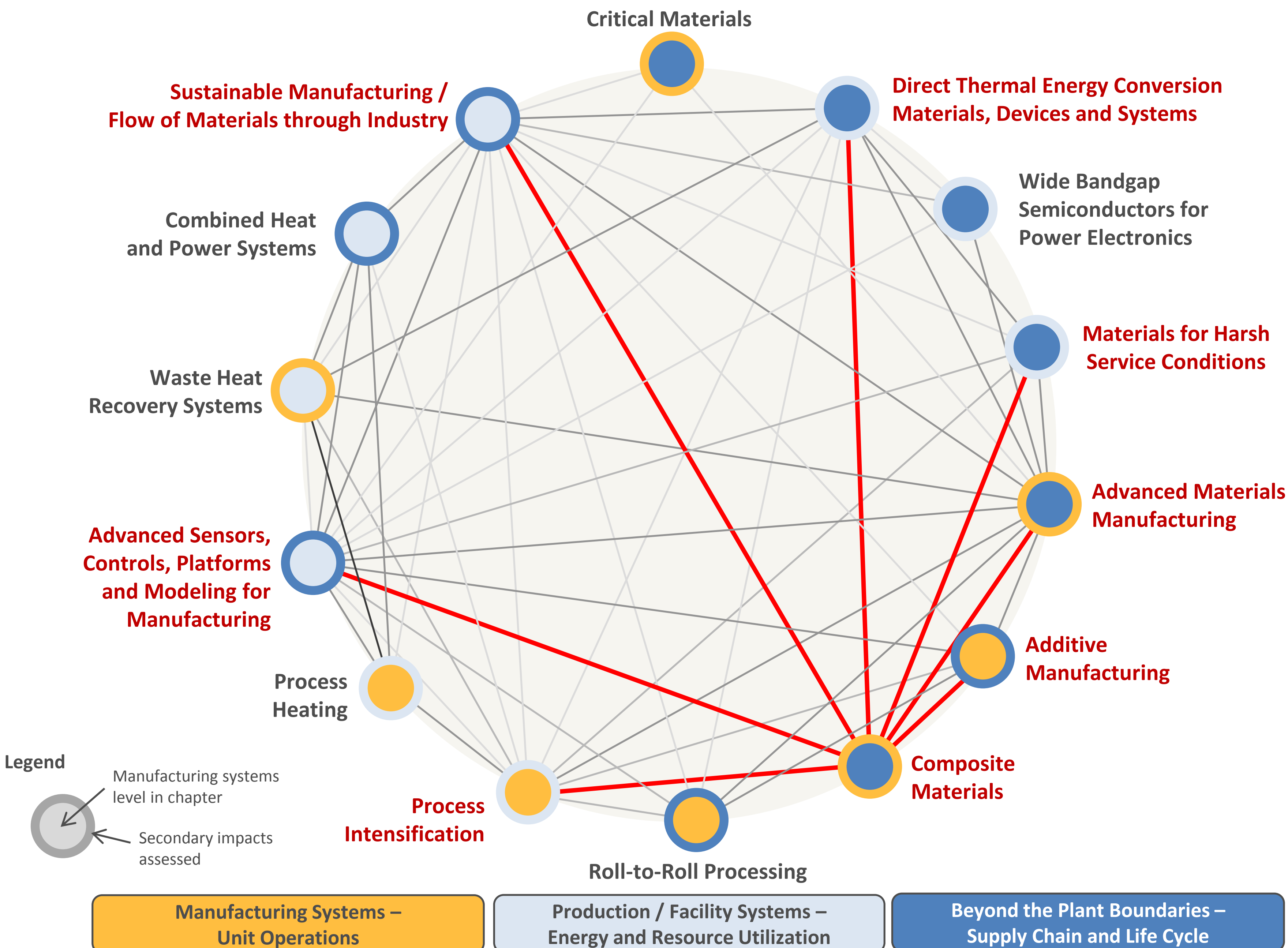
Manufacturing Systems/Unit Operations

Develop composite molding process with <90 second part-to-part cycle time for a structural component with surface area >0.5m^2

https://energy.gov/eere/amo/downloads/advanced-manufacturing-office-amo-multi-year-program-plan-fiscal-years-2017

QTR Technology Assessments - Manufacturing

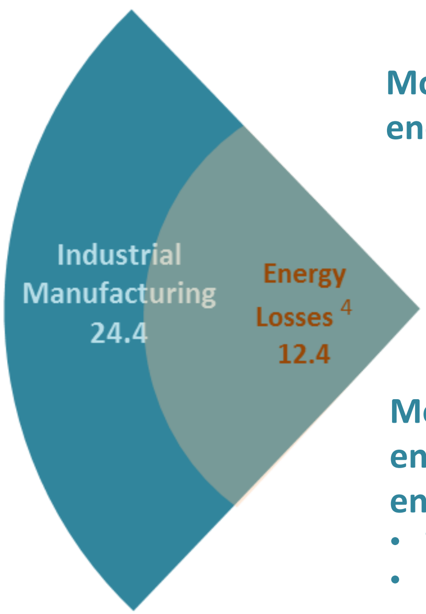
http://www.energy.gov/quadrennial-technology-review-2015



Opportunity Space for Manufacturing

- Improve the productivity and energy efficiency of U.S. manufacturing.
- Reduce life cycle energy and resource impacts of manufactured goods.

Manufacturing Goods

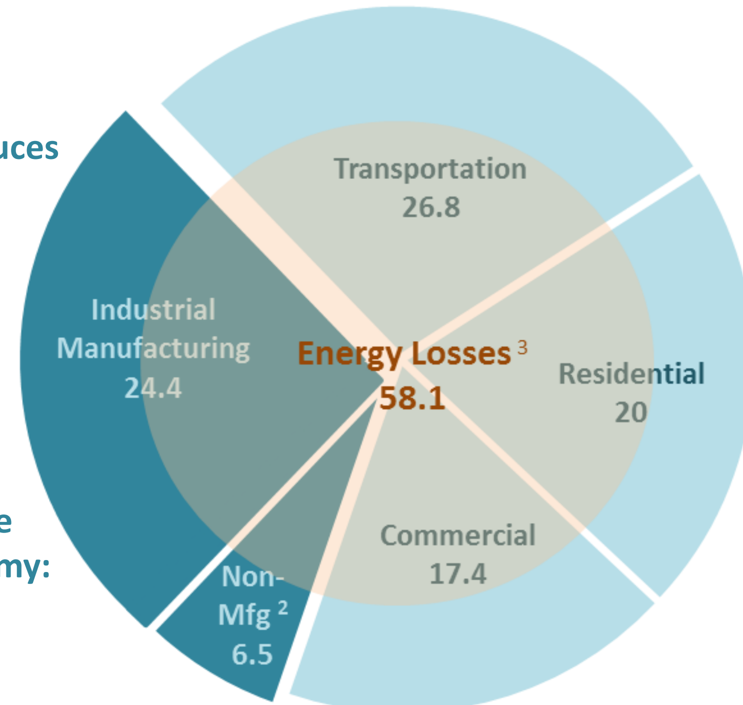


More efficient manufacturing reduces energy losses.

More efficient manufacturing enables technologies that improve energy use throughout the economy:

- Transportation
- Buildings
- Energy Production and Delivery

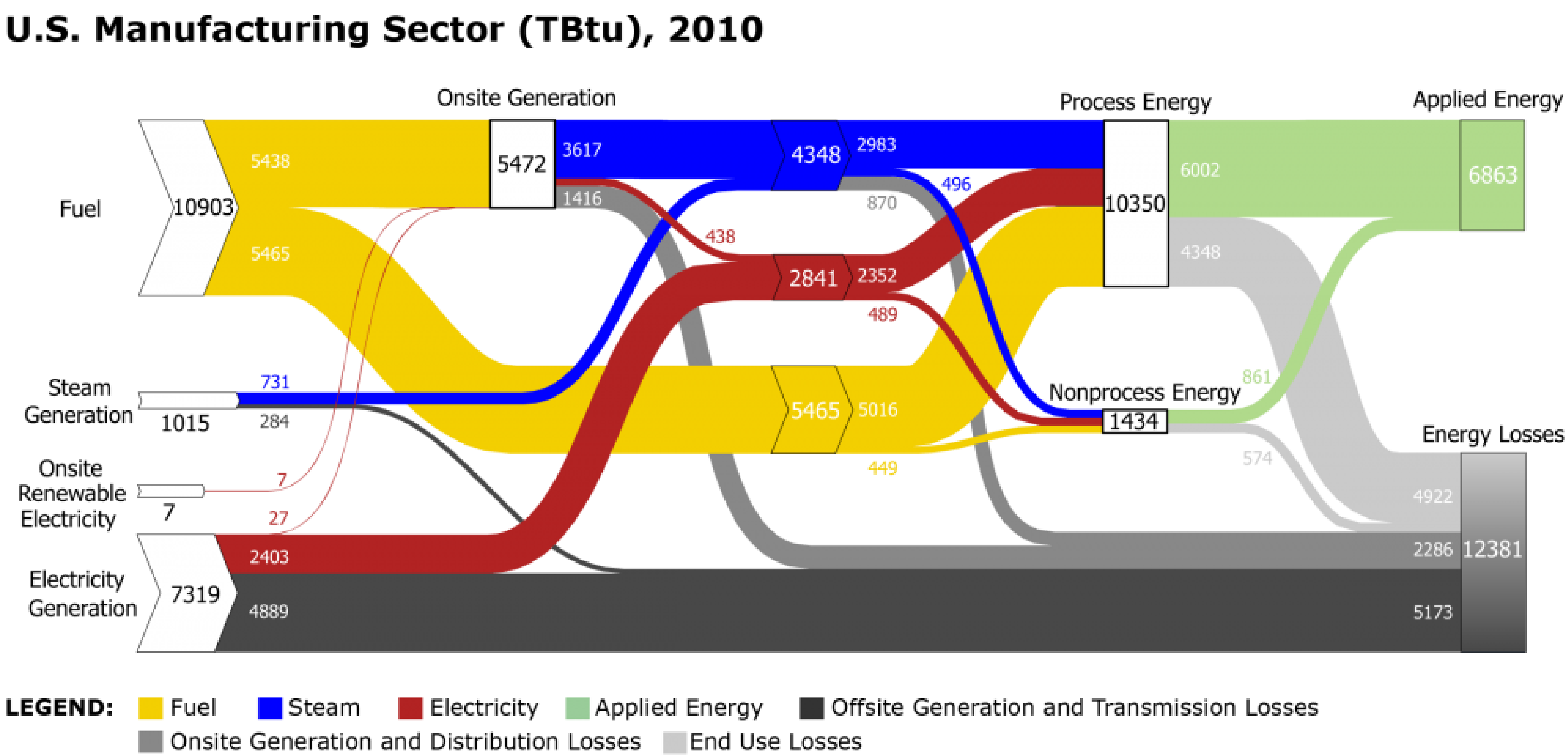
Use of Manufactured Goods



U.S. Energy Economy by Sector
95.1 quadrillion Btus, 2012 [1]

[1] Energy consumption by sector from EIA Monthly Energy Review, 2012
[2] Industrial non-manufacturing includes agriculture, mining, and construction
[3] US economy energy losses determined from LLNL Energy Flow Chart 2012 (Rejected Energy)
[4] Manufacturing energy losses determined from DOE AMO Sankey/Footprint Diagrams (2010 data)

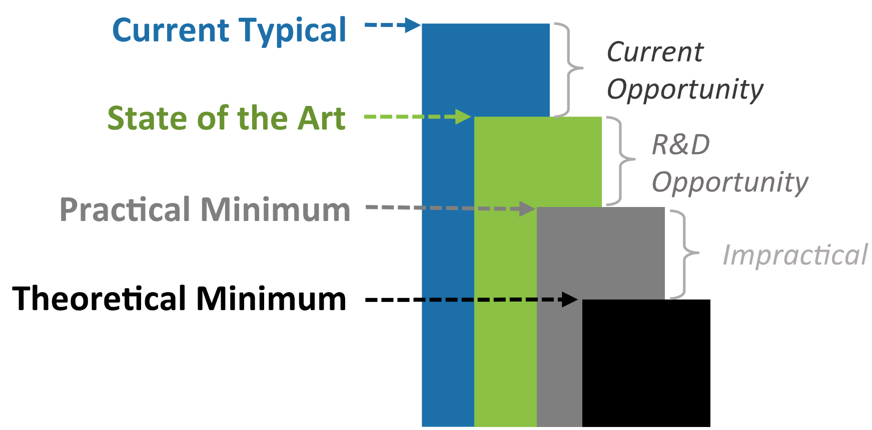
Flow of Energy Through Manufacturing



Note: 1 quad = 1,000 TBtu

Energy bandwidth studies can be a useful tool for assessing energy savings opportunities in 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:

Current Typical (CT)	State of the Art (SOA)	Practical Minimum (PM)	Thermodynamic Minimum (TM)
Determined from a literature review and stakeholder outreach, based on current typical manufacturing processes in the U.S.	Determined from a literature review and stakeholder outreach, based on the most energy-efficient technologies and practices available worldwide	Modeled based on plausible energy savings from identified R&D technologies under development worldwide	Calculated analytically using a Gibbs free energy approach assuming ideal conditions

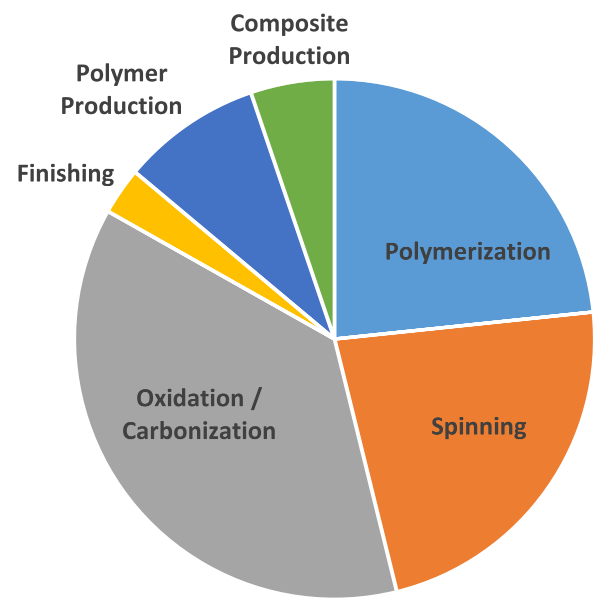
Current Typical (CT) energy intensities assume carbon fiber production from a polyacrylonitrile (PAN) precursor

- **Data are based on the PAN process, which represents approximately 98% of U.S. commercial production by weight***
- **Oak Ridge National Laboratory provided process energy data from their facility, which were assumed to represent current typical manufacturing**

Manufacturing Process	CT (Btu/lb)
Polymerization	85,710
Spinning	83,740
Oxidation / Carbonization	135,900
Finishing	10,740
Polymer Production†	31,940
Composite Production‡	9,570

Overall: 183,580 Btu/lb

(based on a 50 wt% fiber fraction)



† Assumes epoxy. For other polymers, see conference paper.
‡ Assumes autoclave forming. For other production processes, see conference paper.

* Reference: "Carbon fibre: investing cautiously." 2009. *JEC Composites Magazine,* 51: 18–19.

Results presented are draft data; studies are currently being peer reviewed.

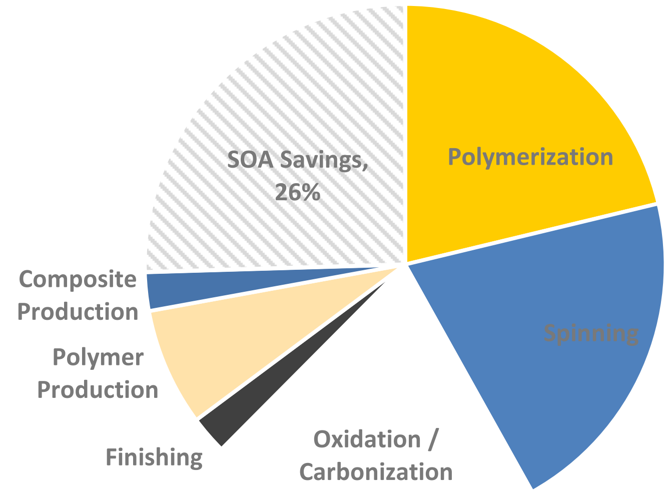
State-of-the Art (SOA) values are also based on the PAN process, but with energy savings from SOA technologies

- SOA energy intensity data for carbon fiber production were not available from literature sources, so an estimate was made by applying assumed energy savings for applicable SOA technologies to the CT intensity
- State-of-the-art technologies considered included carbon fiber recycling, motor re-sizing, improved control systems, and waste heat recovery.

Manufacturing Process	SOA (Btu/lb)
Polymerization	77,990
Spinning	75,820
Oxidation / Carbonization	75,520
Finishing	8,650
Polymer Production	26,880
Composite Production	4,400

Overall: 136,830 Btu/lb

(based on a 50 wt% fiber fraction)



Full pie represents CT energy intensity.

† Assumes epoxy. For other polymers, see conference paper.
‡ Assumes resin transfer molding. For other production processes, see conference paper.

Results presented are draft data; studies are currently being peer reviewed.

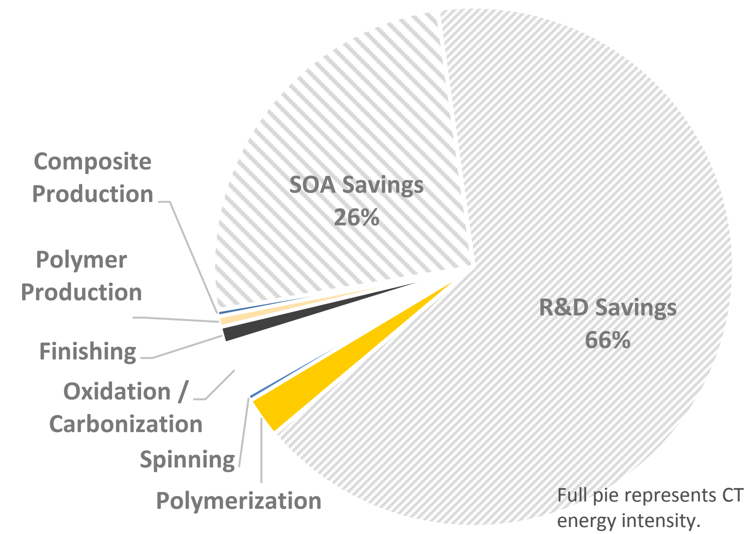
Practical Minimum energy intensities are hypothetical, based on assumed savings from applied R&D technologies

- **A review of applied R&D activities was conducted to identify energy-saving technologies and to estimate plausible energy savings**
- **Practical Minimum technologies considered included an alternative precursor process, microwave carbonization, recovery and recycling of the polymer matrix, and an increased rate of carbon fiber recycling.**

Manufacturing Process	PM (Btu/lb)
Polymerization	9,210
Spinning	1,430
Oxidation / Carbonization	12,620
Finishing	3,880
Polymer Production	2,420
Composite Production	710

Overall: 15,490 Btu/lb

(based on a 50 wt% fiber fraction)

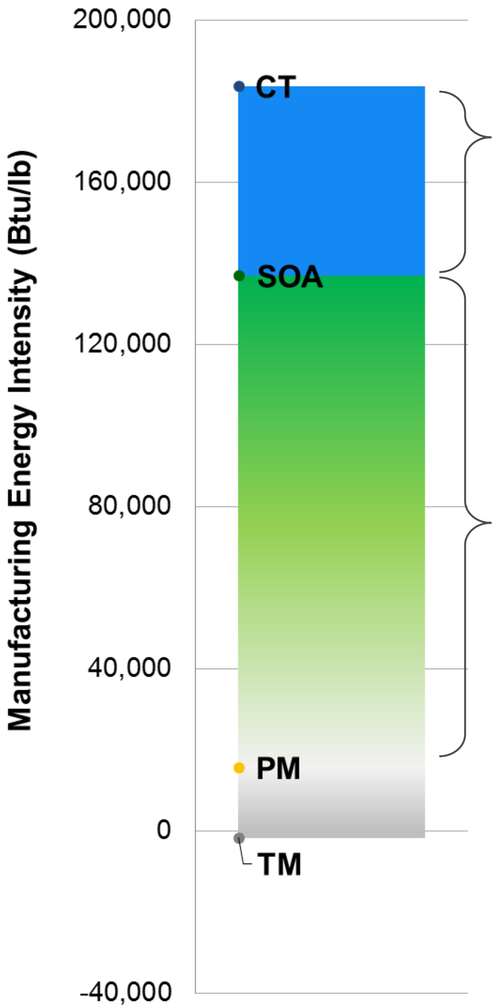


† Assumes polypropylene. For other polymers, see conference paper.

‡ Assumes injection molding. For other production processes, see conference paper.

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



CFRP Composites: Energy Bandwidth Summary

Current Opportunity

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

SOA Technology Examples:

- motor re-sizing and/or variable speed drives
- waste heat recovery
- moderate carbon fiber recycling or down-cycling

R&D Opportunity

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

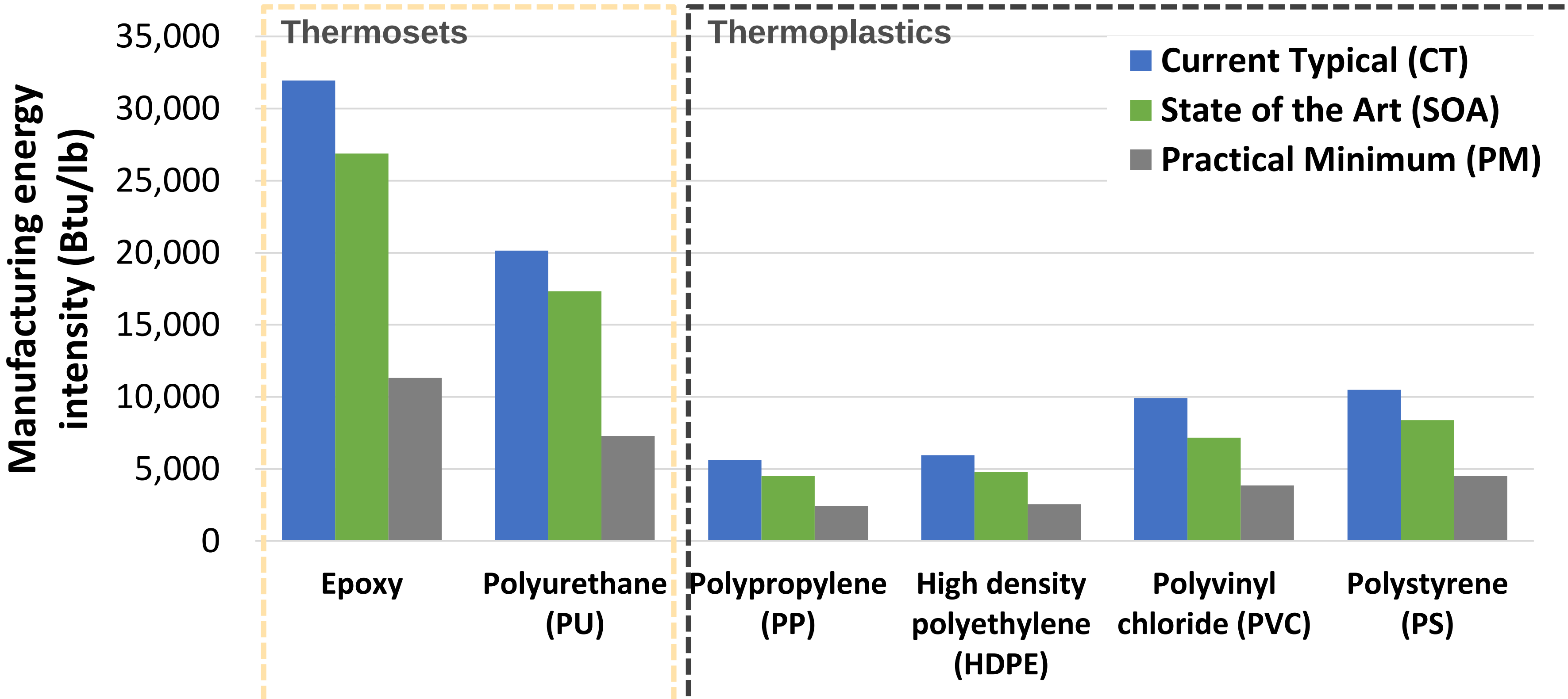
R&D Technology Examples:

- 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.

The choice of matrix polymer also represents an opportunity for energy savings in composites

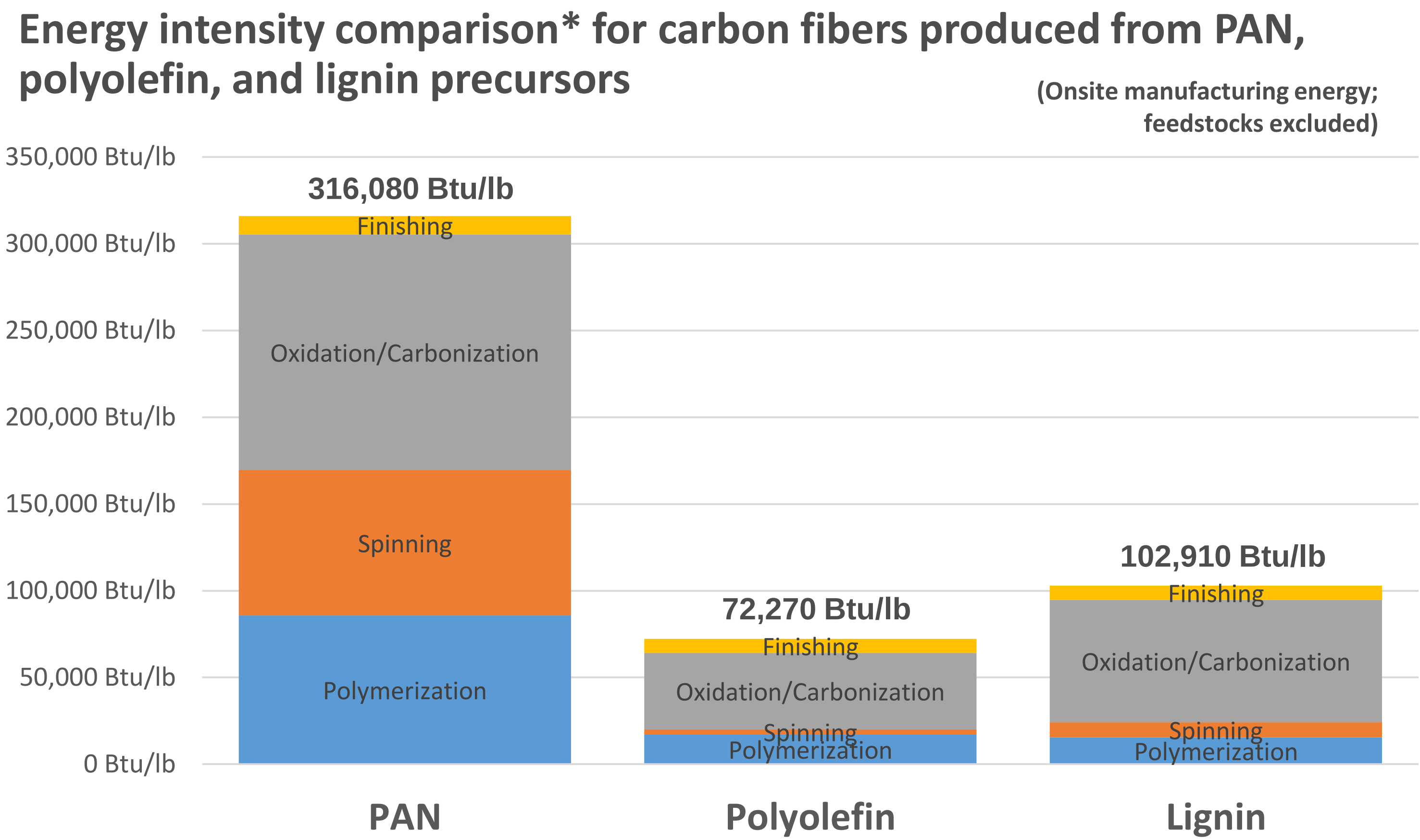
- Thermoplastic resins have much lower energy intensity than conventionally used thermoset resins (such as epoxy)
- Thermoplastic composites are also easier to recycle because the polymer can be separated and recovered simply by melting



(Onsite manufacturing energy; feedstocks excluded)

Results presented are draft data; studies are currently being peer reviewed.

Major energy savings for carbon fibers could be realized through lower-energy-intensity precursor materials

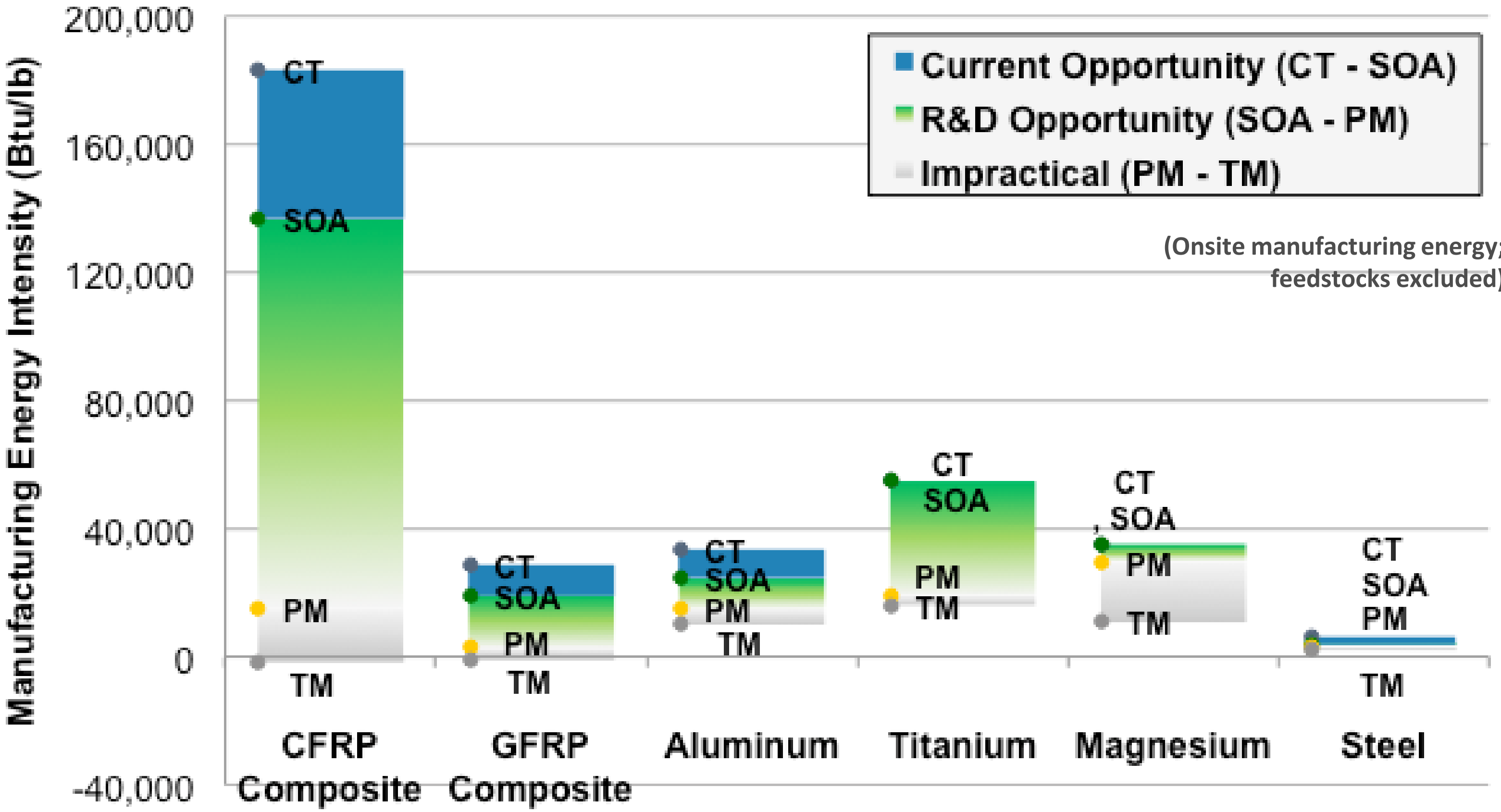


Carbon fiber production from novel precursors (including materials that may not be in use as precursors today) represents a key technology development opportunity for R&D.

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

Results presented are draft data; studies are currently being peer reviewed.

With R&D advances, carbon fiber composites could compete with incumbent materials on an energy intensity basis



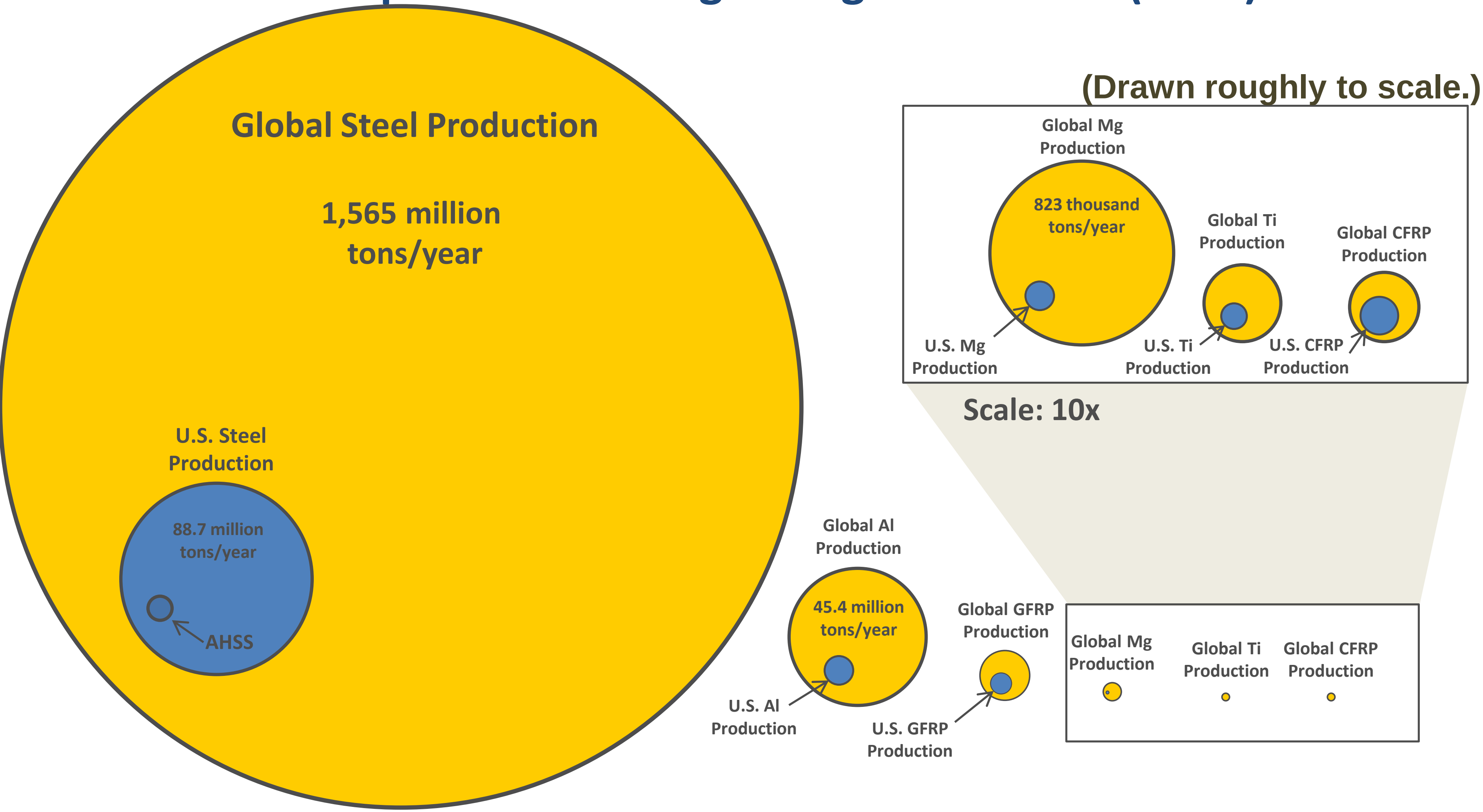
High manufacturing energy use drives costs up and reduces competitiveness with incumbent materials

CFRP composites have the highest manufacturing energy intensity, they also have the largest energy savings opportunity.

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

Results presented are <u>draft data</u>; studies are currently being peer reviewed.

Global and U.S. production of lightweight materials (2010)



Steel: Global 1,565 million tons/year; U.S. 88.7 million tonnes/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

Supply Chain / Value Chain Analysis

Manufacturing location decisions

Cost of mfg in different locations, by cost category (e.g., labor, capital)

Supply chain analysis

Raw materials, Production & capacity by mfr and location

Economic competitiveness

Examples: labor availability, reliability of grid, currency, quality

- What is the global & regional supply chain?
- How does competitiveness align with roadmaps?
- How is competitiveness changing?
- What are competitiveness drivers?

The Clean Energy Manufacturing Analysis Center (CEMAC), sponsored by the U.S. Department of Energy (DOE), provides objective analysis and up-to-date data on global supply chains and manufacturing competitiveness of advanced energy technologies.

Oak Ridge National Laboratory · NREL National Renewable Energy Laboratory · Pacific Northwest National Laboratory · Berkeley Lab · Idaho National Laboratory · Argonne National Laboratory · Sandia National Laboratories

Website: www.manufacturingcleanenergy.org

Competitiveness Analysis of Global Carbon Fiber Composites Manufacturing Supply Chain – Wind, Auto, CGS, Aero

CEMAC Clean Energy Manufacturing Analysis Center

Global Carbon Fiber Composites Supply Chain Competitiveness Analysis

Sujit Das, Josh Warren, and Devin West
Energy and Transportation Science Division, Oak Ridge National Laboratory

Susan M. Schexnayder
The University of Tennessee, Knoxville

OAK RIDGE National Laboratory

CEMAC is operated by the Joint Institute for Strategic Energy Analysis for the U.S. Department of Energy's Clean Energy Manufacturing Initiative.

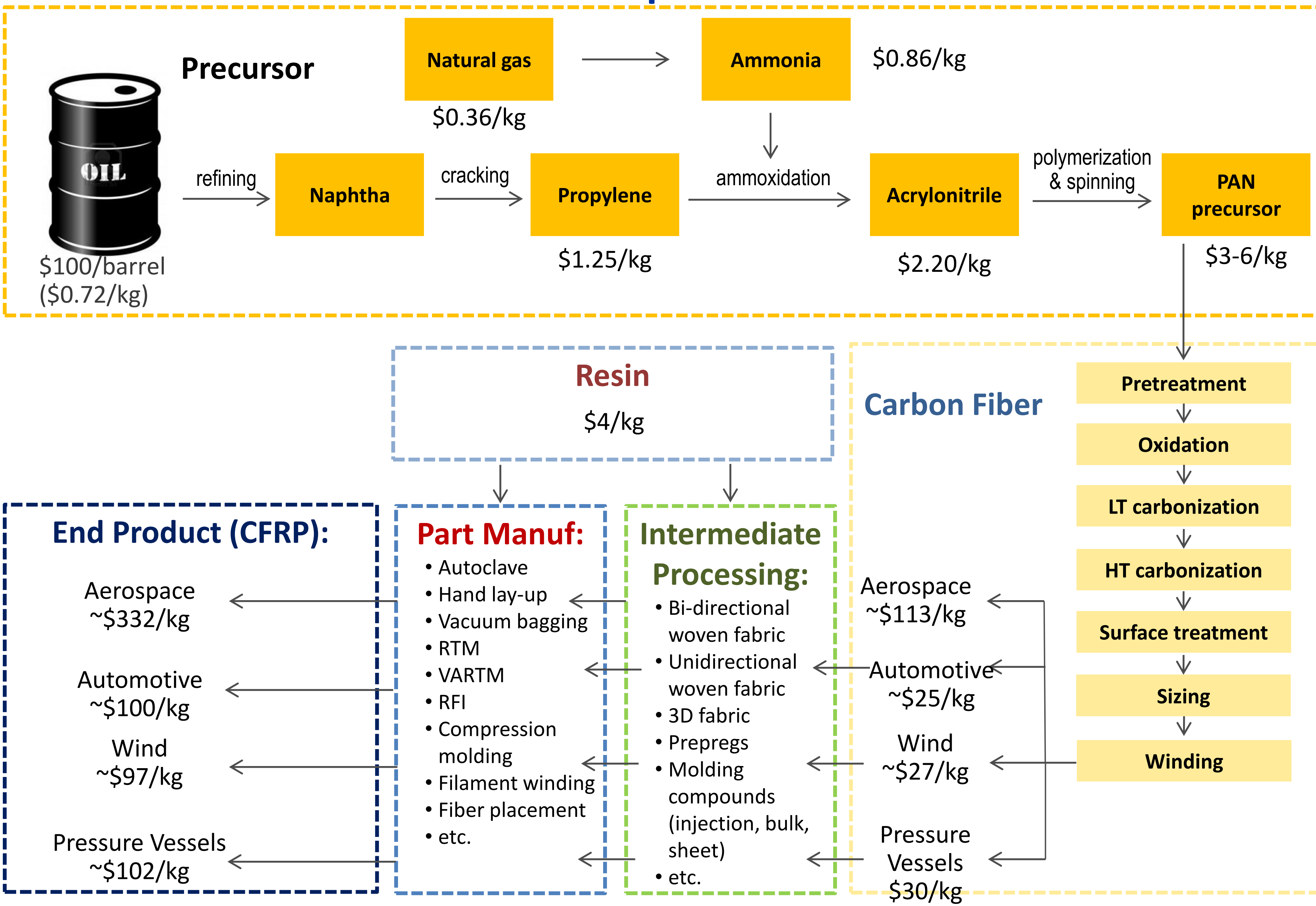
Technical Report
ORNL/SR-2016/100 | NREL/TP-6A50-66071
May 2016

Contract No. DE-AC36-08GO28308

- Potential major application areas and driving force behind projected growth
- Industry value chain by major supply chain level
- Current* and future forecasts of supply and demand by four major markets based on available market forecasts
- Existing trade flow and balance
- Existing supply chain and partnerships developed
- Industry perceptions of issues and opportunities for growth
- Current status of industry competitiveness

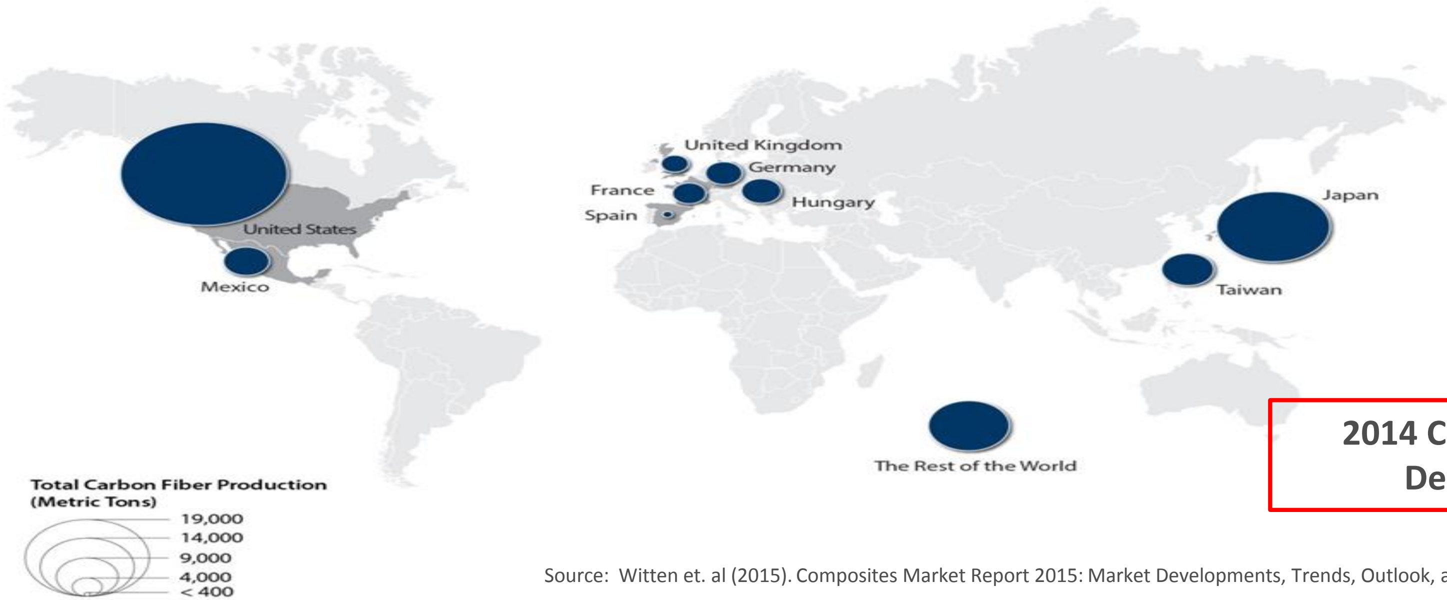
http://www.nrel.gov/docs/fy16osti/66071.pdf

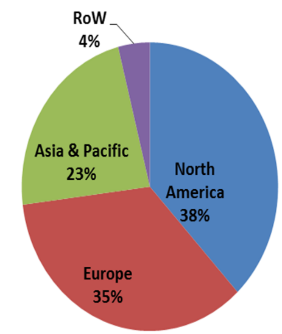
Carbon Fiber Composites Value Chain



Source for CF and CFRP prices: (2)

Carbon Fiber Manufacturing Capacity Increasing Beyond US





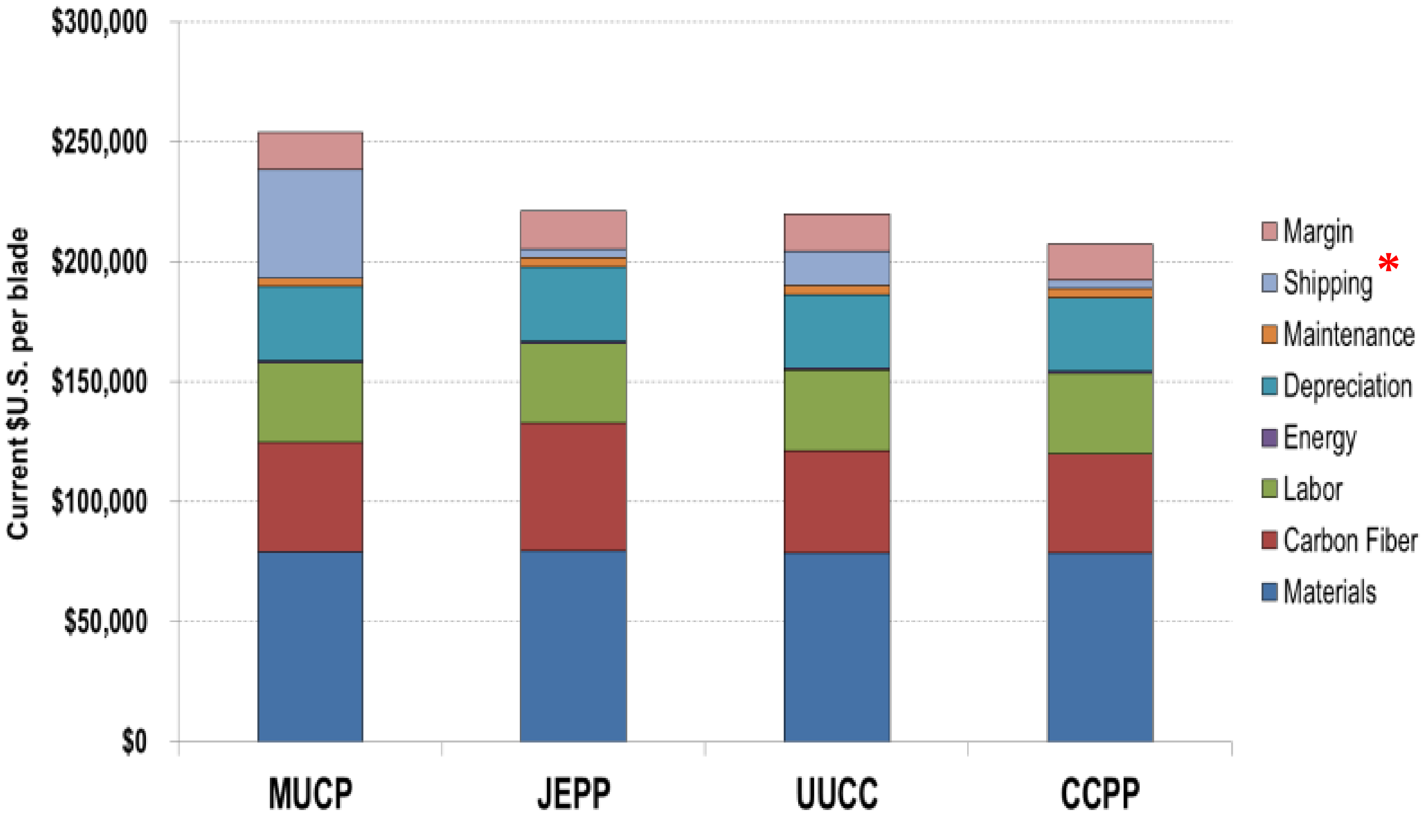
2014 Carbon Fiber Composites Demand =105 ktonnes

Source: Witten et. al (2015). Composites Market Report 2015: Market Developments, Trends, Outlook, and Challenges, Sept.

- CF manufacturing sites concentrated in three main regions of total 125 ktonnes capacity vs 53 ktonnes demand in 2014:
  - North America (31% of global capacity – *Hexcel* is the only U.S. Ownership with ~6% of global capacity)
  - Highly concentrated industry with ~88% of global fiber capacity held by ten leading manufacturers (*Toray* the leading producer with 36% of total global capacity with *Zoltek* acquisition)
  - Japan and Europe with about 20%, but *Japan* with the largest worldwide ownership
- China, Russia, and S. Korea are the new market entrants -- ~7 ktonnes/y in China but faced with technology needs and final product quality challenges

Competitiveness Analysis of Global Carbon Fiber Composites Manufacturing Supply Chain

- 61.5m Carbon Fiber Spar Cap Blade shipping cost is detrimental to the final wind energy blade manufacturing supply chain (Fiber → Fabric → Blade → Turbine/Generation) competitiveness



MUCP: Mexico → US → Central US → US Offshore

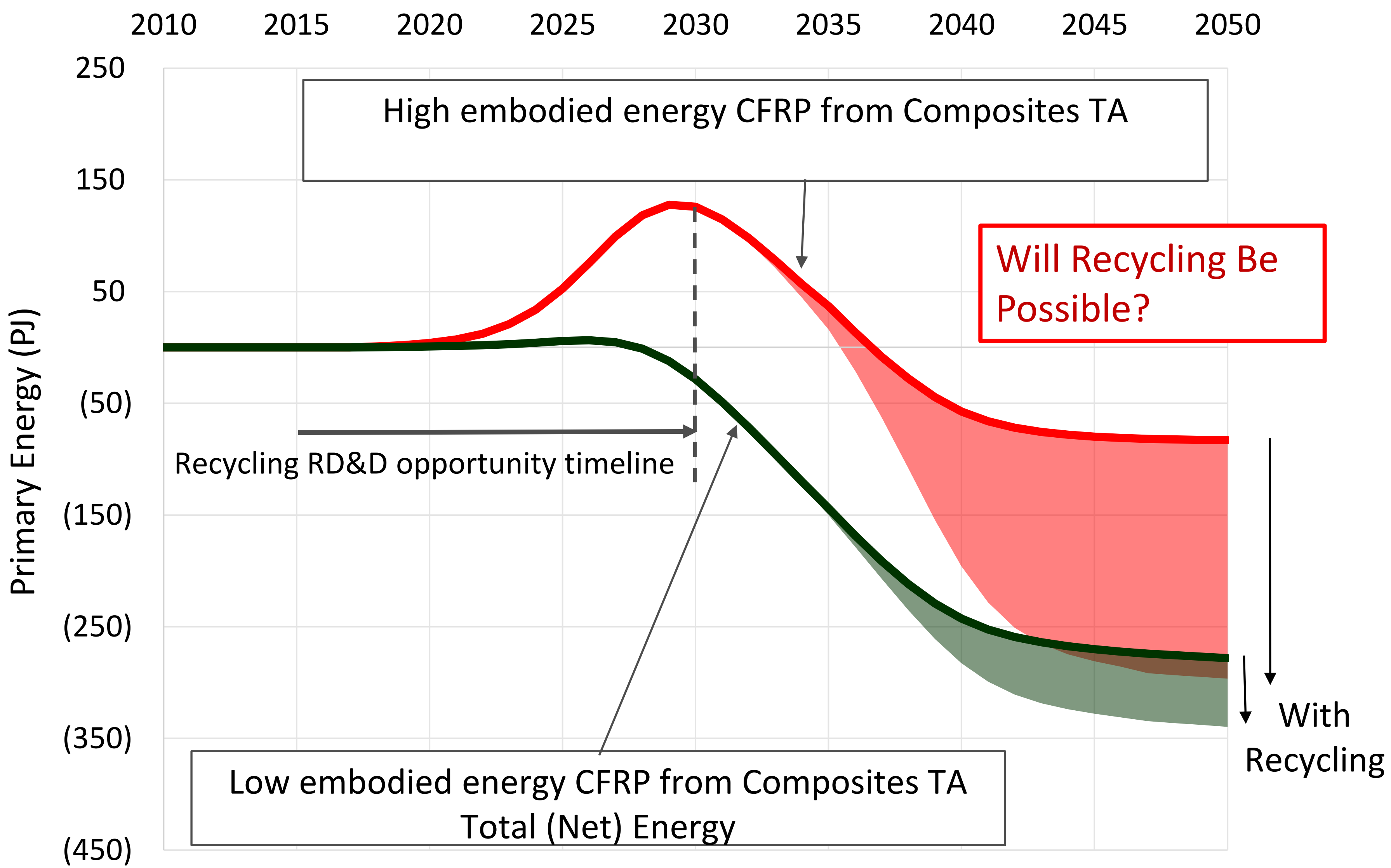
JEPP: Japan → UK → US Offshore → US Offshore

UUCC: US → US → Central US → Central US

CCPP: China → China → US Offshore → US Offshore

*Shipping includes only final blade shipping cost
Fiber/Fabric shipping cost included under "Materials" -- <1% of total material cost

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



https://energy.gov/sites/prod/files/2016/05/f31/QTR2015-6L-Sustainable-Manufacturing.pdf

Thank you.

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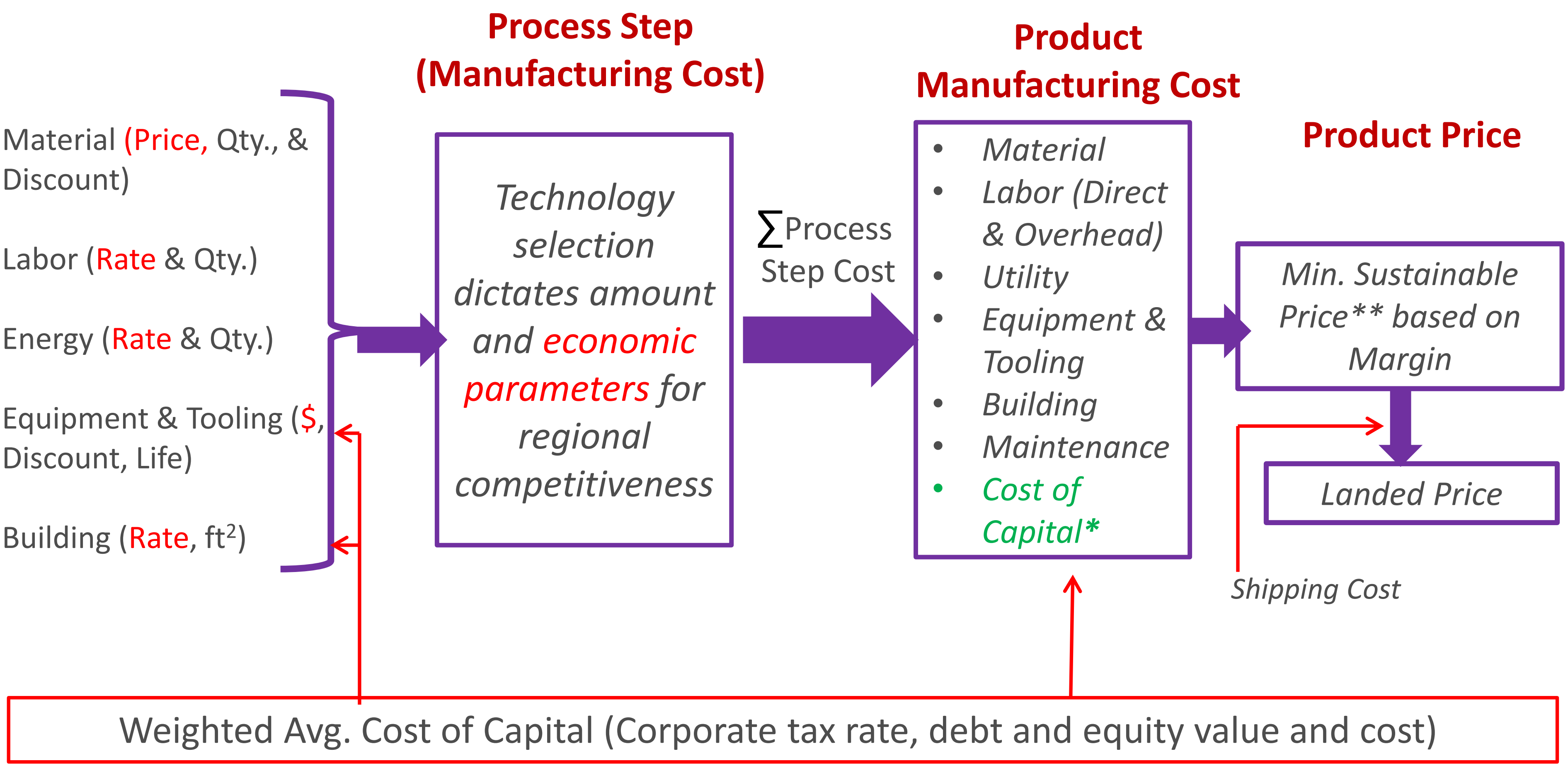
Back-up Slides

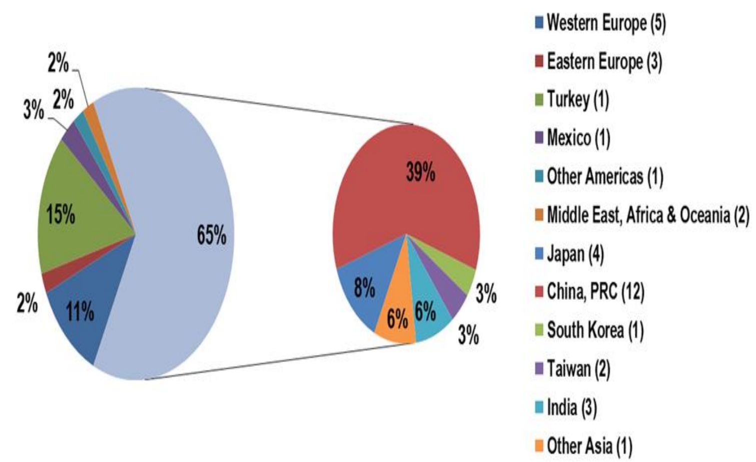
Methodology - Landed Product Cost Determines Regional Supply Chain Competitiveness

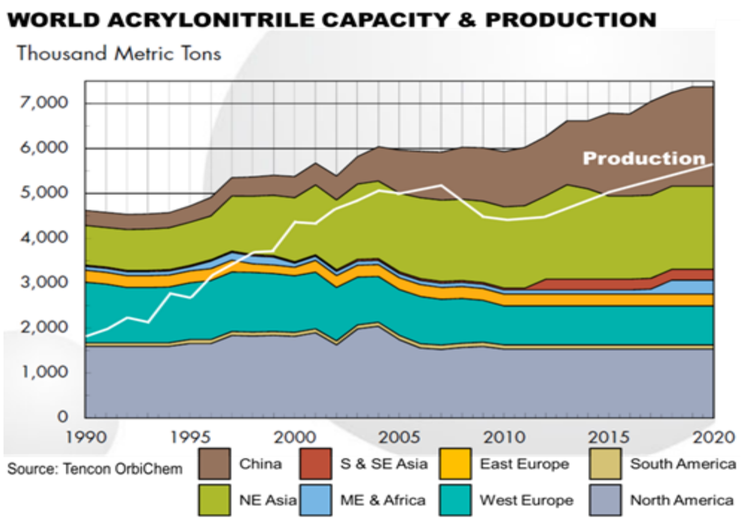


Low Cost Heavy Tow Textile Acrylic Carbon Fiber – Supply Chain Competitiveness

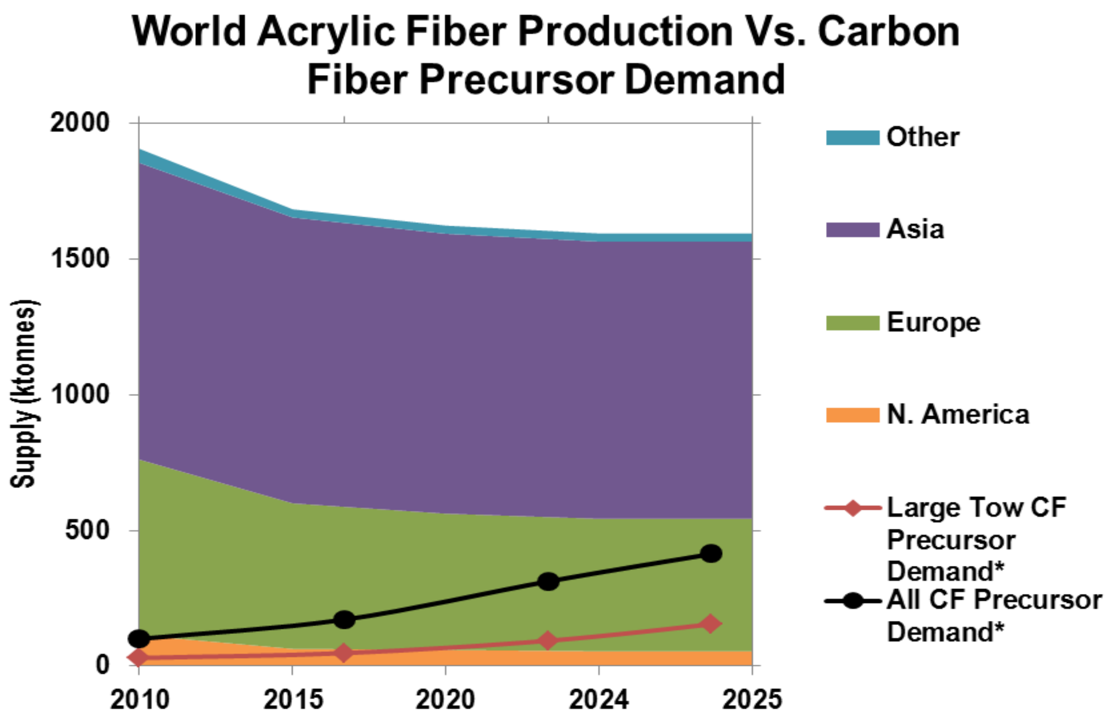
- Major foreign precursor manufacturers (Far East, Turkey, India, Mexico, and South America) – limited in Europe (Dralon and Fisipe) – 65% in Asia with 39% in China; Aksa (Turkey) leads today
- US activities limited to *spinning* acrylic tow and staple into yarns (low cost Chinese imports) -- DuPont was the lead (Orlon trademark) but no production since 2006
- Acrylic fiber share of total acrylonitrile demand continues to decline (advances in alternative low-cost fibers in a mature textile market)
- Only three existing major acrylic fiber producers manufacture carbon fiber (AKSA, FISIPE, and Mitsubishi Rayon)
- Consistent overcapacity for both acrylonitrile and acrylic fiber – (North America, China, and NE Asia are the major acrylonitrile producers to meet demand from China, ME & Africa)

2015 Worldwide Acrylic Production = 1.8M Metric Tonne

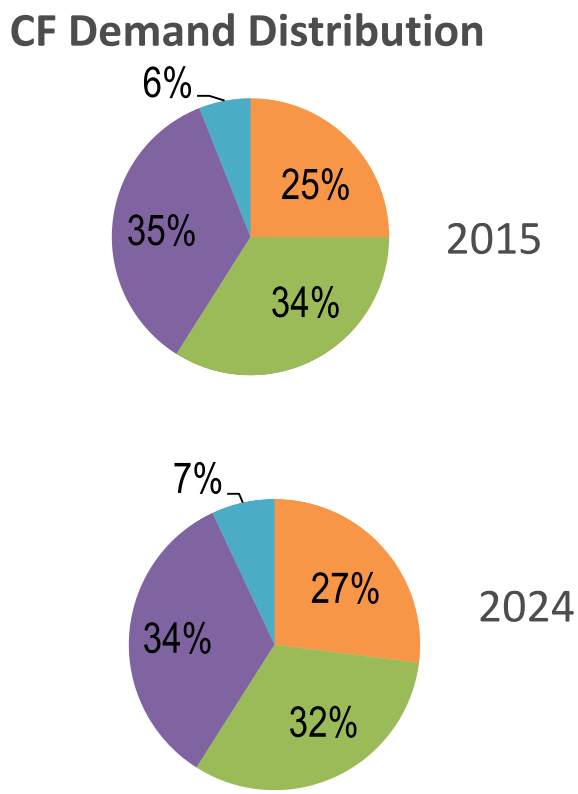




Textile Acrylic Fiber Supply vs. CF Precursor Demand



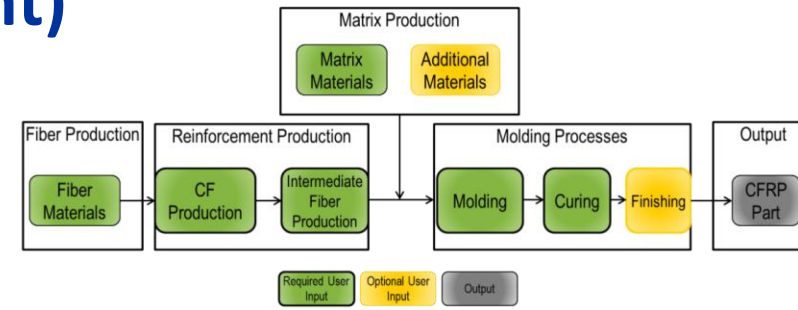
Sources:
Acrylic: Global Fibrer Production, PCI Wood Mackenzie 2016
CF: Red, C. (2015). 2015 Global Markets for Carbon Fiber Composites: Adaptations to High Growth and Market Maturity



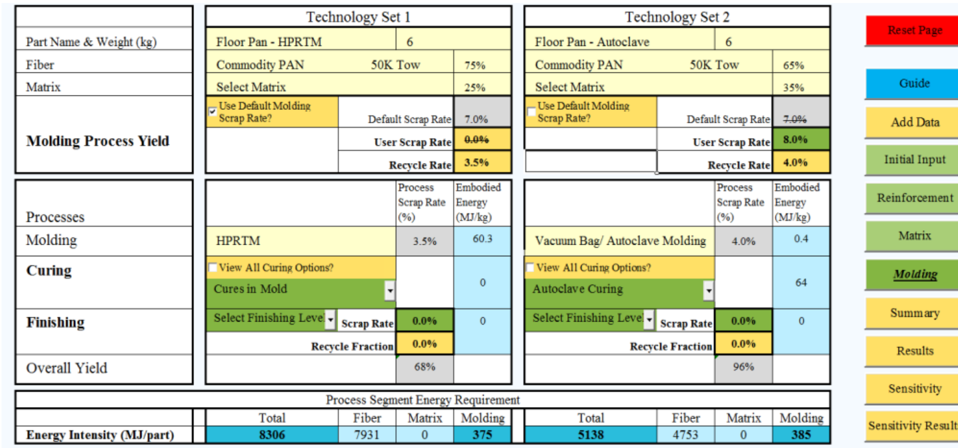
- Overall, a declining acrylic fiber production trend while CF demand growth continues (but a significantly smaller share even for projected higher total CF precursor demand)
- N. America and Europe contributes to a major share of total CF demand contrary to a limited projected acrylic fiber supply from these two regions

CFRP Manufacturing Energy Estimator Tool (under development)

- Evaluates *embodied* energy intensity of CFRP product manufacturing for several technology pathways via major manufacturing steps



- Contains manufacturing energy data by major manufacturing steps for various technology pathways (add-on capability for new technology pathways)



- Allows to examine the potential pathways by specific manufacturing steps for total *embodied* manufacturing energy reduction opportunity

50% Reduction in Fiber Energy
↓
44% Reduction in Total Energy