Prospective Life Cycle and Technology Analysis

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DOE-AMO Analysis Summary – ANL/NU

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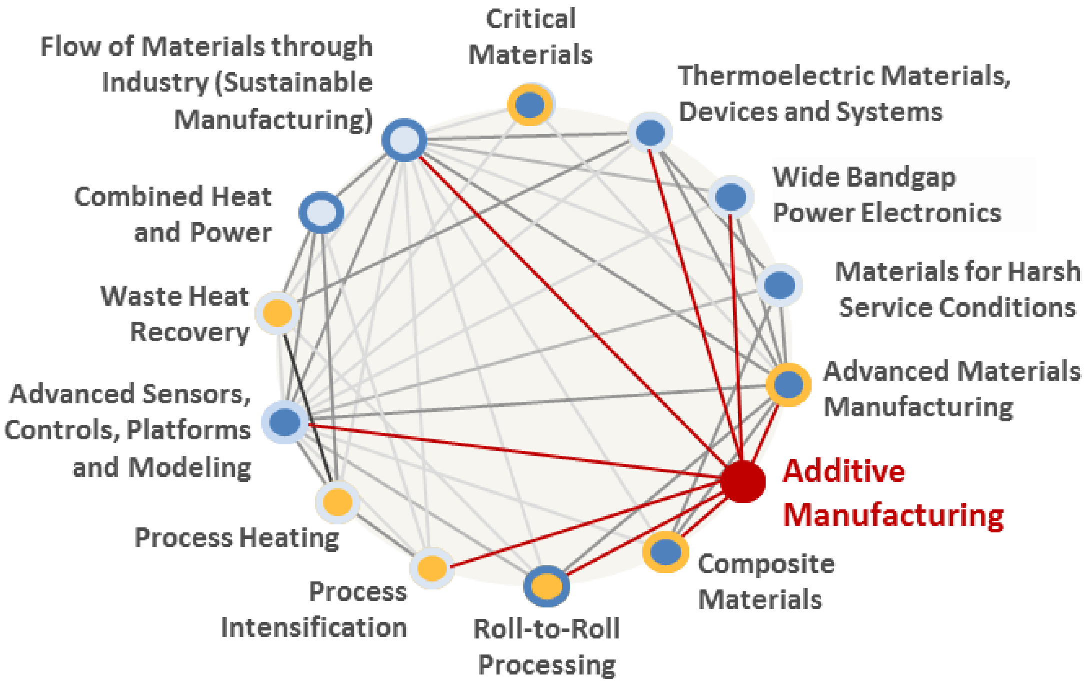
- Quantifying, from a life-cycle perspective, the ***enabling effects*** of advanced manufacturing in achieving AMO's mission for energy savings across the economy
- Assessing net energy, emissions, and economic effects over different scales of time and space
- Providing robust early information on the drivers and potentials of advanced manufacturing, rooted in deep technical understanding of emerging applications
- Analyzing key emerging technologies and trends: vehicle lightweighting, wide band gap materials, **additive manufacturing**, natural gas to chemicals, and distributed manufacturing

Additive Manufacturing

- **Motivation:** Resource efficiency, flexibility, and modular design of additive manufacturing could be transformative, enabling competitiveness and distributed manufacturing

- **R&D challenges**
  - Low throughput
  - Residual stresses
  - Repeatability
  - Surface quality
  - High cost



- AM industry: 29% growth in the last three years - predicted to be > 30% CAGR through 2020

- **Aircraft industry case study** - key early adopter (12.3% of AM industry)

Additive manufacturing – model framework and methodology

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Framework rooted in deep technical understanding of AM process and markets

Data source

1 Aircraft component selection

Factor:
- Material use
- Geometric volume
- Load
- Complexity

2 Replaceable mass estimation

Major systems:
- Interior
- Engine
- Propulsion
- Nacelle
- Body

3 Cradle to gate life-cycle inventory model

Materials	Manufacturing	Transportation
Metals: • Steel, Al, Ti, Ni alloys Forms: • Ingot • Powders	CM process: • Casting • Machining AM process: • SLM, EBM, DMLS	Mode: • Road • Air • Ship • Rail

4 Fleet-wide temporal adoption

- Availability starts at 2019-2034
- Slow, mid and rapid adoption scenarios

5 Fleet-wide fuel consumption

- 100kg weight reduction saves 13.4-20.0 TJ of fuel over a 30 year life of an airplane

Rigorous modeling of conventional and emerging metals manufacturing technologies

Technology adoption and stock turnover modeling

Cradle-to-gate life cycle impacts

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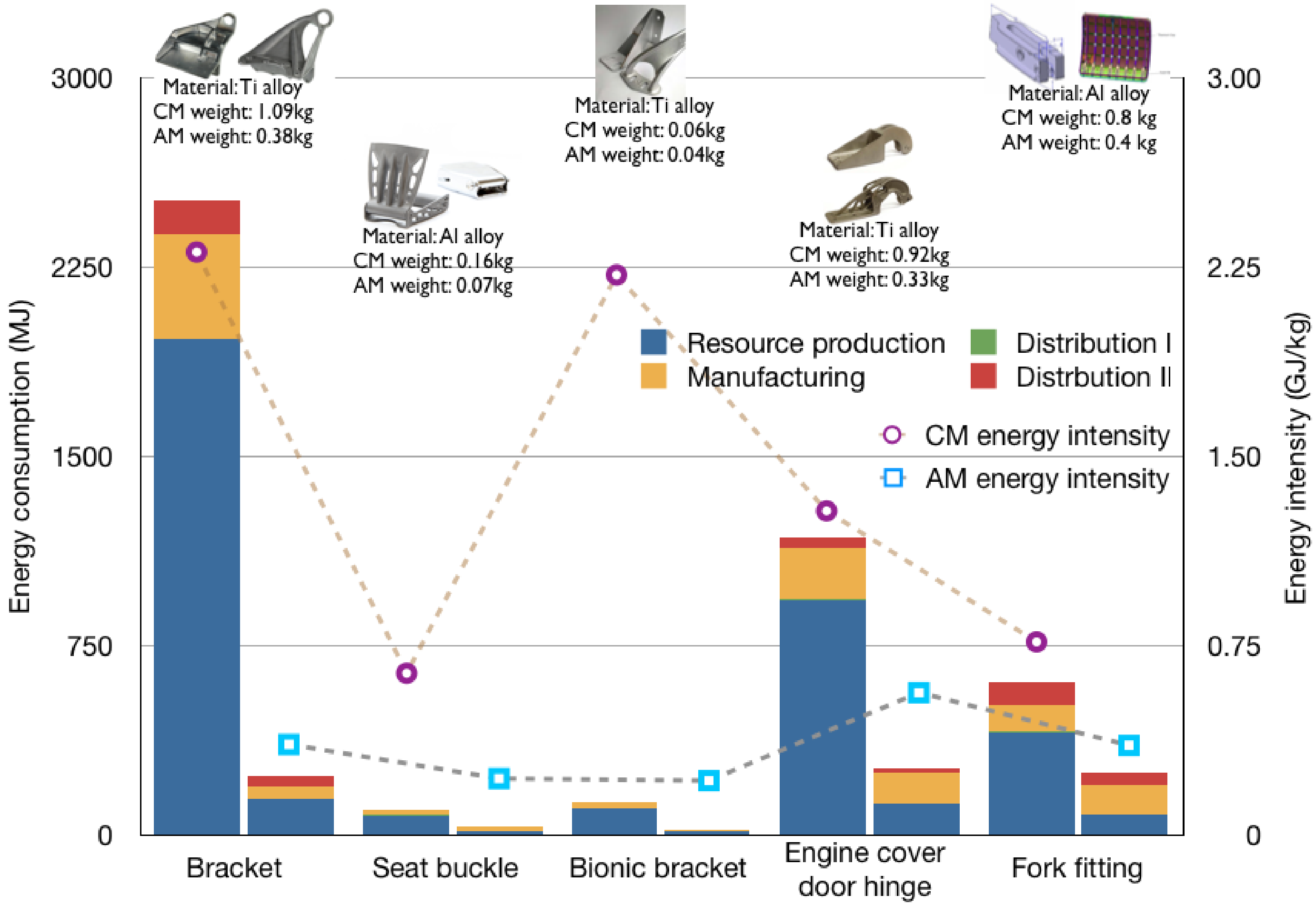
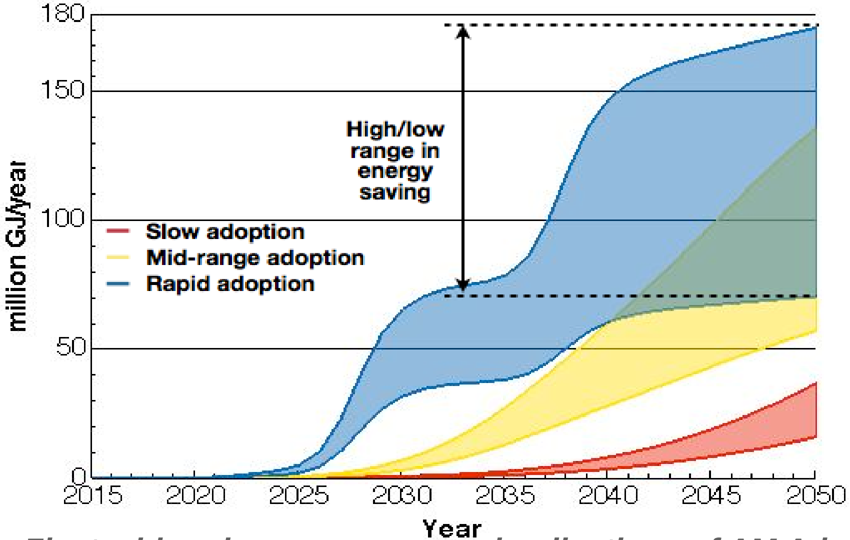


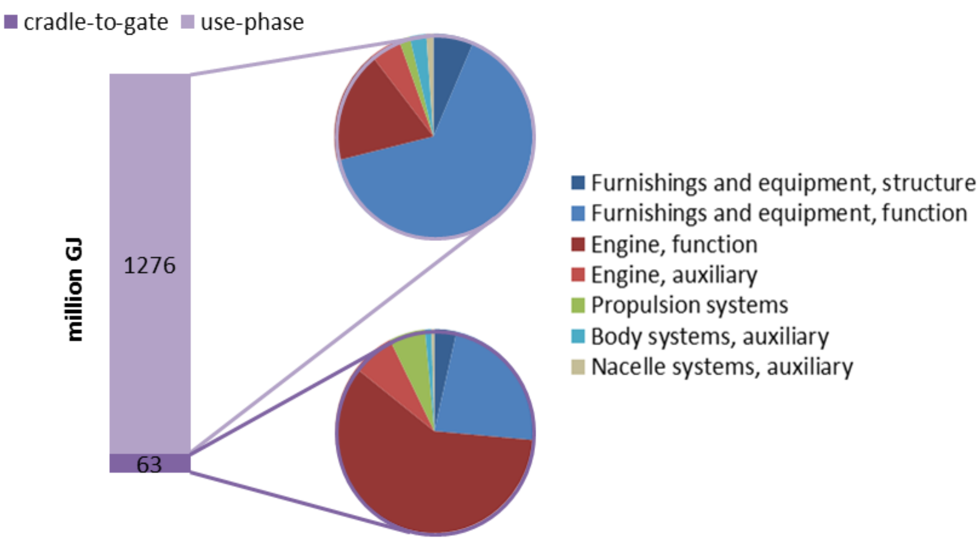
- Resource production dominates cradle-to-gate energy consumption
- Significant ***materials efficiency*** gained with AM
- Energy savings potentials vary by component – highlights strategic target markets

Cradle-to-grave life cycle impacts

- Potential metal alloy savings by 2050: 4050 tonnes/year aluminum, 7600 tonnes/year titanium; and 8110 tonnes/year nickel
- Total primary energy savings potential 70-173 million GJ/year by 2050; cumulative primary energy savings of 1.2-2.8 billion GJ through 2050.
- Most of the energy savings from reduction in use-phase fuel consumption – further lightweighting achievable with **improved component design**
- Rapid adoption scenario highlights benefits of aggressive deployment and more immediate progress to overcome engineering limitations (surface roughness, residual stress, etc.)

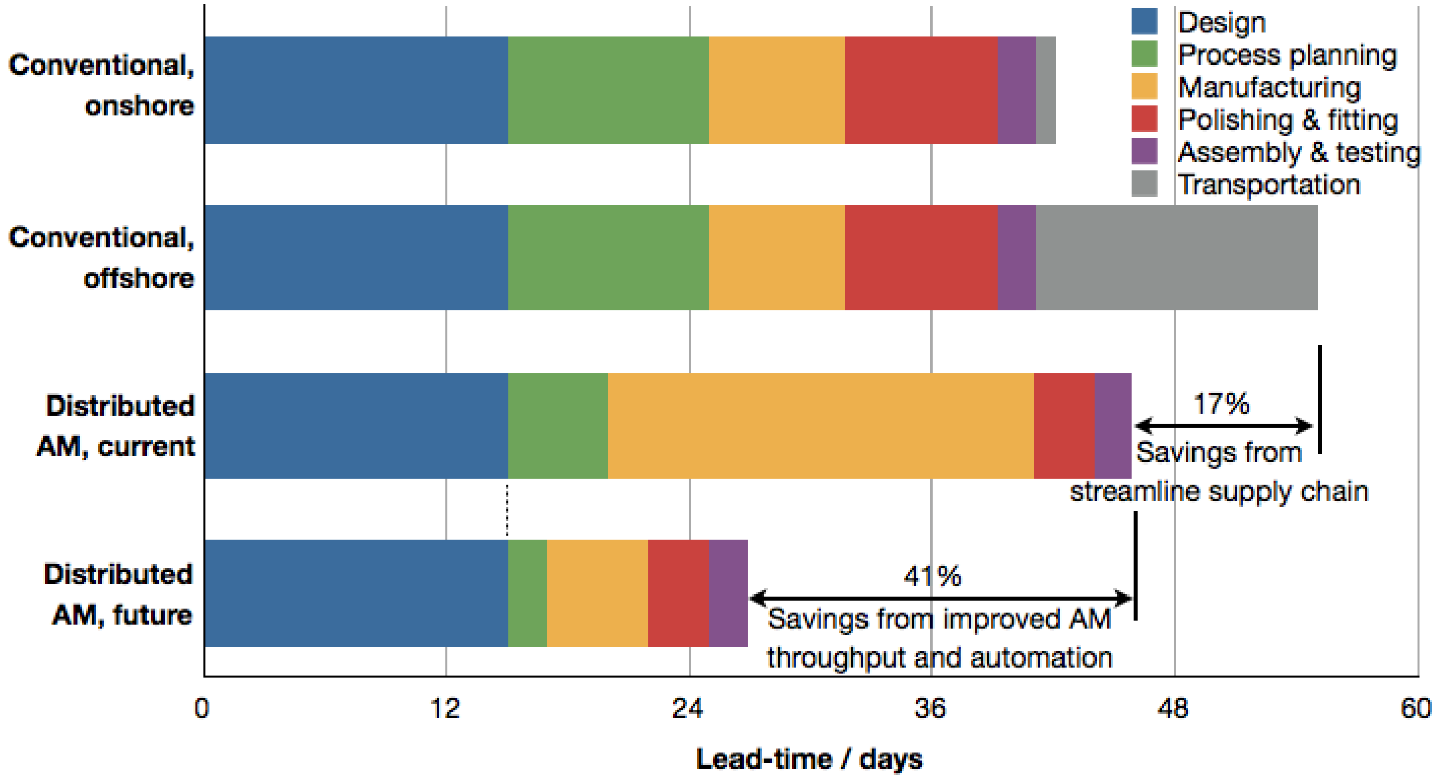


Fleet-wide primary energy use implications of AM Adoption



Fleet-wide cumulative primary energy savings through 2050 – breakdowns by life cycle phase and by component for mid-range adoption scenario, high end of range

Additive Manufacturing – Enabling Competitiveness & Distributed Manufacturing



- Consideration of benefits to production economics and competitiveness - shed light on the potential business case for AM investments
- Analysis of projected trends in technology improvement
- Uncertainty and scenario analysis to enable robust AMO assessments

Publications

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Published

- Huang, R., M.E. Riddle, D.J. Graziano, J.A. Warren, S. Das, S. Nimbalkar, J. Cresko, and E. Masanet (2015). “The Energy and Emissions Saving Potential of Additive Manufacturing: The Case of Lightweight Aircraft.” *Journal of Cleaner Production*. In press.
- Yao, Y., D.J. Graziano, M.E. Riddle, J. Cresko, and E. Masanet. (2014). "Greener Pathways to Energy-Intensive Commodity Chemicals: Opportunities and Challenges." *Current Opinion in Chemical Engineering*. Volume 6, Pages 90-98.

Under final revision

- Das, S., D.J. Graziano, V. K. Upadhyayula, E. Masanet, M.E. Riddle, and J. Cresko. (2015). Vehicle Lightweighting from a Life Cycle Energy and Emissions Perspective. Under revision (submitted to *Environmental Science & Technology*).
- Warren, J. A., M. E. Riddle, D. J. Graziano, V. K. Upadhyayula, S.Das, E. Masanet, and J. Cresko. (2015). Life Cycle Energy Impacts of Wide Band Gap Semiconductors in Electric Vehicles. Submitted to *Environmental Science & Technology*.
- Huang, R., D.J. Graziano, M. Riddle, J. Cresko, and E. Masanet. (2015). Environmental and Economic Implications of Distributed Additive Manufacturing: The Case of Injection Molding. In draft.
- Yao, Y., D.J. Graziano, M.E. Riddle, J. Cresko, and E. Masanet. (2015). Bounding the life cycle energy and GHG emissions of U.S ethylene production, today and tomorrow. In draft.

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