Can additive manufacturing save energy and resources? Cutting through the hype.

Eric Masanet, Ph.D.

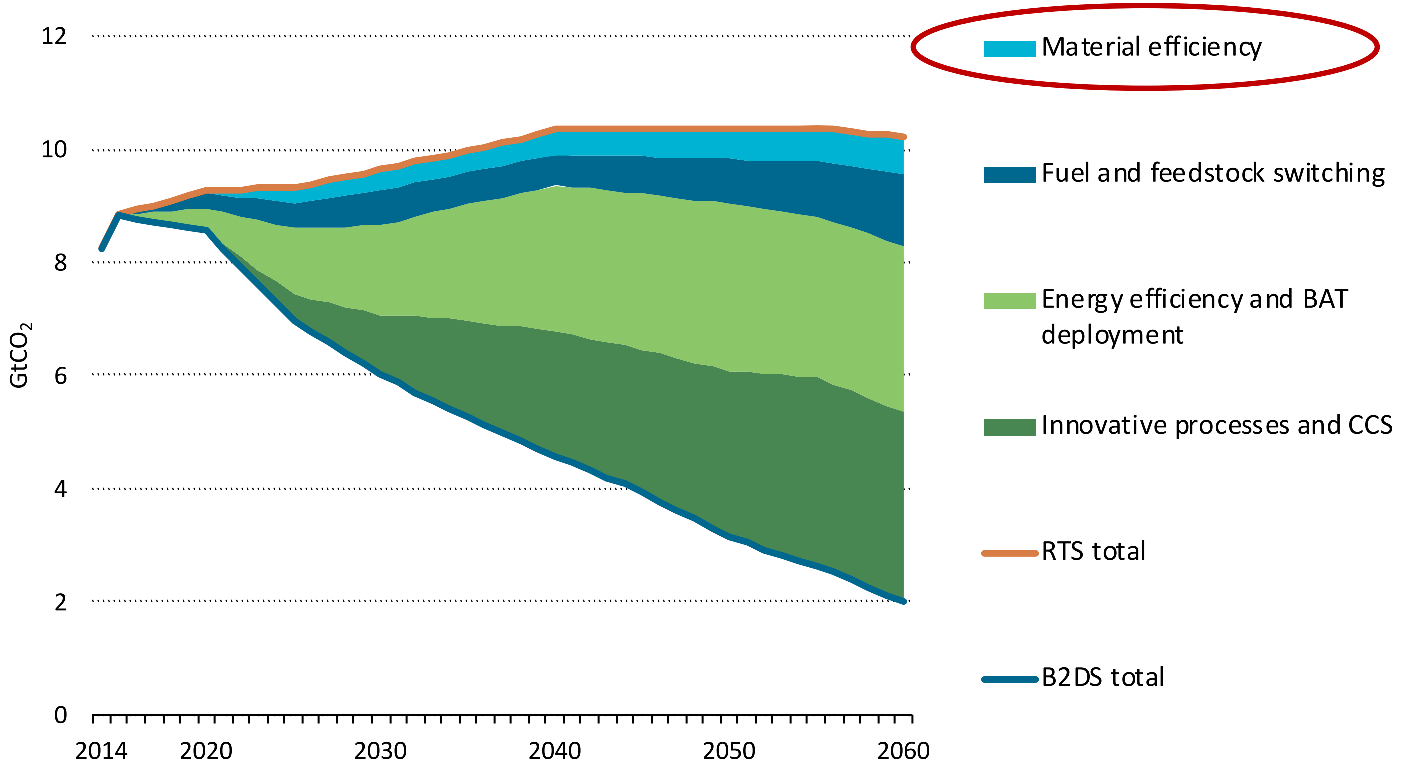
Associate Professor
McCormick School of Engineering and Applied Science
Director, Energy and Resource Systems Analysis Laboratory (ERSAL)
Guest Faculty Researcher, Argonne National Laboratory
eric.masanet@northwestern.edu

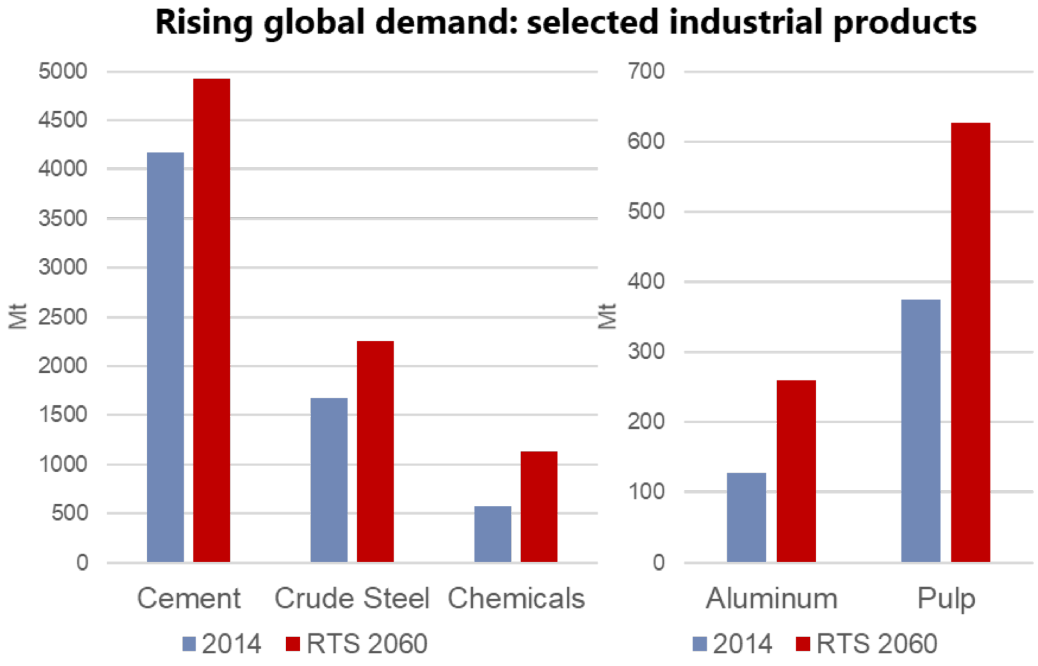
ERSAL

http://ersal.mccormick.northwestern.edu/

How can the industrial low-carbon transition be realised?

Energy Technology Perspectives 2017 - Global direct industrial CO_2 emissions





A poorly understood mitigation wedge – deep analysis needed!

A number of strategies contribute to industrial emissions reductions – there is no silver bullet

Source: IEA ETP 2017

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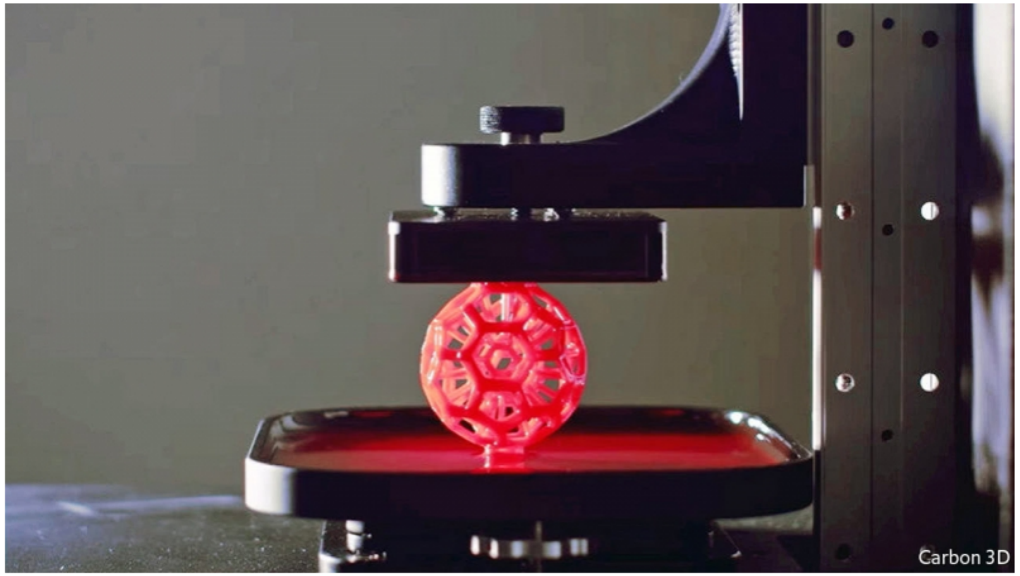
AM in the news …

The Economist

Additive manufacturing

3D printers will change manufacturing

Sceptics doubt the technology can be used for mass production. Just wait



https://www.economist.com/leaders/2017/06/29/3d-printers-will-change-manufacturing

Who Needs The Paris Climate Accords When You Have 3D Printing?

Forbes

Richard A. D'Aveni Contributor

I cover the strategic management of business and government

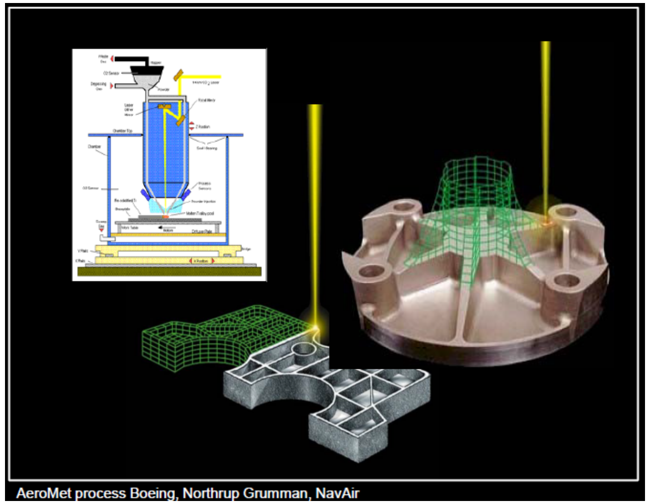
https://www.forbes.com/sites/richarddaveni/2017/08/02/who-needs-the-paris-climate-accords-when-you-have-3d-printing/#1284e4db8645

https://3dprintingindustry.com/news/oecd-say-3d-printing-will-replace-traditional-machining-within-10-years-120509/

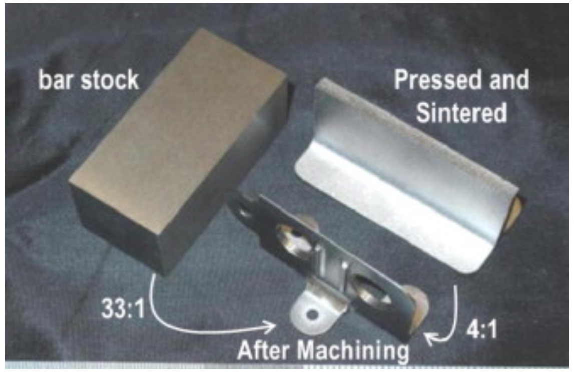
There are many potential benefits to AM …

Potential benefits

- 3-D graphical models, parts built in layers
- No tools, dies, or forms
- Near final shape
- Reduced delivery times
- Mechanical properties equivalent to wrought
- Reduced material use
- Reduced inventory
- Significant cost and energy savings



Buy-to-fly ratio examples



Chen et al. (2012)

Airbus example (120 brackets)

Additive Manufacturing

0.38 kg finished part from 0.7 kg raw material

Conventional Machining

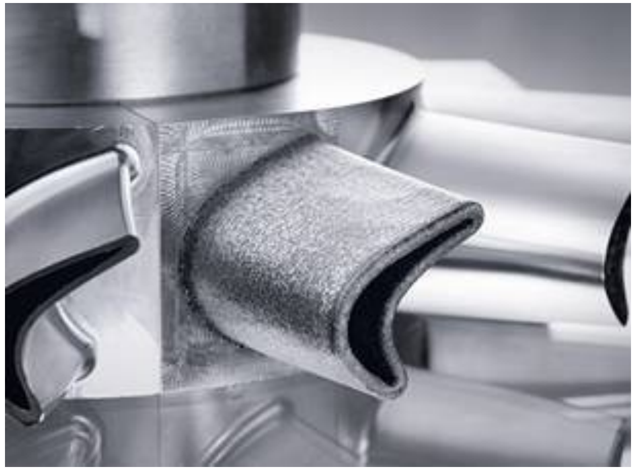
1.09 kg finished part from 9.7 kg raw material

… but also many important barriers and limitations!

Important considerations

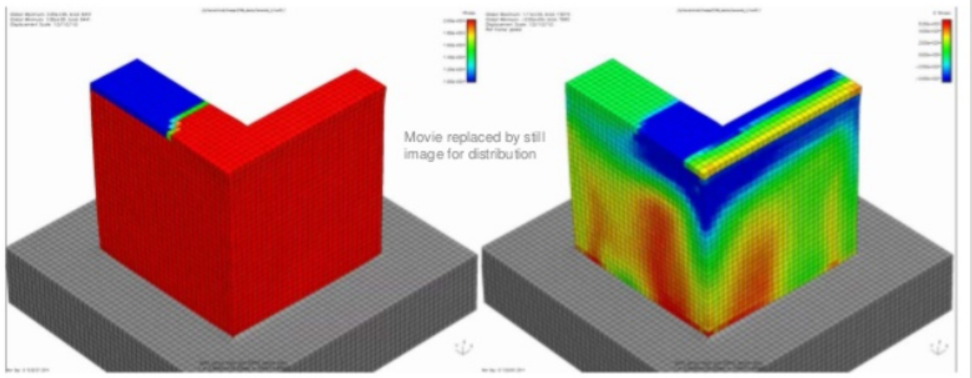
- Residual stresses (e.g., SLM)
- Surface roughness
- Fatigue life, loading
- Dimensional accuracy
- Throughput rates
- Availability
- Cost!

➢ Benefits and barriers are highly application specific!!!



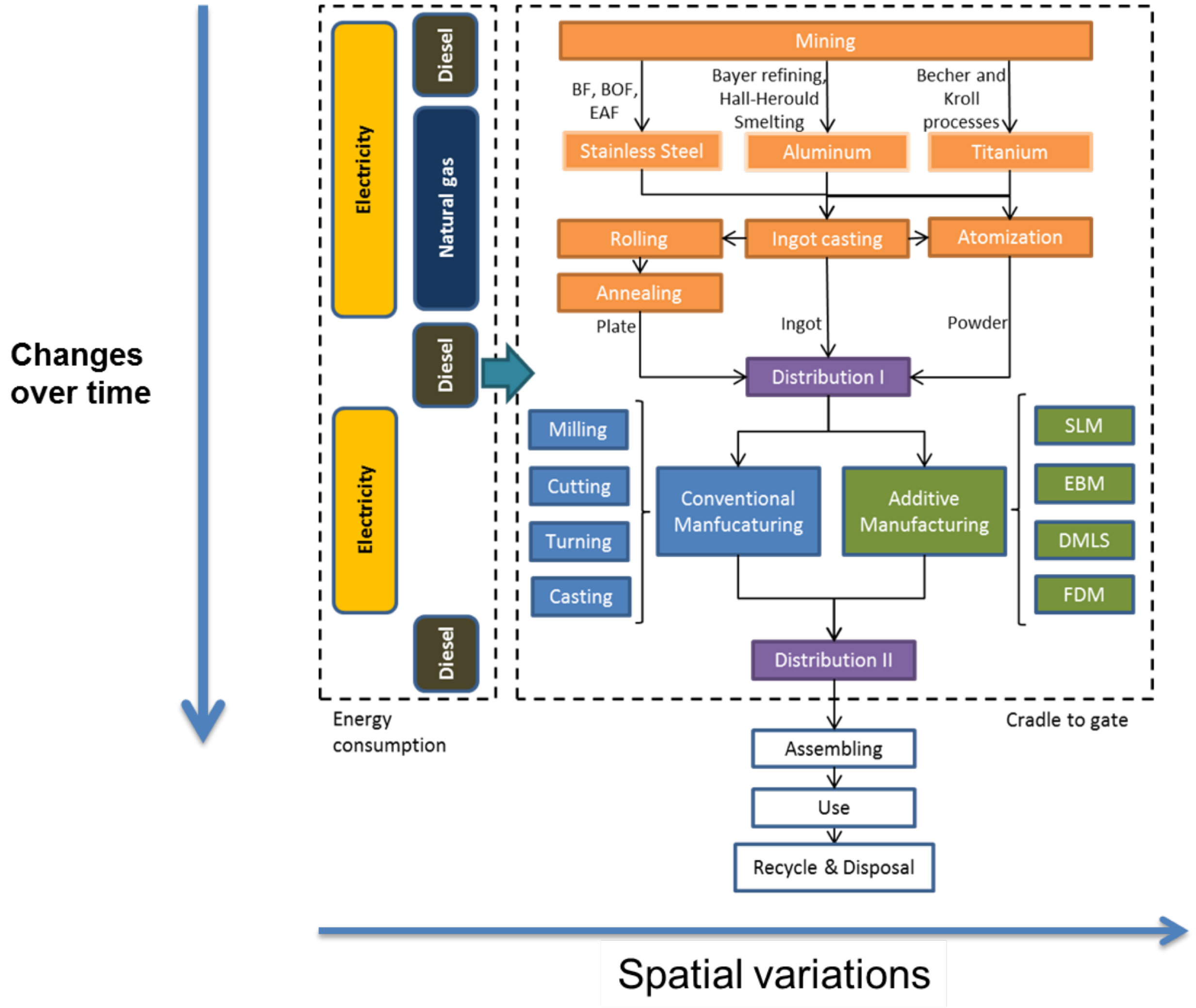
https://3d-printing-engineering.com/easyblog/entry/additive-manufacturing-technologies

Diablo (LLNL) simulation of residual stress during build



Hodge, N.E., Ferencz, R.M., Vignes, R.M., 2016. Experimental Comparison of Residual Stresses for a Thermomechanical Model for the Simulation of Selective Laser Melting. Additive Manufacturing DOI. http://dx.doi.org/10.1016/j.addma.2016.05.011.

So how do we assess AM's potential? A dynamic, integrated systems modeling approach is required!



Multi-stakeholder performance evaluation criteria

- Life-cycle flows:
  - Resource use
  - Primary energy use
  - Air pollutant emissions
- Engineering functionality
- Production economics
  - Lead time
  - Inventory
  - Capital and O&M costs
- Technology readiness

Methods/tools integrated

- Life-cycle assessment
- Energy systems modeling
- Production economics
- Engineering process modeling
- Materials property assessment

Source: Huang et al. (2016) https://doi.org/10.1016/j.jclepro.2015.04.109.

U.S. Aircraft Fleet Case Study (2015-2050)

Source: Huang et al. (2016) https://doi.org/10.1016/j.jclepro.2015.04.109.

Technical analysis: Which parts are AM compatible?

Table 2: Aircraft component system attribute ratings

Component systems	*Component category*	Mass fraction	Load rating	Shape complexity rating	Geometric volume rating	Feasibility evaluation score*
Wing systems		0.24				
	Structural	*0.95*	*High*	*Medium*	*High*	*4*
	Auxiliary	*0.05*	*High*	*Low*	*Low*	*5*

Source: Huang et al. (2016) https://doi.org/10.1016/j.jclepro.2015.04.109.

Technical analysis: How much mass can be replaced, and by when?

Replaceable mass by metal alloy, component system, and component category.

Component system	Category	Replaceable mass in average aircraft (kg)[a]			
		Al alloy	Ti alloy	Ni alloy	Steel
Body systems	Auxiliary	80–200			
Furnishings and equipment	Structural	70–130			
	Functional	1450–1930			
Engine	Functional		680–1350	940–1880	100–190
	Auxiliary		50–90	50–90	50–90
Propulsion systems	Functional		330–810		
Nacelle systems	Auxiliary		20–40		
	Total	**1590–2260**	**1070–2290**	**980–1960**	**140–280**

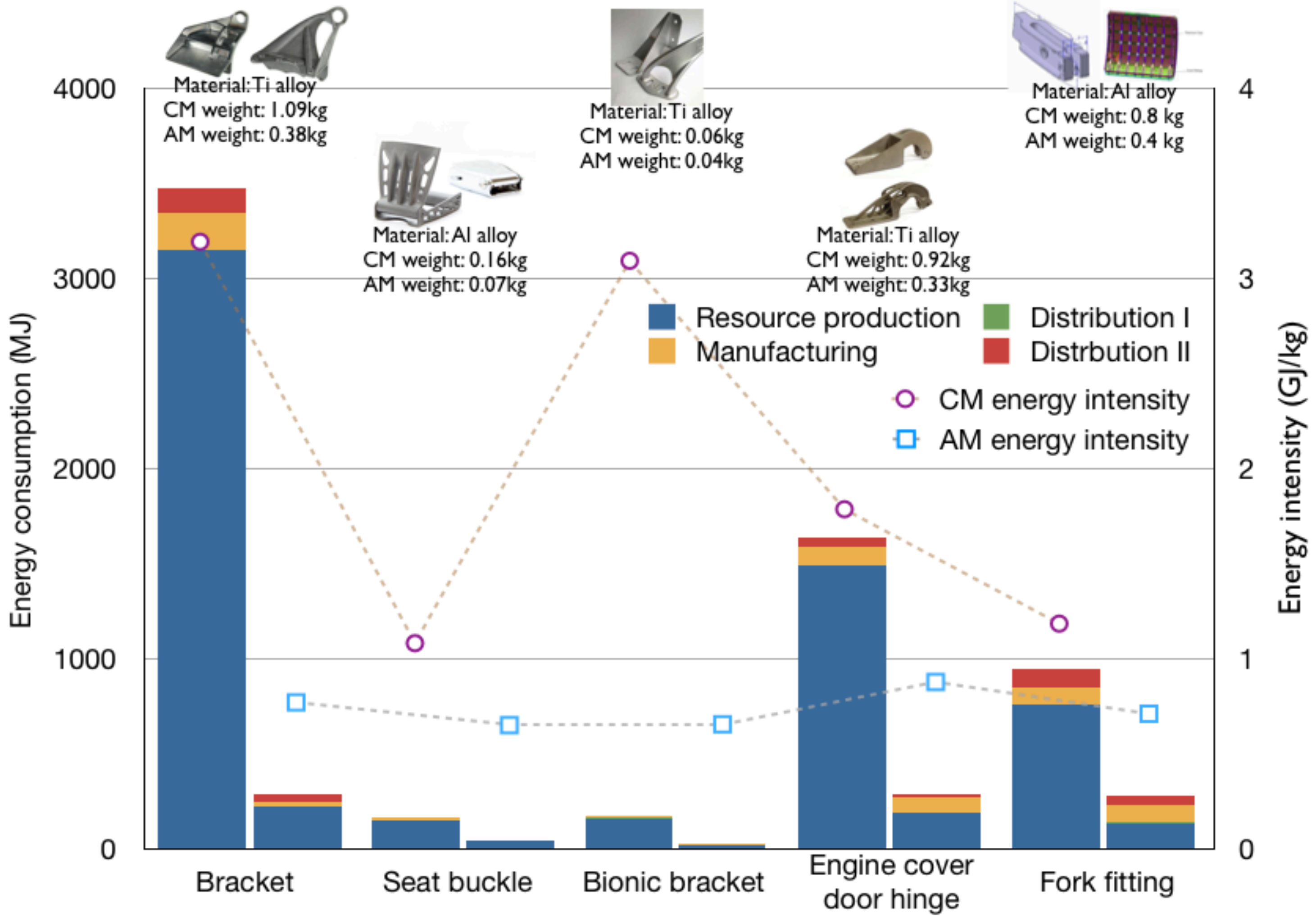
[a] Based on an average aircraft empty operating mass of 40,622 kg (Airliners.net, 2013; Bureau of Transportation Statistics (BTS), 2013).

Temporal availability assumptions.

Component system	Component category	Availability
Body systems	Auxiliary	10 years (2024)
Furnishings and equipment systems	Structural	5-10 years[a] (2019–2024)
Furnishings and equipment systems	Functional	10 years (2024)
Engine	Functional	20 years (2034)
Engine	Auxiliary	10 years (2024)
Propulsion systems	Functional	20 years (2034)
Nacelle systems	Auxiliary	5 years (2019)

[a] 5 years for galley and lavatory, 10 years for floor panel, fasteners and other.

"Cradle to gate" AM energy savings: one size does not fit all!

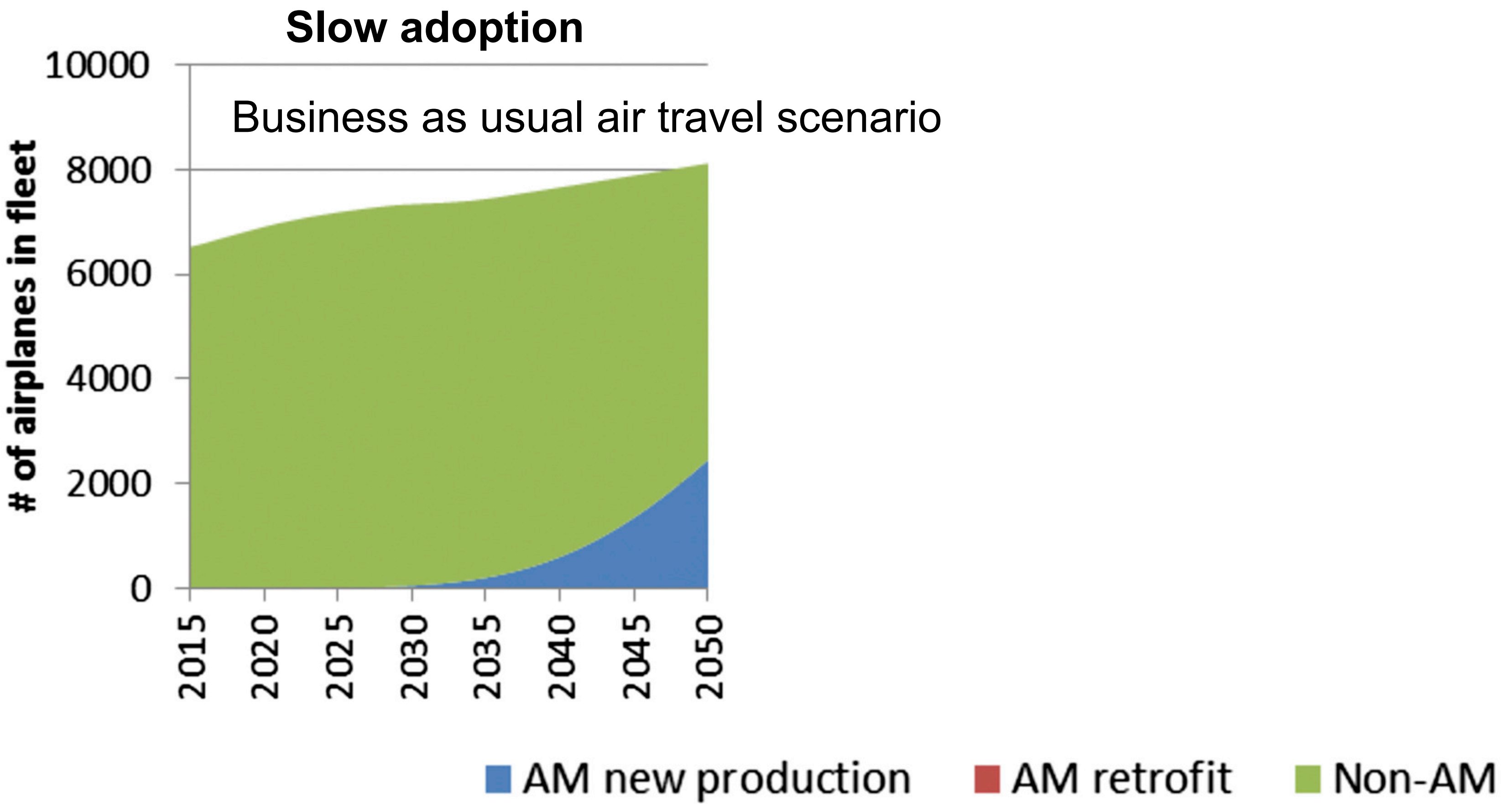


When does AM beat conventional processes?

- Small production quantities
- High part complexities
- Expensive materials with significant scrap
- Low part mass (i.e., small total volume)
- Minimal load/fatigue (in the near term)
- **Significant redesign potential**

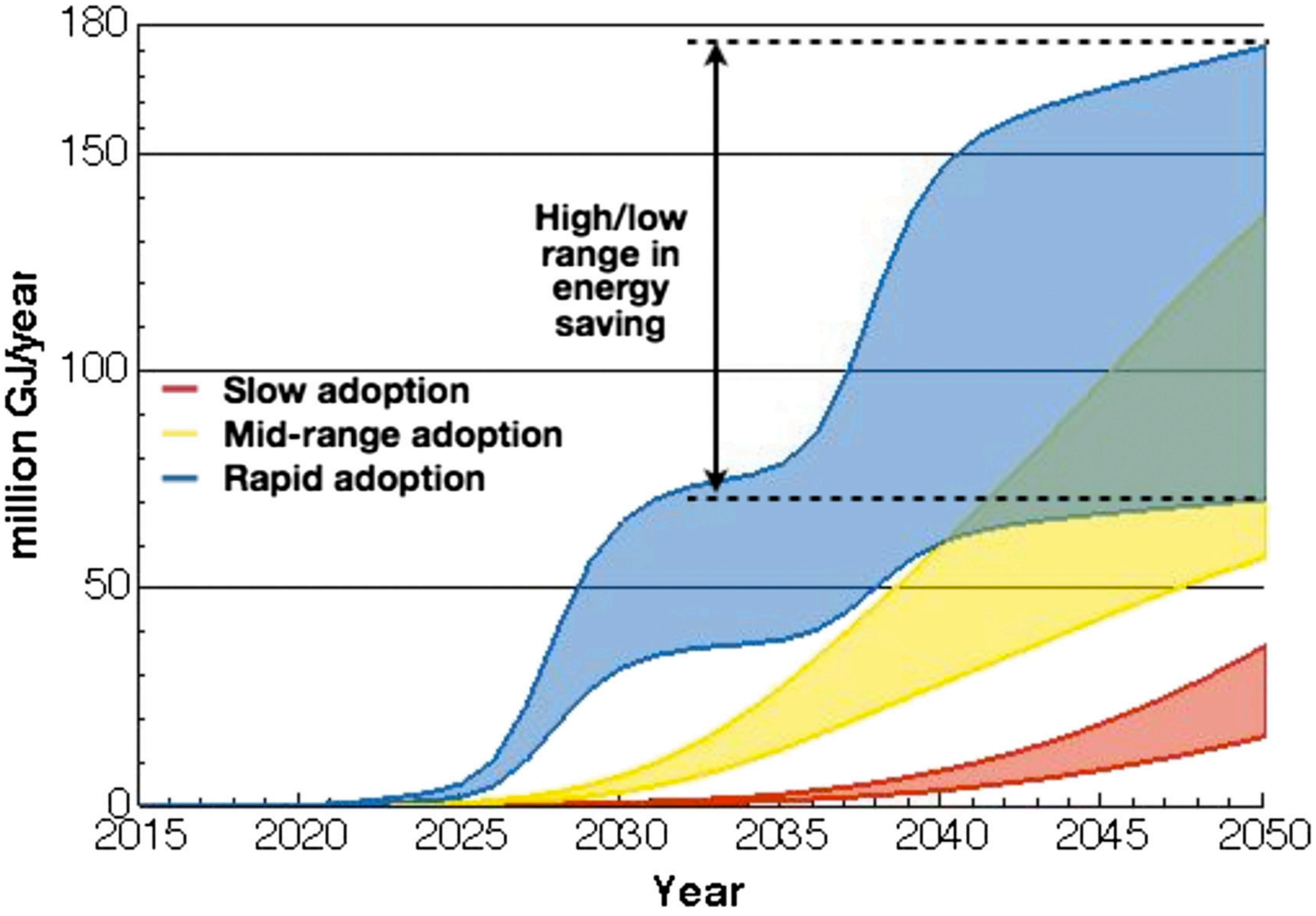
Source: Huang et al. (2016) https://doi.org/10.1016/j.jclepro.2015.04.109.

Aircraft AM adoption scenarios: How can we accelerate depoloyment?



Source: Huang et al. (2016) https://doi.org/10.1016/j.jclepro.2015.04.109.

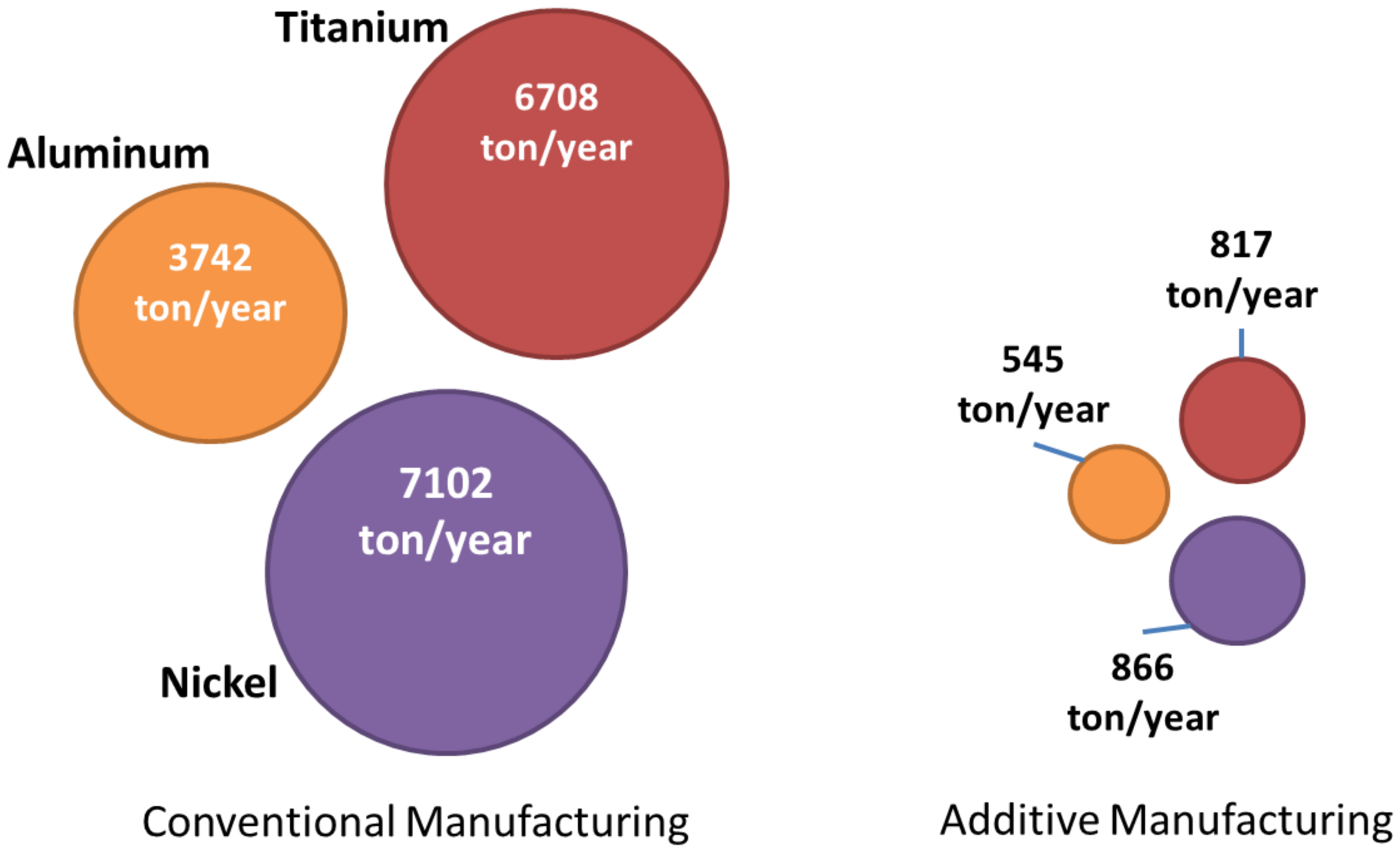
Accelerating fuel saving benefits: the role of science policy



Policy and R&D levers for accelerated adoption:

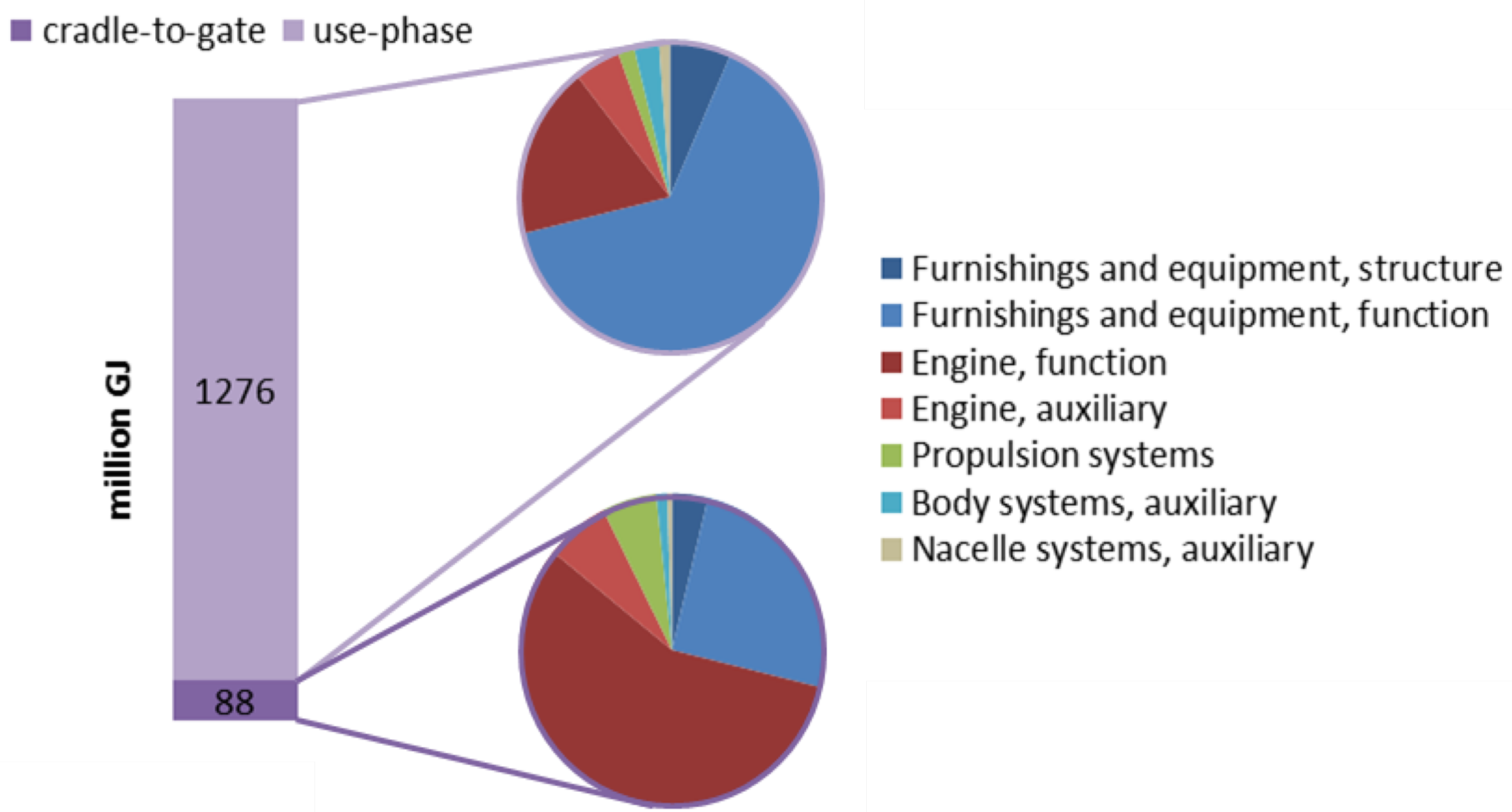
- Improved surface finish (basic research)
- Reduced residual stresses (basic research)
- Pilots and demonstrations
- Technology transfer programs
- Cost and externality incentives for AM adoption

In 2050, AM delivers significant resource savings in <u>feasible</u> applications



Source: Huang et al. (2016) https://doi.org/10.1016/j.jclepro.2015.04.109.

However, it is improved design functionality that delivers the greatest energy savings!



Source: Huang et al. (2016) https://doi.org/10.1016/j.jclepro.2015.04.109.

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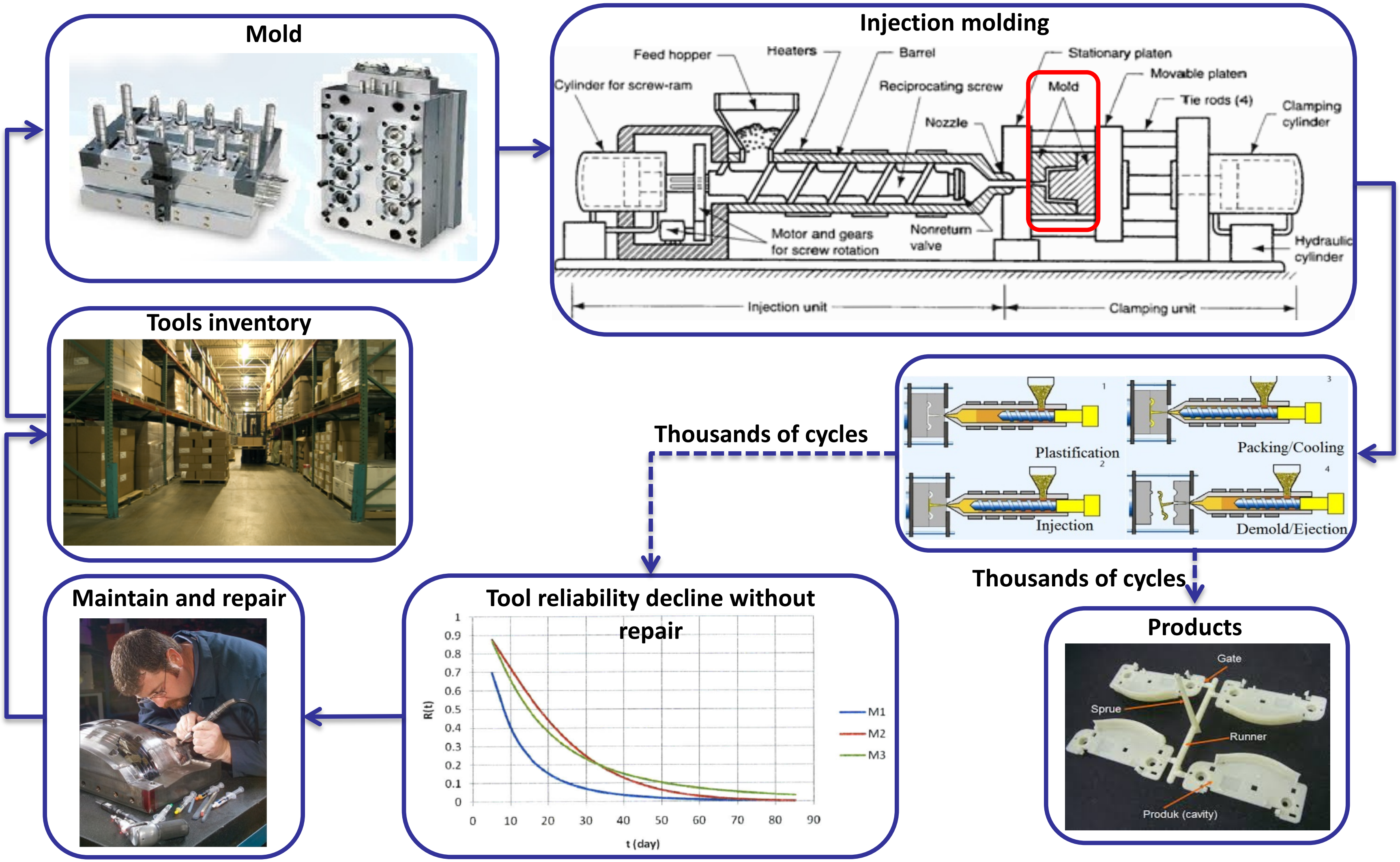
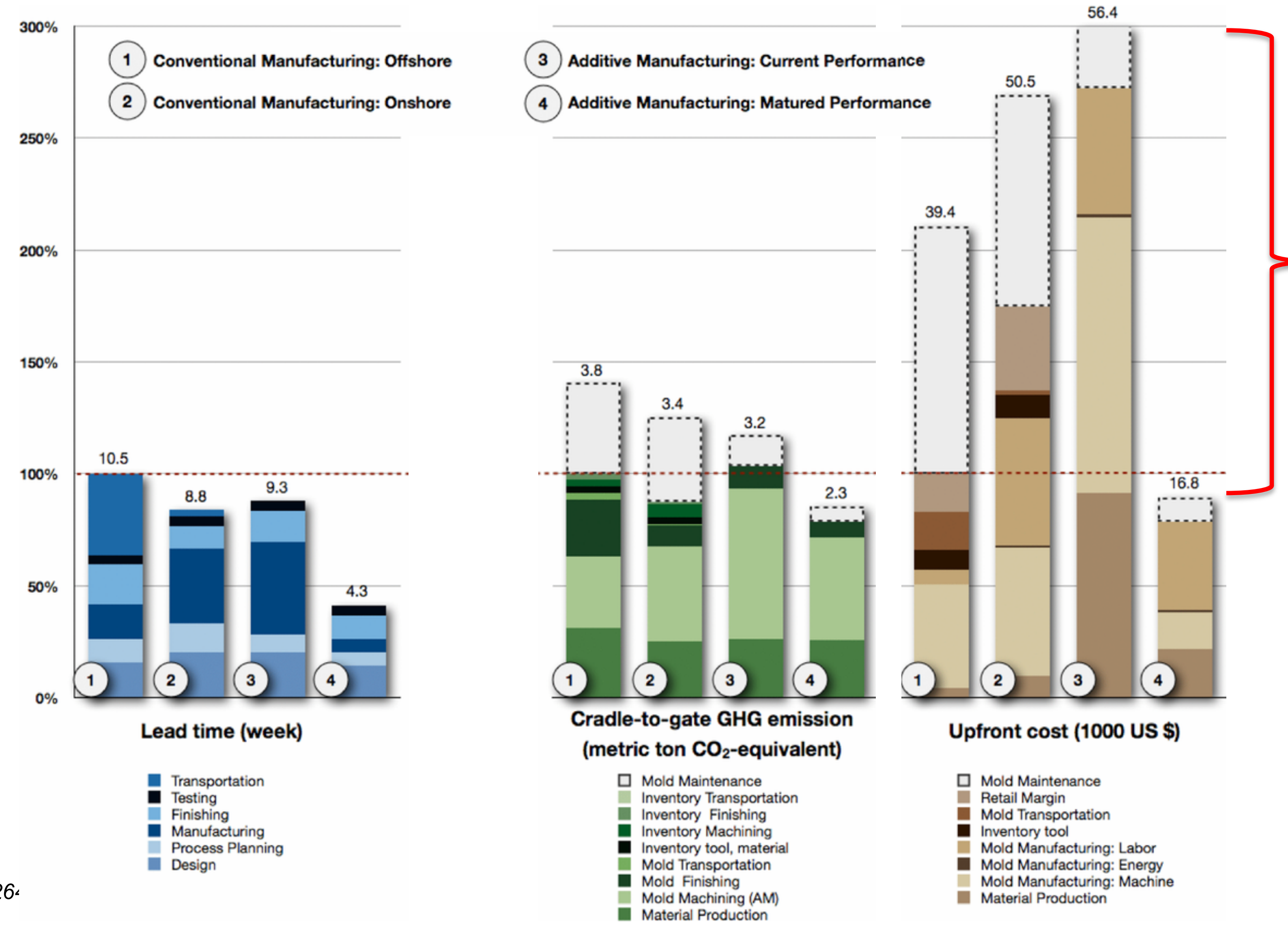
What about cost? Injection molding example



Is there a business productivity case for AM adoption?

AM injection mold tooling case study (functional unit = 1M molded parts)



Enabling policies and investments are critical to close this gap

Huang et al. (2017) doi:10.1111/jiec.126

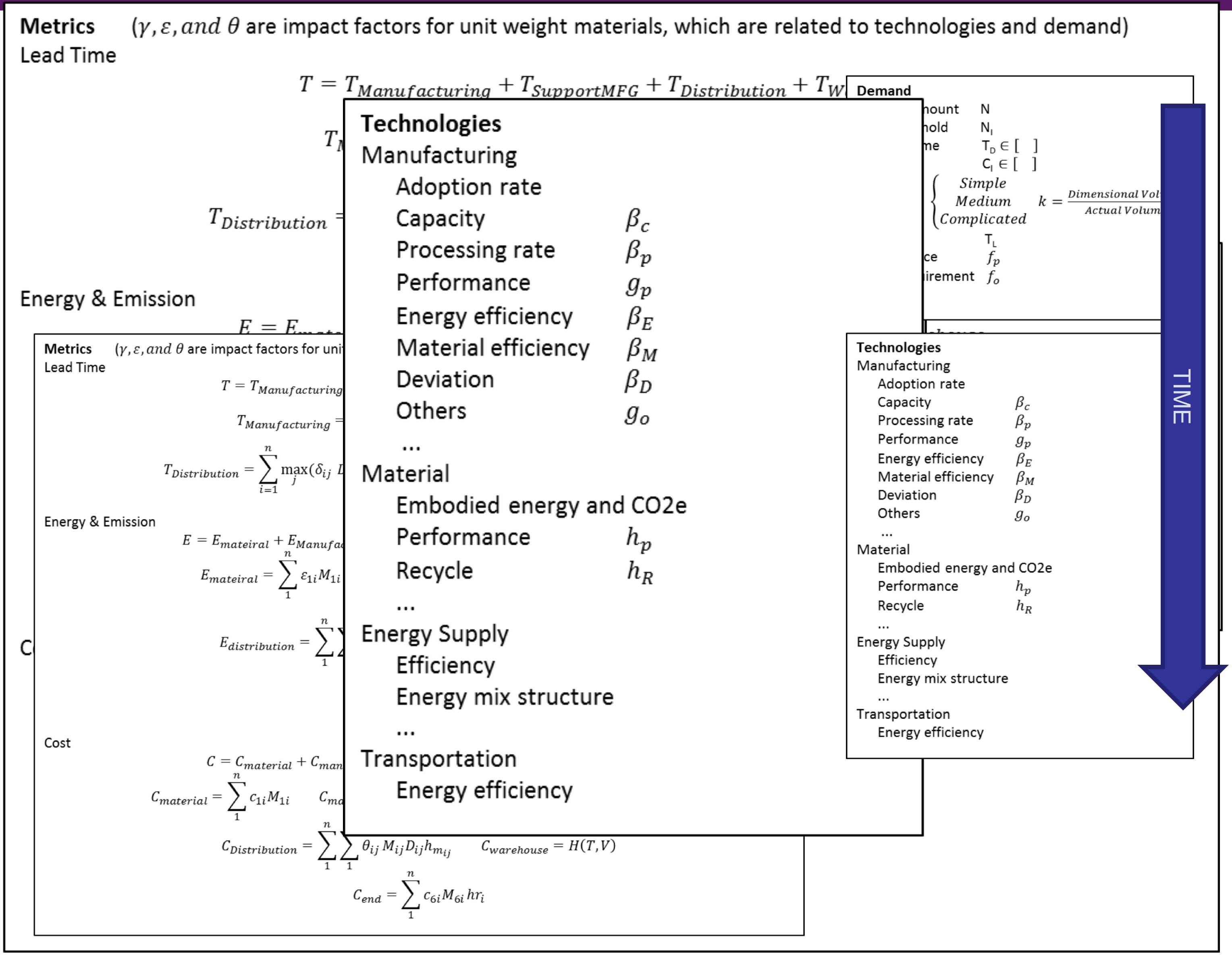
Conclusions

- AM can deliver savings, but savings are highly case specific
- To realize its potential, technical barriers must be overcome
  - Surface roughness, residual stresses, process throughput, technology cost, etc.
- Consideration of systems effects is critical for the AM value proposition
- Deep techno-economic and engineering analysis is required
  - Broad brush generalizations must be avoided!

Insights for integrated assessment modeling

- AM is one of many emerging industrial technologies that are not well represented in IAMs
- To fill these knowledge gaps, priority research areas include:
  - Greater linkages between lab- and pilot-scale technology research and prospective techno-economic systems modeling research
  - Development and codification of prospective modeling approaches
  - Improved training in prospective techno-economic assessment tools and methods

THANK YOU!



Sources: Huang et al. (2016) https://doi.org/10.1016/j.jclepro.2015.04.109; Huang et al. (2017) doi:10.1111/jiec.12641