U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Additive Manufacturing in Fuel Cells Applications

Perspectives from the Advanced Manufacturing Office

November 19, 2014

DOE Hydrogen and Fuel Cell Technical Advisory Committee Meeting

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Additive Manufacturing

Advanced Manufacturing Office

www.manufacturing.energy.gov

Outline

- Advanced manufacturing office overview
- Additive manufacturing overview
- Potential fuel cell applications

Advanced Manufacturing Office (AMO) Overview

Energy Efficiency and Renewable Energy
U.S. Department of Energy

What is Advanced Manufacturing?

A family of activities that:

- Depend on the use and coordination of information, automation, computation, software, sensing, and networking; and/or
- Make use of cutting edge materials and emerging capabilities.

Advanced Manufacturing involves both:

- *New ways to manufacture existing products*; and
- The manufacture of *new products emerging from new advanced technologies*.

Definition from: President's Council of Advisors on Science and Technology, "Report to the President on Ensuring America's Leadership in Advanced Manufacturing," June 2011, p. ii

www.whitehouse.gov/sites/default/files/microsites/ostp/pcast-advanced-manufacturing-june2011.pdf.

Or more Simply

Manufacturing

Making Stuff or Doing Value Added Work Using the Stuff that is Made

Advanced Manufacturing

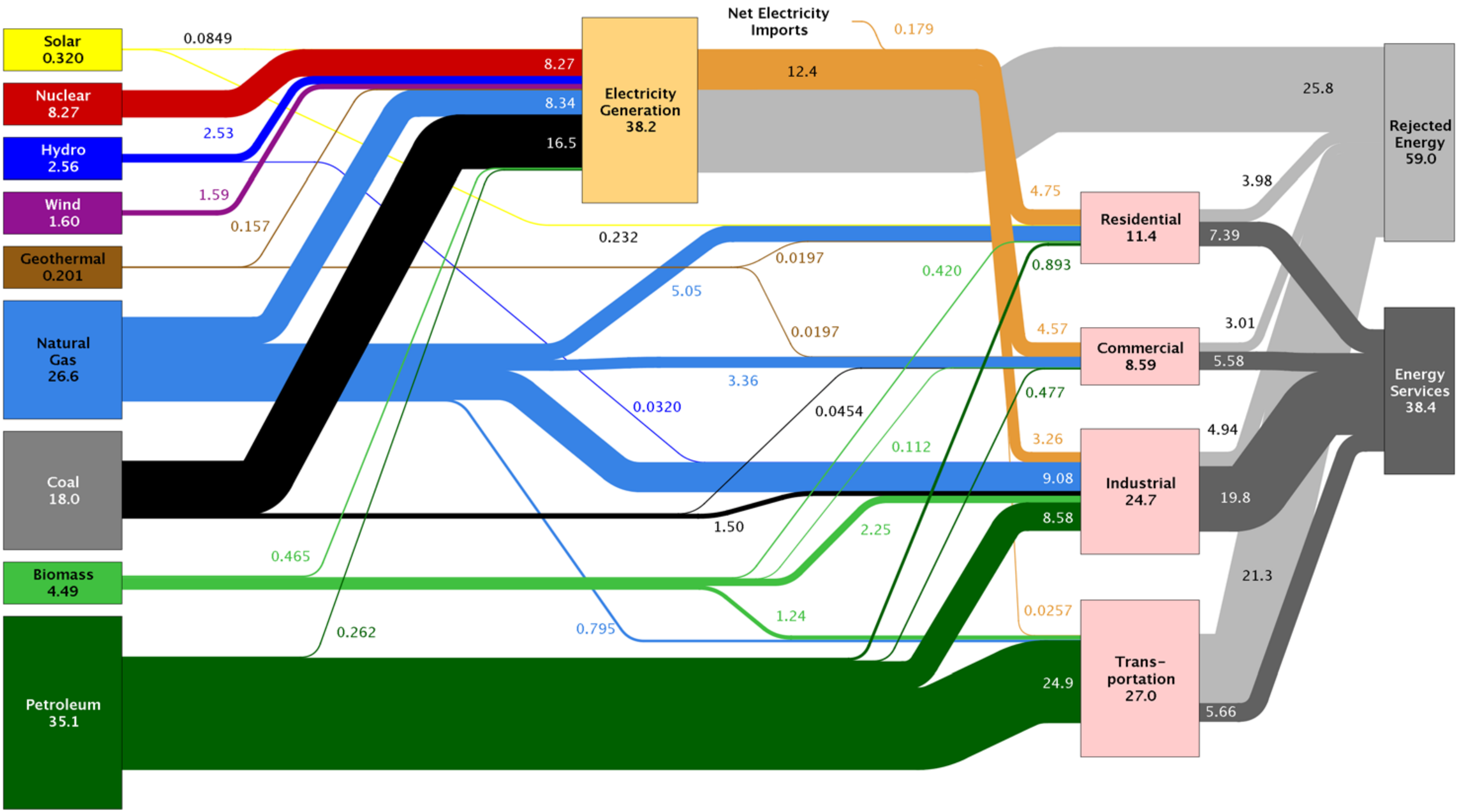
Making Stuff Using Technology as a Key Enabler or as a Relative Competitive Advantage

Clean Energy Manufacturing

Making Stuff that Reduces Energy or Environmental Impacts in its Making, Use, or Disposal.

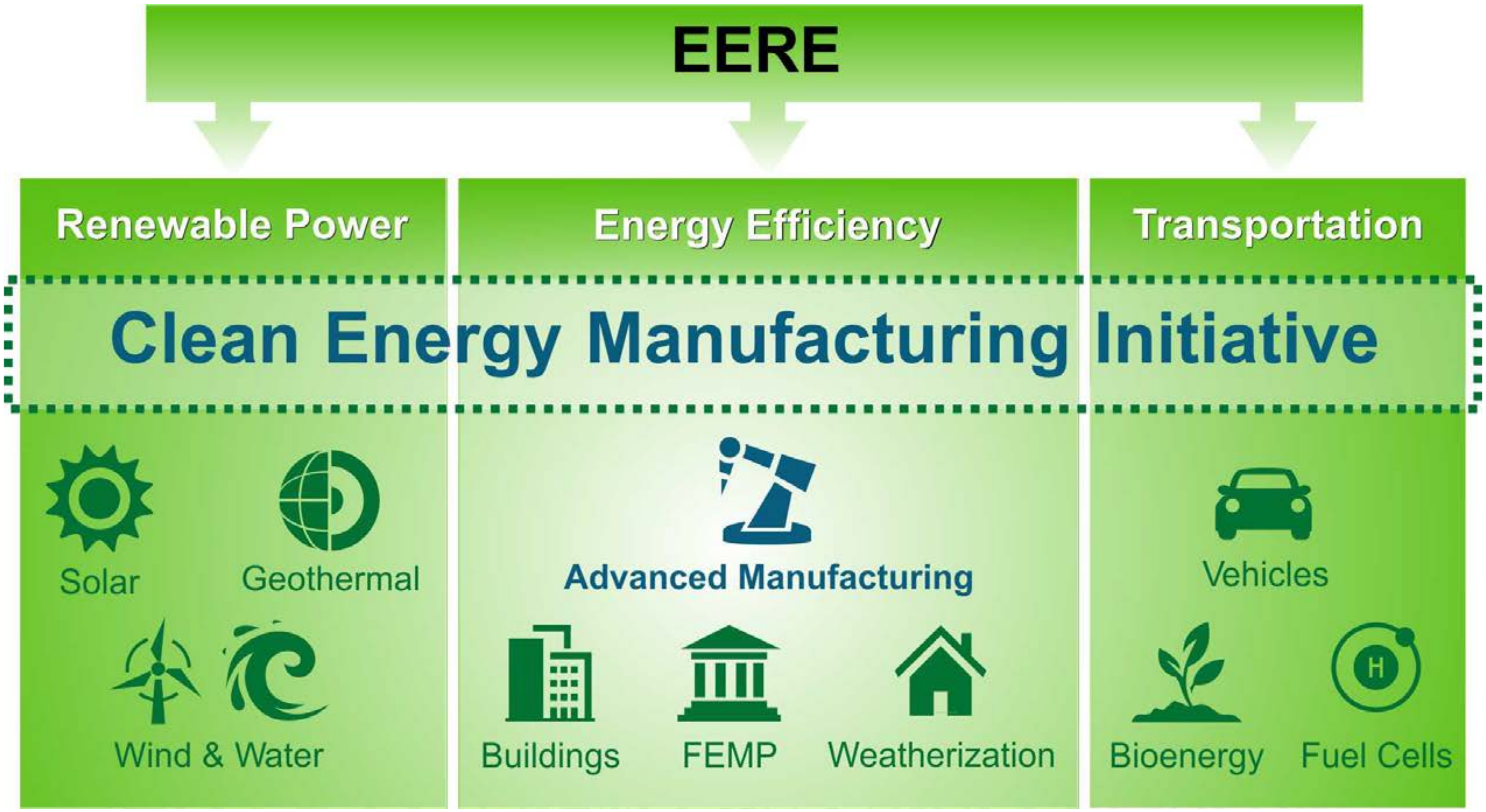
Energy Efficiency & Manufacturing Technology

Estimated U.S. Energy Use in 2013: ~97.4 Quads



Source: LLNL 2014. Data is based on DOE/EIA-0035(2014-03), March, 2014. 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

Clean Energy Manufacturing Initiative – DOE



Collaboration toward:

- Common goal to collectively ***increase U.S. manufacturing competitiveness***

Coordination for:

- Comprehensive Strategy
- Collaborative Ideas

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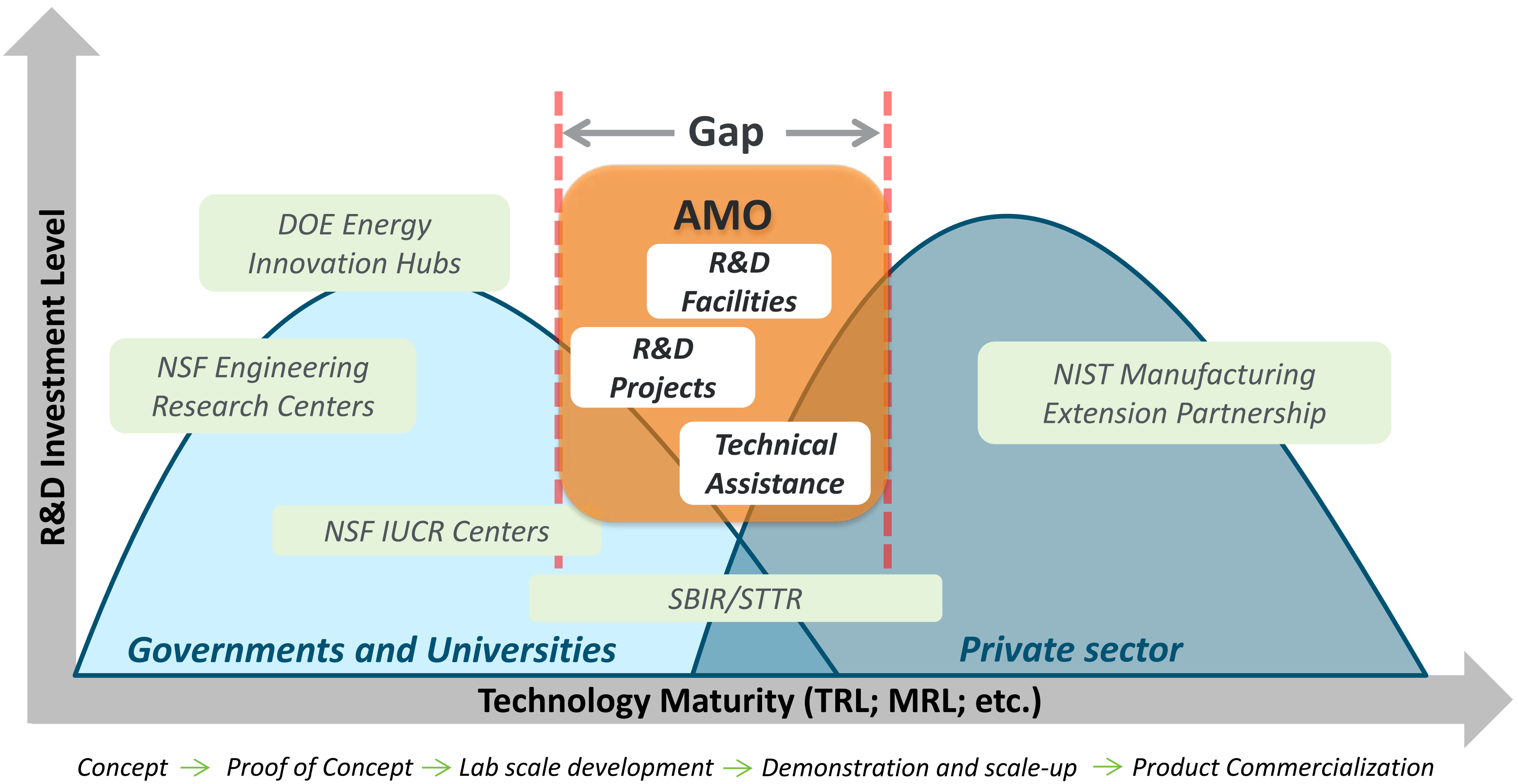
Bridging the Gap to Manufacturing

AMO: Advanced Manufacturing Office



Manufacturing Sector Whitespace

Embedded Energy Intense Manufacturing

Traditional Industry Sector Focus Areas

- Metals
- Glass & Ceramics
- Forest & Biomass
- Petrochemicals
- Extraction
- Concrete

Energy Use-Impactful Manufacturing

- Transportation
- Efficient Systems
- Power Generation
- Energy Delivery

Cross-Cutting Impact Opportunities

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Broad Topical Areas

- **Platform Materials and Technologies for Energy Applications**
  - Advanced Materials Manufacturing (Mat'l Genome, Nanomaterials, etc.)
  - Critical Materials
  - Advanced Composites & Lightweight Materials
  - 3D Printing / Additive Manufacturing
  - 2D Manufacturing / Roll-to-Roll Processes
  - Wide Bandgap Power Electronics
  - Next Generation Electric Machines
- **Efficiency in Manufacturing Processes (Energy, CO_2)**
  - Advanced Sensors, Controls, Modeling and Platforms (i.e., Smart Manf.)
  - Advanced Chemical Process Intensification
  - Grid Integration of Manufacturing (CHP and DR)
  - Sustainable Manufacturing (Water, New Fuels & Energy)
- **Emergent Topics in Manufacturing**

AMO Elements

Three primary partnership-based vehicles to engage with industry, academia, national laboratories, and local and federal governments:

1. **Research and Development Projects**
2. **Technical Assistance**
3. **Shared R&D Facilities** - affordable access to physical and virtual tools, and expertise, to foster innovation and adoption of promising technologies

MDF

America Makes

AMO supported additive manufacturing facilities

Shared R&D Facilities

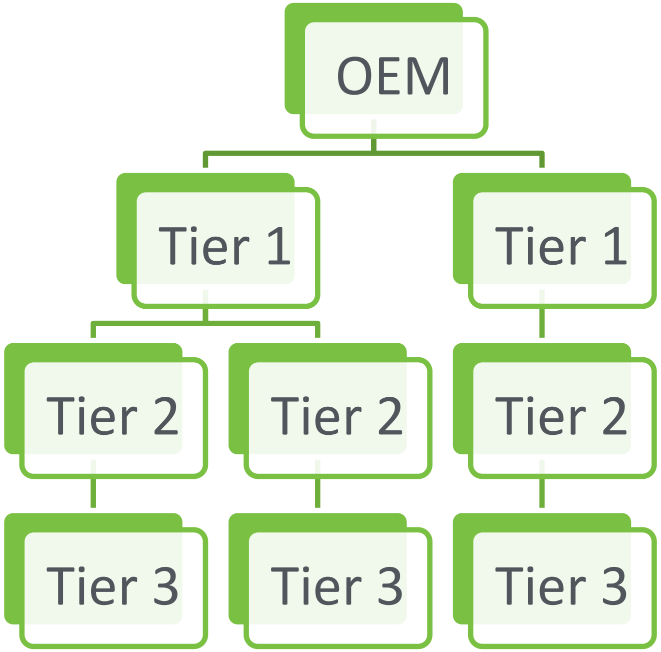
- Address market disaggregation to rebuild the industrial commons

Then

Ford River Rouge Complex, 1920s

Photo: Library of Congress, Prints & Photographs Division, Detroit Publishing Company Collection, det 4a25915.

Now



- **How do we get innovation into manufacturing today?**

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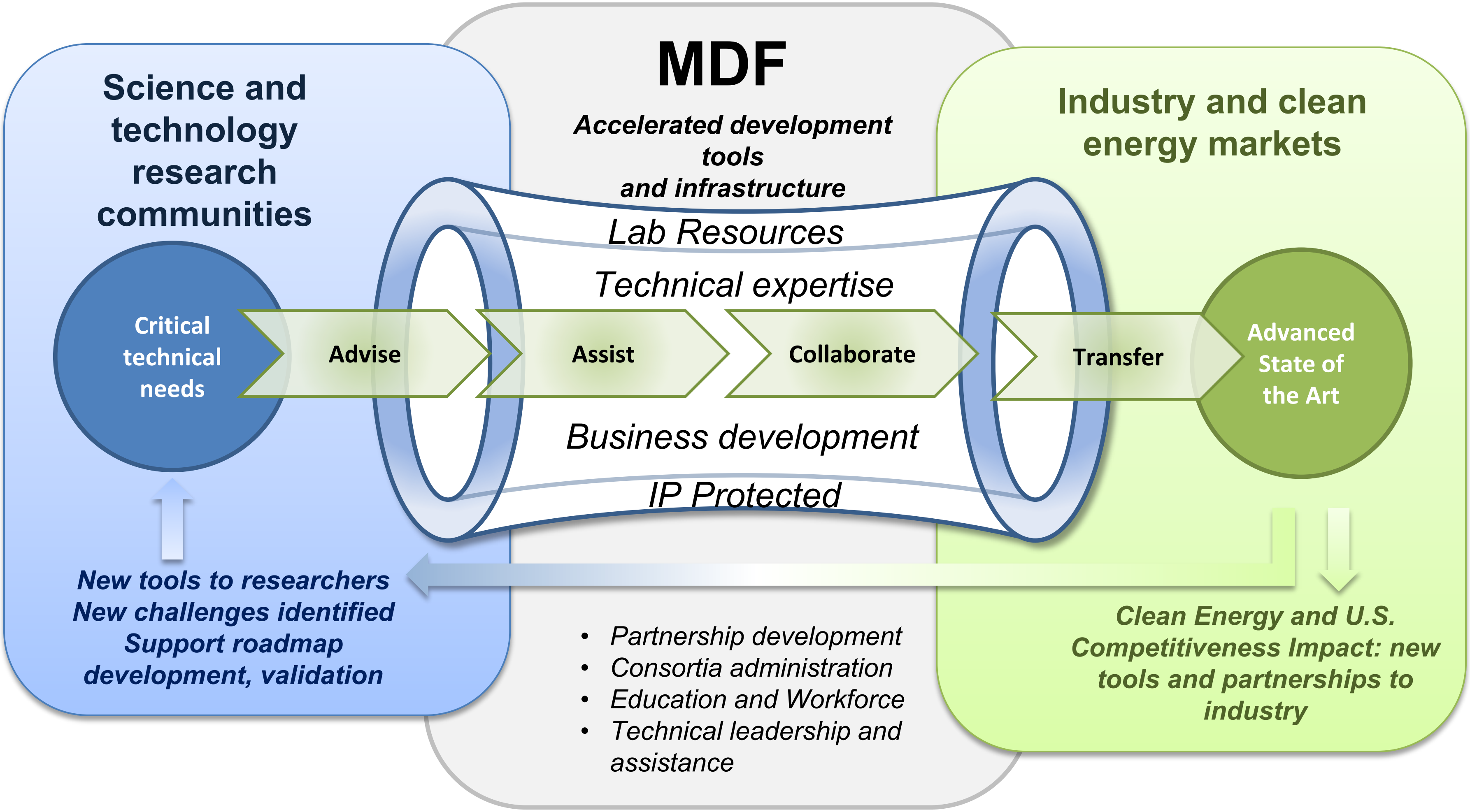
Manufacturing Demonstration Facility at Oak Ridge National Lab



AMO Manufacturing Demonstration Facility Model

Who

Technology Impact

MDF

"Industrial Commons"

- Expert research staff
- Design capability
- Advanced manufacturing technologies
- Modeling and Simulation Tools
- Characterization/test equipment
- Administrative and legal functions

AM Toolmakers → **Multi-year R&D projects** → **New AM tools**

Collaborations

AM Tool users → **Short projects and collaborative partnerships** → **New AM markets**

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AMO Supports America Makes

- *Multi-agency collaboration and public-private partnership (industry, government, academia)*
- *Mission: Widespread adoption of additive manufacturing (3D printing)*

- Launched in Aug 2012 by Air Force Research Laboratory (Manufacturing Technology) with very quick procurement timeline
- Non-profit Lead: National Center for Defense Manufacturing and Machining (NCDMM)
- Addressing manufacturing readiness level (MRL) 4 - 7
- $50M federal investment pledged, to support development and management of the institute over 5 years, as well as applied research projects
- Will be self-sustaining by Aug 2017

Flagship (first) Manufacturing Innovation Institute and example for others

Why America Makes?

America Makes creates mechanisms for collaboration…

Cooperative Development of
- Training
- Assessments
- Case Studies

Pooling Resources / Pooling Risks

Cooperative Development of
- Material Specs
- Process Specs
- Material Databases
- Design Rules
- Application Guides

Solving Problems Collaboratively

Leveraging Community Knowledge

Public/Private Funded Projects
Crowd Funded Projects

Work Shops, Working Groups, Projects

Knowledge Base, Online Collaboration Tools, Databases, Specifications, Application Guides, Curriculum

Additive Manufacturing Overview

What is additive manufacturing?

Why use additive manufacturing?

What is Additive Manufacturing?

Additive manufacturing, commonly known as "3D Printing," is a **set of emerging technologies** that fabricate parts using a layer-by-layer technique, where **material is placed precisely as directed** from a digital file.

What is Additive Manufacturing?

Process Type	Ex. Companies	Materials	Market
Powder Bed Fusion	EOS (Germany), 3D Systems (US), Arcam (Sweden)	Metals, Polymers	Direct Part, Prototyping
Directed Energy Deposition	Optomec (US), POM (US)	Metals	Direct Part, Repair
Material Extrusion	Stratasys (Israel), Bits from Bytes (UK)	Polymers	Prototyping
Vat Photopolymerization	3D Systems (US), Envisiontec (Germany)	Photopolymers	Prototyping
Binder Jetting	3D Systems (US), ExOne (US)	Polymers, Glass, Sand, Metals	Prototyping, Casting Molds, Direct Parts
Material Jetting	Objet (Israel), 3D Systems (US)	Polymers, Waxes	Prototyping, Casting Patterns
Sheet Lamination	Fabrisonic (US), Mcor (Ireland)	Paper, Metals	Prototyping, Direct Part

- 7 Process Categories by ASTM F42 these vary by: materials, speed to build, accuracy, finished part quality, cost, accessibility and safety, multi-color or multi-functional part capabilities

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Processes vary and are generally undergoing considerable development

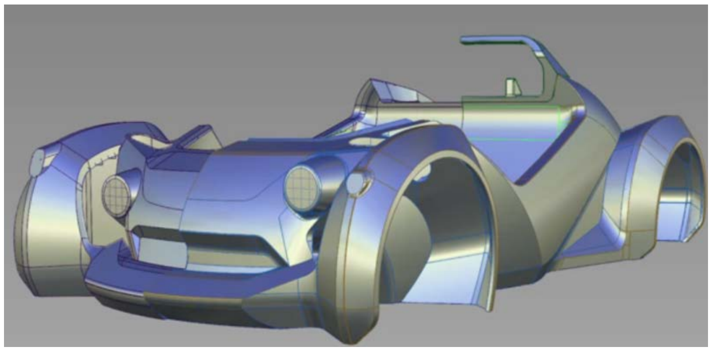
No silver bullet solutions!

- 7 Process Categories by ASTM F42 these vary by: materials, speed to build, accuracy, finished part quality, cost, accessibility and safety, multi-color or multi-functional part capabilities

What is Additive Manufacturing?

*Conventional production**

Design (Digital in this case)



Courtesy Local Motors

Decomposed into sub-assemblies and matched to tiered material suppliers and process

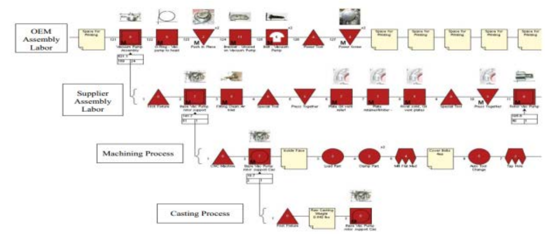


Figure 4-9: Example Illustrating the Various Levels Associated with Process Mapping a Vacuum Pump Base Support

http://www.epa.gov/otaq/climate/420r09020.pdf

Components produced

www.carbodydesign.com

"Body in white" assembly;
Thousands of welds/cuts/stampings/etc.

www.thedetroitbureau.com

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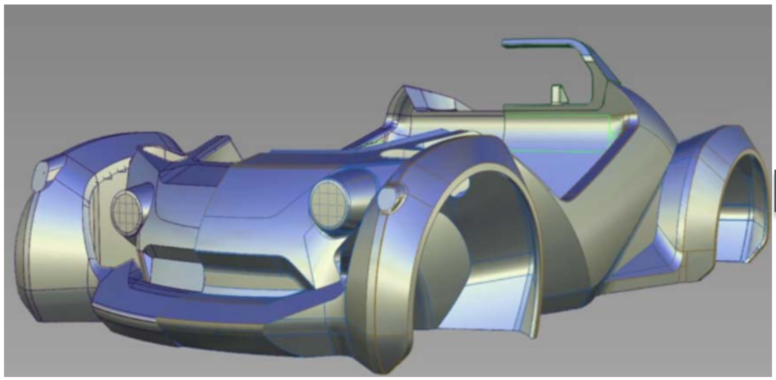
* Processes intentionally oversimplified to highlight differences; vehicles not comparable

What is Additive Manufacturing?

*Additive manufacturing**

Digital Design

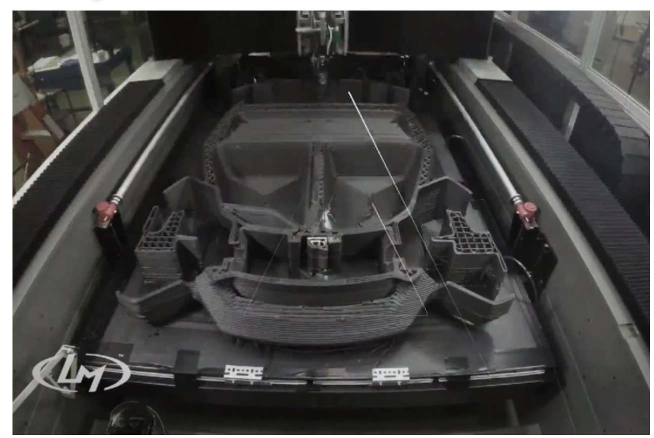


Courtesy Local Motors

Digital file transfer

Courtesy Cincinnati Inc.

Print



Courtesy Local Motors

One piece chassis/body;
One process step

Courtesy Local Motors

* Processes intentionally oversimplified to highlight differences; vehicles not comparable

Additive Manufacturing Overview

What is additive manufacturing?
Why use additive manufacturing?

Why use Additive Manufacturing?

- Enables entirely new, freeform designs
- Short lead time and fast prototyping
- Higher performance parts
- Supply chain and inventory benefits
- Distributed, on-demand production
- Consolidation of complex assemblies
- Mass customization
- Increased design control

Great for design innovation, complex an topologically complex parts, smaller runs, customized components, prototyping, materials R&D

For example…

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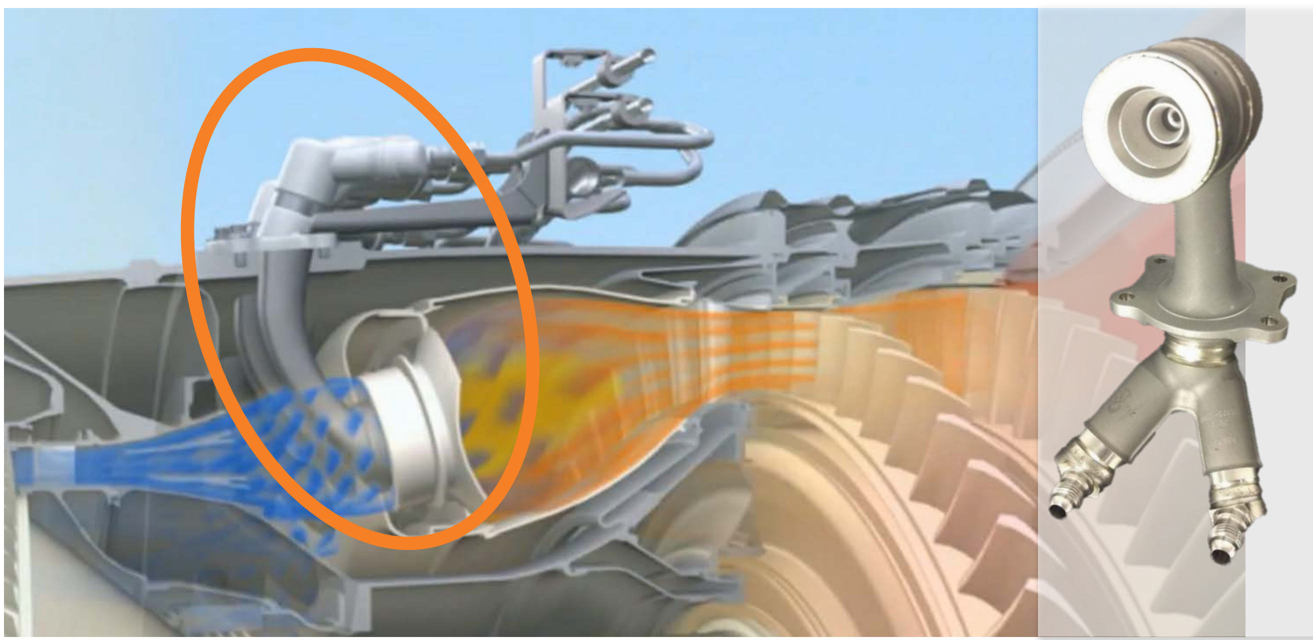
Why use Additive Manufacturing?

Ex. GE LEAP Fuel nozzle

- New topology that was previously impossible
- Consolidation of assemblies into single parts: 20 to 1
- Frees constraints imposed by traditional processes



"I need very complex shapes. I need shapes that a machine tool cannot generate."

-Joshua Mook, Lead Engineer

GE Aviation

https://www.asme.org/engineering-topics/media/aerospace-defense/video-printing-high-performance-fuel-nozzle. Photo credit: GE Aviation

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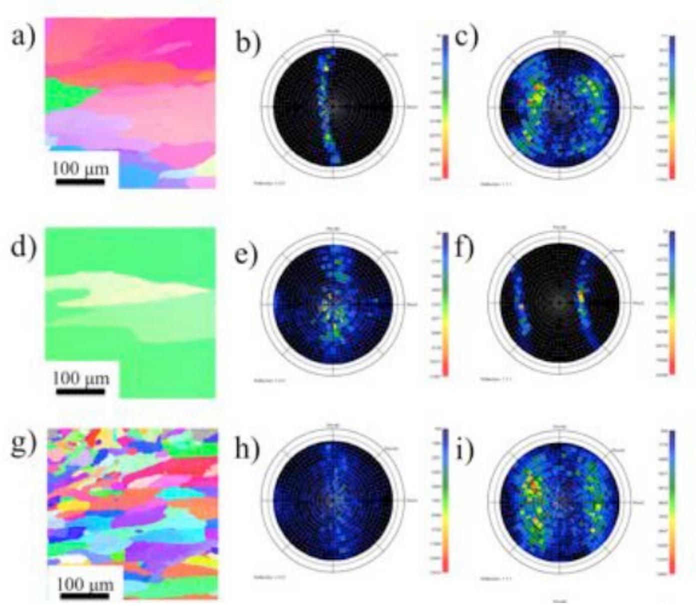
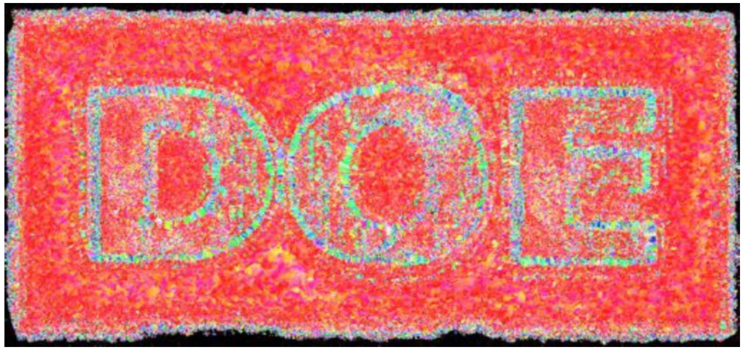
Why use Additive Manufacturing?

Localized modification of materials and properties throughout

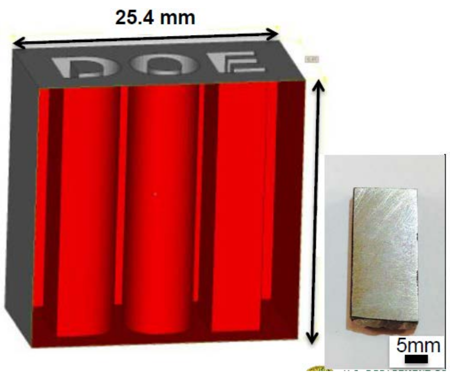
Crystallographic texture modification:



Grain orientation modification:



Test component:

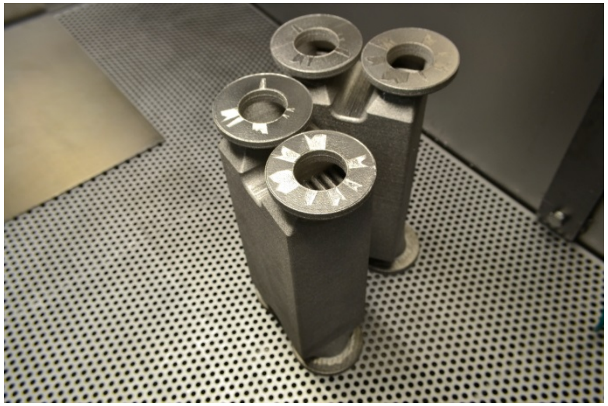


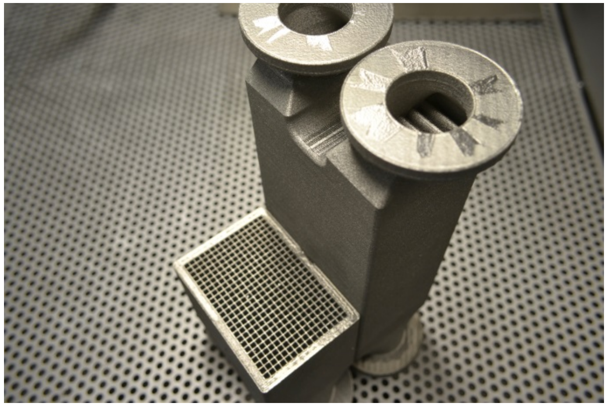
Results from AMO funded research at the Manufacturing Demonstration Facility at Oak Ridge National Laboratory

Why use Additive Manufacturing?

S-RAM Air Variable Compressor/Expander for Heat Pump and Waste heat to Power Applications

- Heat pump replaces hydrofluorocarbon (HFC) refrigerants with air
- Targeting 50% reduction in energy consumption
- AM of heat exchanger designs allows for improved prototype performance and efficiency and optimized fabrication costs
- Small privately-owned company started in 2011 in Franklin, TN
  - Heat pumps manufactured in the U.S.
- Project currently on-going (AMO sponsored)





Example AMO project with S-RAM

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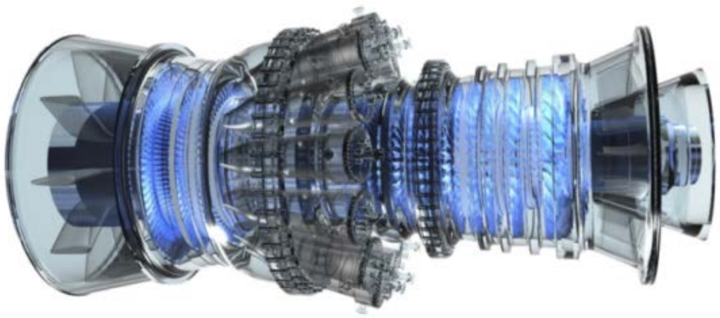
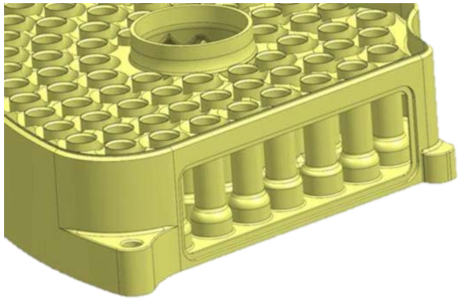
Why use Additive Manufacturing?

- Design, develop, and commercialize a highly efficient AM turbine combustor
  - Enabling an increase in efficiency 1%-2% by eliminating leaks and reducing cooling requirements
- Full scale micromixer fabricated from CoCr
  - Reduced part count from 200+ to 1
  - 15,000 braze joints eliminated
  - Increased reliability
- Redesign of turbine combustor incorporating multi-tube mixer design enables:
  - Increase burn temperature by at least 100F
  - Reduce cooling requirements
  - Eliminate leakages by reducing part count
- 1% efficiency gain*
  - Potential 205 Tbtu/year energy and 12 million tons CO_2/year savings

Evaluation of AM technologies for gas turbine components





*38 Quads electrical generation in US with 18% coming from natural gas (7 Quads)
1% gain in efficiency (58% to 59%) correlates to 205 Tbtu/year and 12 million tons CO_2/year savings (100% penetration)

Example AMO project with GE

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Why use Additive Manufacturing?

CINCINNATI®
CINCINNATI INCORPORATED

Big Area Additive Manufacturing (BAAM)

- Pellet-to-Part
  - Pelletized feed replaces filament to enable **50x reduction in material cost**
- Deposition rate **100x commercially available systems**
- Prototype system **8’x8’x8’** build volume
- Huge initial interest by aerospace and tooling industry

www.caradvice.com

Example AMO project with Cincinnati, Inc.

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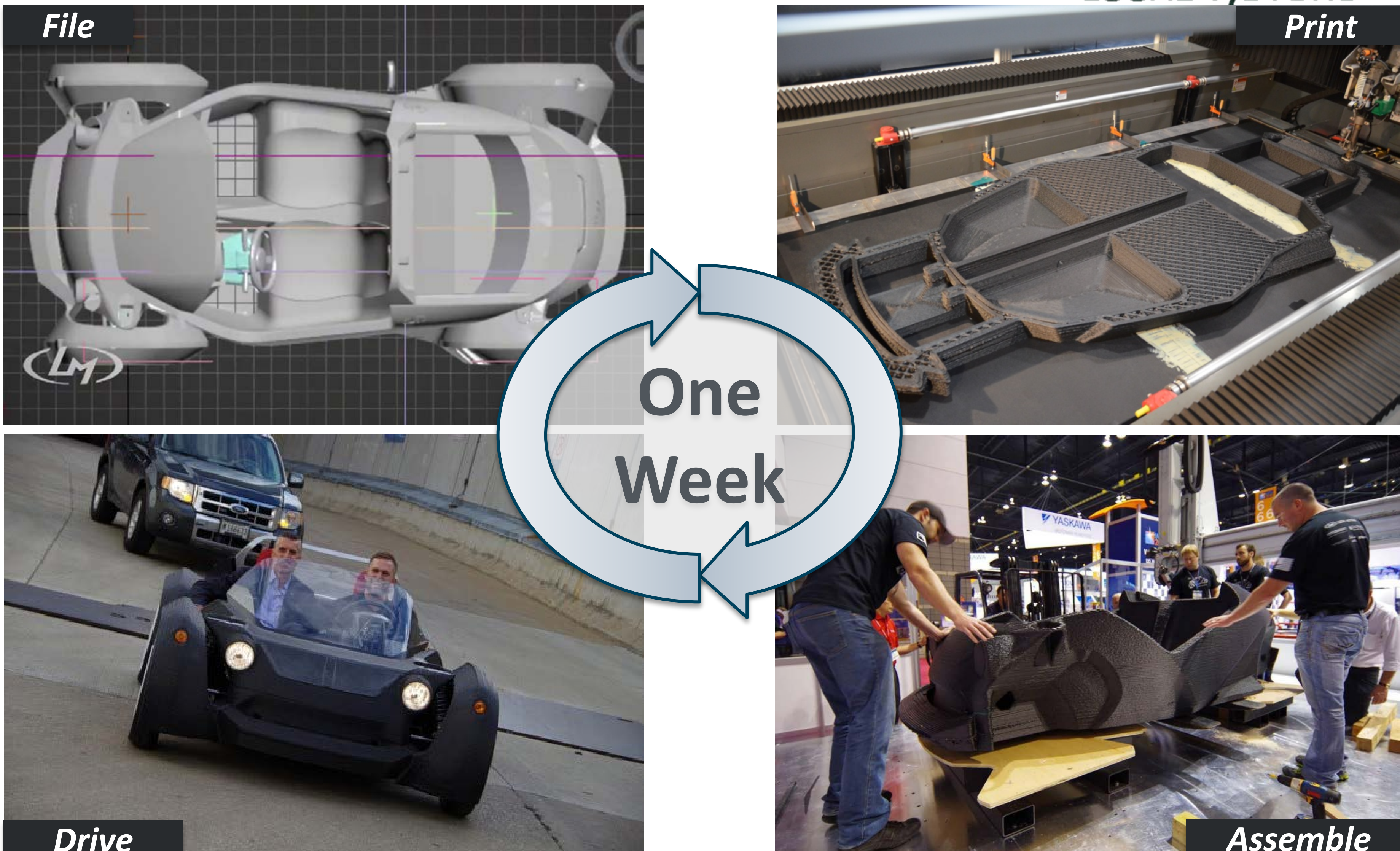
Why use Additive Manufacturing?

LOCAL MOTORS



Photos courtesy Local Motors, El blog del Plastico, Revealedtech.com

Example AMO project with Local Motors

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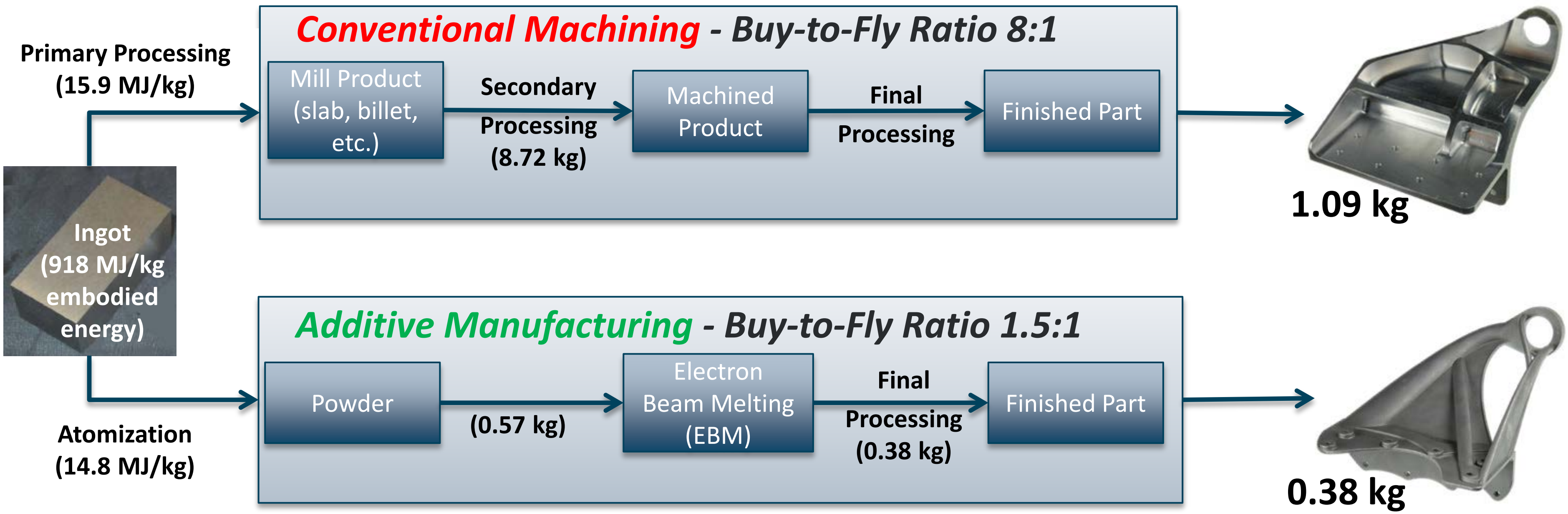
Why use Additive Manufacturing?

Energy Impacts



Process	Final part (kg)	Ingot consumed (kg)	Raw mat'l (MJ)	Manuf (MJ)	Transport (MJ)	Use phase (MJ)	Total energy per bracket (MJ)
Machining	1.09	8.72	8,003	952	41	217,949	**226,945**
EBM (Optimized)	0.38	0.57	525	115	14	76,282	**76,937**

Why use Additive Manufacturing?

One perspective on scenarios suited for additive manufacturing, courtesy of Senvol:

1. Expensive to manufacture
2. Long Lead-times
3. High Inventory Costs
4. Sole-sourced from Suppliers
5. Remote Locations
6. High Import/Export Costs
7. Improved functionality

Senvol provides additive manufacturing analytics for business: http://www.senvol.com/

** Senvol is a Member of America Makes. All content above is courtesy of Senvol and does not represent any position of the Department of Energy.*

Additive Manufacturing for Fuel Cells Applications

Design Innovations

- DMLS was used to prove out a concept for a fully integrated ejector and anode flow valve. The flow valve is controlled by anode pressure acting on a piston.
- The complete assembly was made from 3 pieces, and designed to twist lock, eliminating the need for tools and hardware to assemble.
- This would have been difficult and expensive to machine.
- DMLS is a cost effective way to prove the concept, MIM is envisioned for higher volumes.

Courtesy Benjamin Lunt "Additive Manufacturing for Fuel Cells", Feb 11 2014
http://energy.gov/eere/fuelcells/2014-webinar-archives#date021114

NUVERA
Making hydrogen make sense.

Weight Reduction

- An example of weight reduction is shown below. This first design on the right had ports through a solid body. The body was intended to be hollow, but removal of un sintered build material would have been difficult, so the body was built solid. The second design eliminated the face and replaced it with thin spokes, allowing for a hollow build.

Courtesy Benjamin Lunt "Additive Manufacturing for Fuel Cells", Feb 11 2014
http://energy.gov/eere/fuelcells/2014-webinar-archives#date021114

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Multiple Design Variations in a Single Build

- Design optimization can be achieved by testing of certain variable that are sensitive to performance.
- In this case, multiple parts where made in a single build. This can be done economically as long as all of the parts being build can fit onto the build table of the DMLS machine being used.
- This build was done to come up with a family of similar designs which would satisfy a wide range of fuel cell systems. In this case, how many different size ejectors would be required to meet the performance targets for systems varying from about 10-90kw gross.

Courtesy Benjamin Lunt "Additive Manufacturing for Fuel Cells", Feb 11 2014

http://energy.gov/eere/fuelcells/2014-webinar-archives#date021114

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Product Development – Component Integration

- DMLS was used again to test another variation of a similar part.
- Here, a manifold is added to integrate a solenoid valve directly to the hydrogen inlet of the ejector.

Courtesy Benjamin Lunt "Additive Manufacturing for Fuel Cells", Feb 11 2014
http://energy.gov/eere/fuelcells/2014-webinar-archives#date021114

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Conclusions

- DMLS was used to achieve an optimized ejector design with several iterations. Even with several iterations of the design, this was accomplished with only a few builds.
- The final designs are now optimized, and with a high level of confidence, tooling could now be created for high volume manufacturing.

Courtesy Benjamin Lunt "Additive Manufacturing for Fuel Cells", Feb 11 2014
http://energy.gov/eere/fuelcells/2014-webinar-archives#date021114

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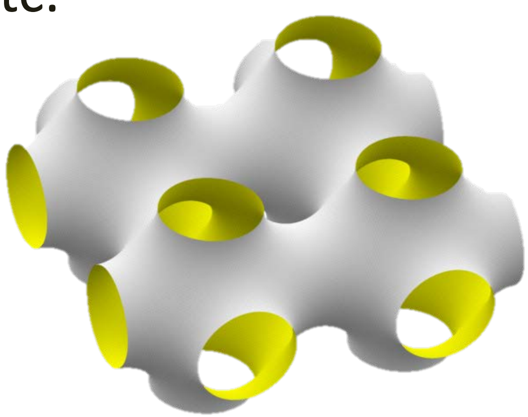
Additive Manufacturing for Fuel Cells Applications

Other possibilities

- Novel flow-field designs for bipolar plates
- Tailored surface chemistries & active surfaces
- Balance of Plant component design, assembly, and sizing
  - Integrate complex assemblies to reduce part count
  - Print conformal mechanical supports around fuel cell plates/shapes
- Conformal gas storage; e.g. Schwarz minimal surfaces
- Extreme high-surface areas for heat transfer, mass transfer, etc.



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Thank You

Questions?

For more information:

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