U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

2021 PROJECT PEER REVIEW

U.S. DEPARTMENT OF ENERGY
WIND ENERGY TECHNOLOGIES OFFICE

NREL Transforming ENERGY

OAK RIDGE National Laboratory

T08 – Manufacturing and Additive Design of Electric machines enabled by Three-dimensional printing (MADE3D)

Technology RD&T and Resource Characterization – Materials, Manufacturing, and Design Innovation

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National Renewable Energy laboratory

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FY21 Peer Review - Project Overview

Project Summary:

- As offshore wind turbine technologies continue to scale beyond 10MW, more efficient, reliable and high torque dense drivetrains are needed.
- Direct-drive generators are popular, but scale disproportionately with power ratings (12MW generators can weigh > 300 tons and measure 10m in diameter).
- Traditional methods for lightweighting direct-drive generators are limited → suboptimal, excessive use of rare-earth; computationally expensive, laborious, wasteful

Need for transformations in design and manufacturing

MADE3D

Enable lightweighting by full design space exploration and better near-net shaping using machine-learning (ML) & on-site multimaterial additive manufacturing.

Partners: ORNL, Carpenter Technology, Renishaw, ExOne

Project Objective(s) 2019-2020:

- Evaluate weight-reduction potential of a baseline direct-drive generator (IEA-15MW wind turbine).
- Develop machine-learning tools for accelerating magnetic design optimization for weight reduction from active parts and cost models for magnetic parts.
- Develop multimaterial processes for near-net shaping of soft magnets and hard magnets with reduced rare-earth content.

Successful completion determined by the following outcomes:

- A new software was developed to identify single- and multi-material designs that can reduce weight by up 30% from rotor active parts. Cost models for selective laser melting and binder jet additive manufacturing of Fe3Si steel were developed.
- Binder jet and selective laser melting processes produced crack-free Fe3Si steel with saturation flux density >1.2 Tesla. New methods for AlNiCo magnet and NdFeB magnets with reduced dysprosium content were developed.

Overall Project Objectives (life of project):

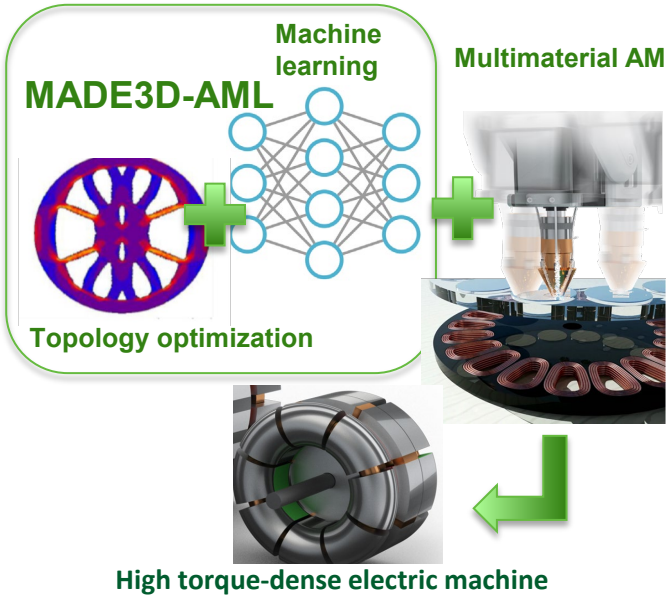
- **Develop a scalable, up to 40-50% lightweight permanent magnet generator.**
- **Advance reduced rare-earth (or) rare-earth free wind generator magnets** to mitigate wind industry's vulnerability to supply chain risks.
- **Advance design tools and cost models** for performing full exploratory, accelerated design and economic evaluation of 3D printed wind generators.
- **Advance multimaterial printing processes** for rapid prototyping of complex lightweight topologies of magnets, windings, electrical and structural steel.
- **A functionally validated advanced high torque dense MADE3D** generator.

Project Start Year: 2020
Expected Completion Year: FY 2023
Total expected duration: 4 years
FY19 - FY20 Budget: **Total : $692,488**
NREL : $392,488
ORNL : $300,000

Key Project Personnel: Latha Sethuraman, Ganesh Vijayakumar, Jonathan Keller, M. Parans Paranthaman, Tej Lamichhane, Haobo Wang and DiLea Bindel

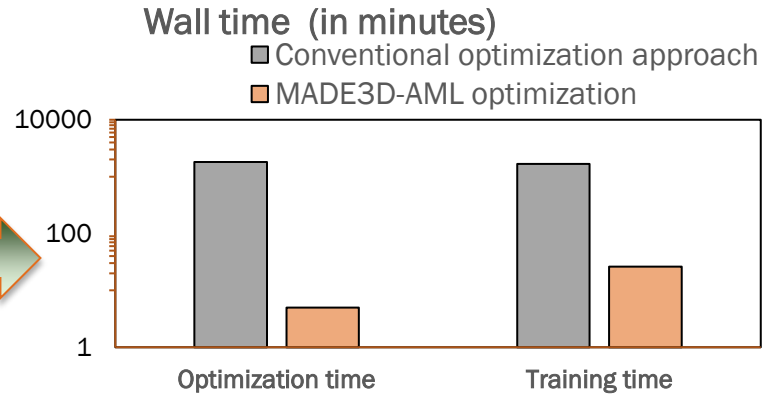
Key DOE Personnel: Benjamin Murray, Michael Derby

ML-AM enabled materials & design



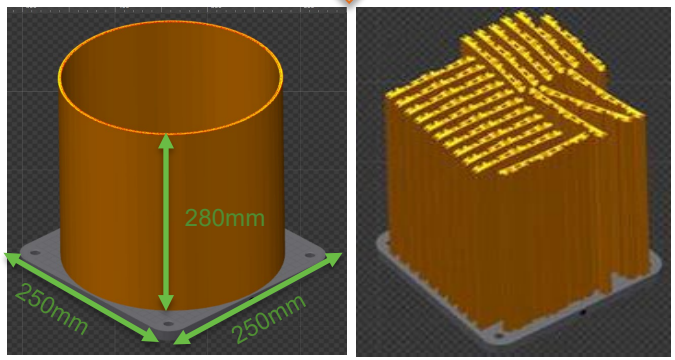
Project Impact - Enabling lightweight wind turbine generators

First-of-its-kind accelerated multimaterial design optimization tool MADE3D–AML : a novel first step in lightweighting wind generators by additive manufacturing.



MADE3D-AML accelerates magnetic design by a factor > 1000

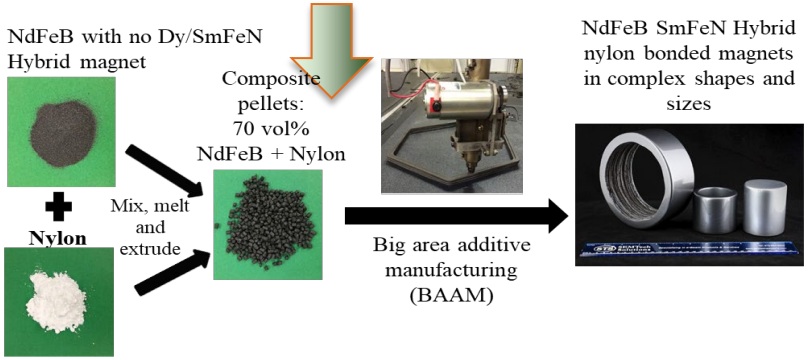
Simplified AM cost models provide early perspectives to costs of printing magnets.



Single part printing $967

Batch printing $1938

First-of-its-kind additive manufacturing process for reduced rare-earth magnets



Can potentially replace traditional sintering

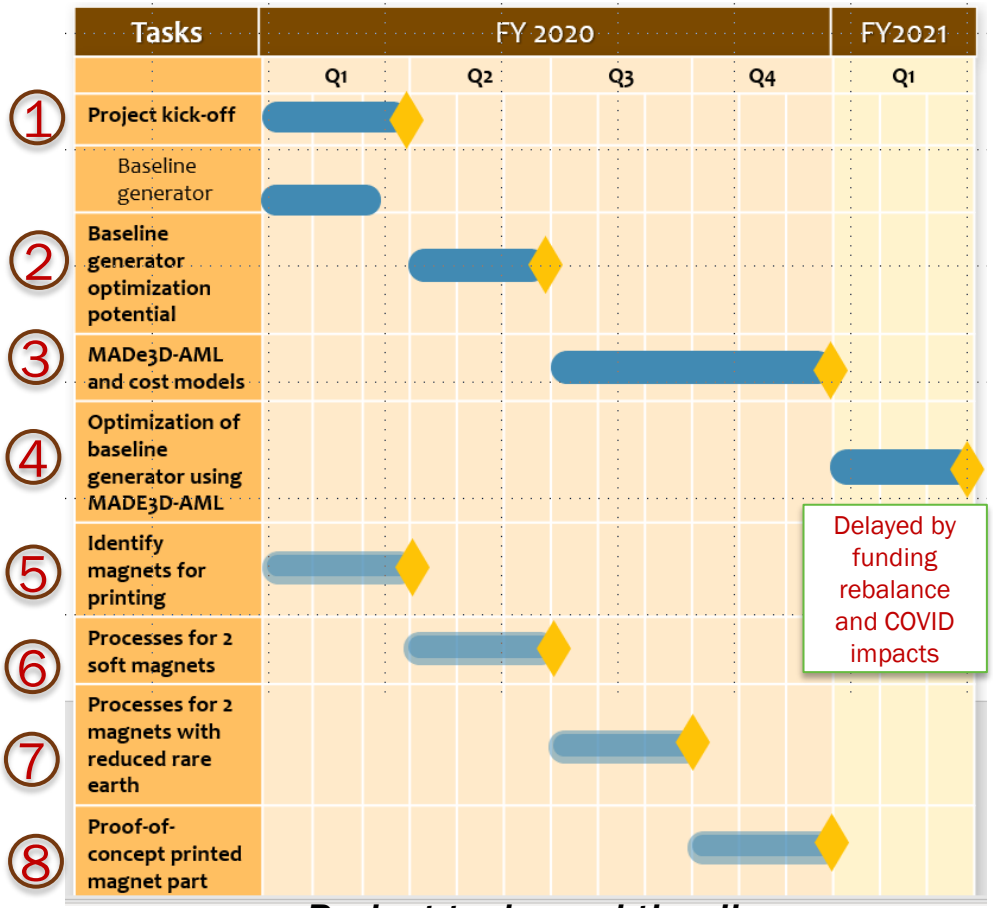
Program Performance – Scope, Schedule, Execution

FY2020 focused on design tools for magnetic optimization and multimaterial printing of magnets

- All, but 1 milestone (#4) met the schedule. The delay was due to a funding rebalance and COVID.
- Access to ORNL's Manufacturing Demonstration Facility was greatly restricted due to COVID. ORNL team mitigated the issues by actively working with external industry partners and University of Tennessee, Knoxville.

- **Highlights in 1st half of FY2020:**
  - IEA-15MW generator design domains.
  - Binder jet additive and laser sintering processes for soft magnets with and without ceramic oxides.

- **Highlights in 2nd half of FY2020:**
  - A new software - MADE3D-AML for performing multimaterial optimization for magnets and cost models
  - A binder jet additive method for AlNiCo magnet and big area additive manufacturing method for NdFeB magnets with reduced dysprosium content.

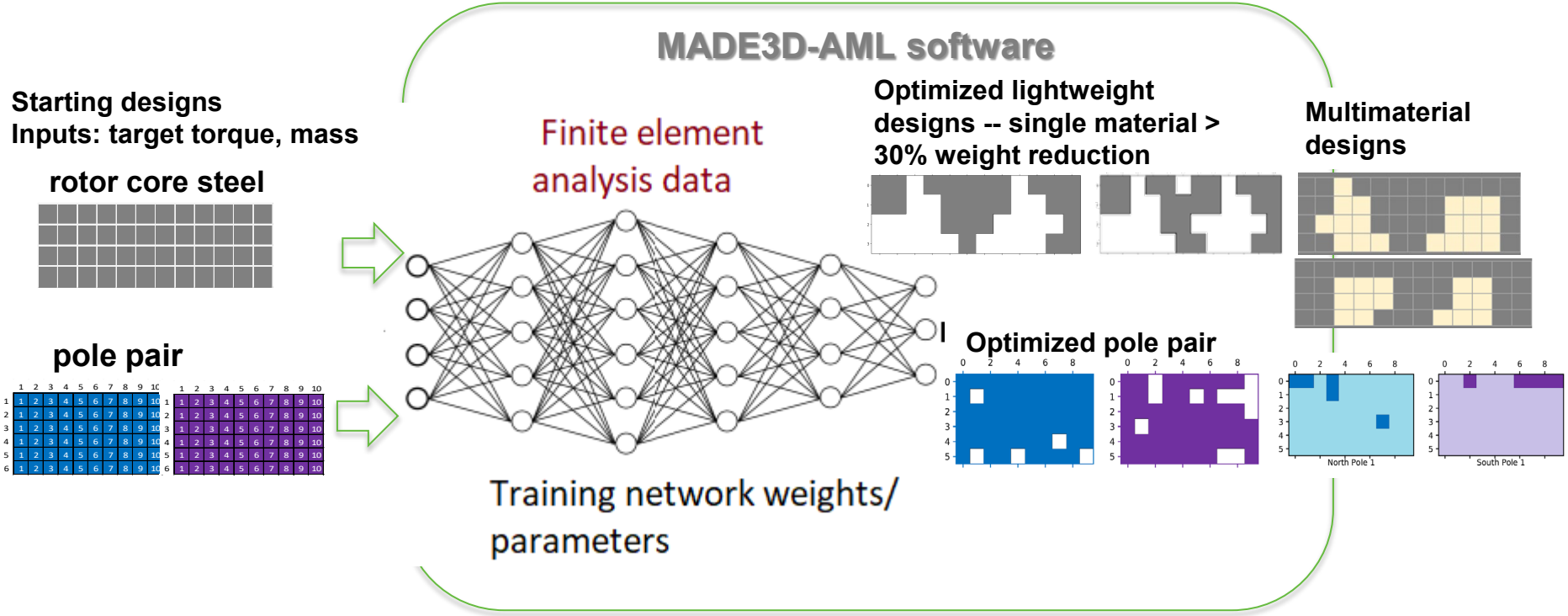


Project tasks and timeline

Program Performance – Accomplishments & Progress

✓ 1- software copyright, 2-patent applications and 2-journal review articles

- Completed the magnetic TO module of MADE3D-AML for optimizing 15MW reference generator



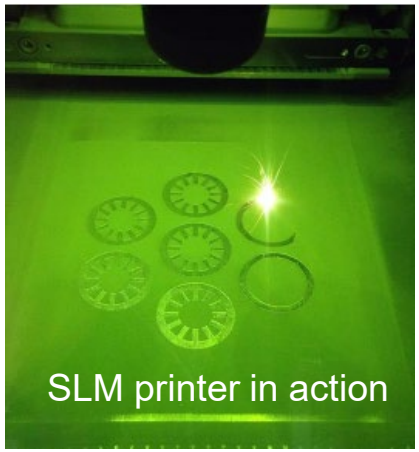
MADE3D-AML uses state-of-the-art deep generative learning models.

- Can handle single and multimaterial design optimization for magnets and rotor core.
- **Can aid material and design discovery :** optimal combination of materials with needed strengths
- Can help identify multiple designs meeting given objective in less than 5 minutes

Program Performance – Accomplishments & Progress

AM methods for crack-free full density soft magnetic parts

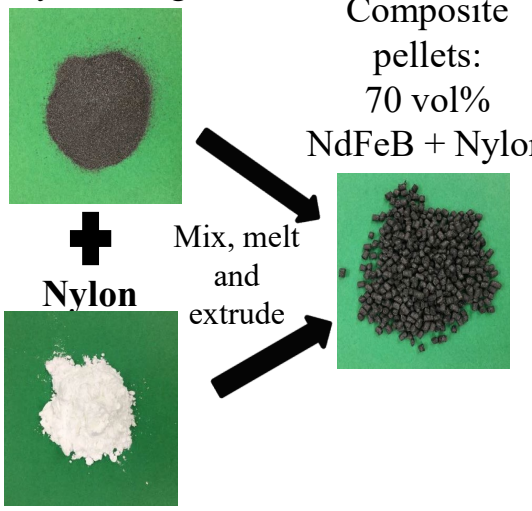
- Selective laser melting (SLM) stator part machined into laminated stacks.
- Post-annealing ↓ losses
- Mechanical properties ↑
- Scalable


SLM printer in action


Proof-of-concept SLM stator

Critical rare-earth free magnets

- BAAM magnets of complex shapes were machined into a rotor
- Eddy loss ↓ x3
- Resistivity ↑ x3
- Scalable
- Recyclable and remanufacturable



Proof-of-concept BAAM rotor

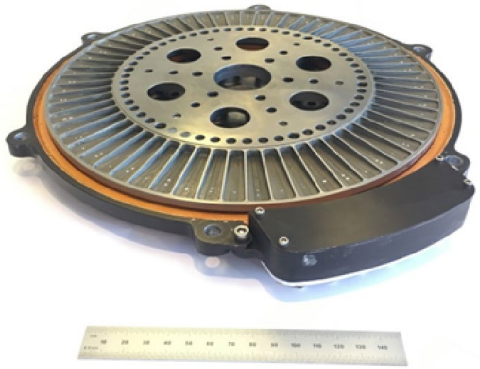
Project Performance - Upcoming Activities

MADE3D-AML and validation — **FY2021**
- magnet TO for a proof-of-concept (POC) machine.
- Printing rotor magnets with Ti6Al4V alloy support
- small POC machine

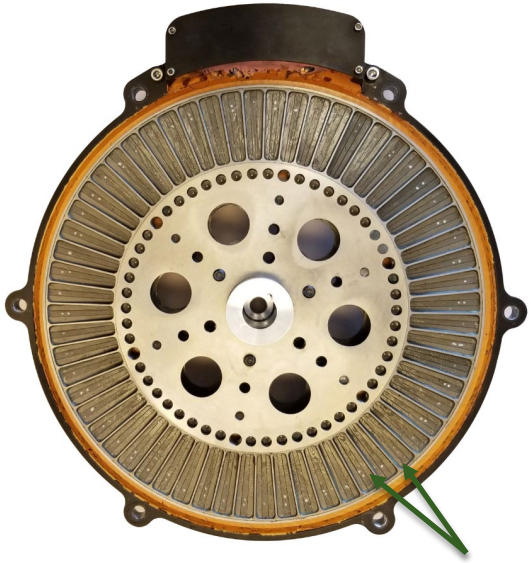
Rotor POC — **FY2022**
- MADE3D-AML for stator and cost models
- Small-scale POC testing of printed rotor
- Printing large magnets with high energy product and windings

Large magnet & stator POC — **FY2023**
- MADE3D-AML for multiphysics optimization and cost models
- POC testing machine with larger magnets
- POC testing of stator

Fully validated prototype — **FY2024**
- MADE3D-AML validation for full machine
- Validation of a fully 3D-printed generator.



Small proof-of-concept permanent magnet machine*



Axial–flux, Halbach array

*Partnership with Launchpoint EPS to design, print and test a small machine, scalable and operated as a generator

Stakeholder Engagement & Information Sharing

Project still in the early-stages of R&D

More than 78 interviews with industry partners in to identify potential partnerships.

ENERGY I-CORPS
U.S. Department Of Energy

Executed multiple multilateral Non-Disclosure agreements (NDA) and one-CRADA

Engagement with a wind OEM, active collaborations with alloy manufacturers and printer manufacturers - Arnold Magnetic Technologies, Carpenter Technology, Neo Magnequench, Aichi Steel/Toyota.

ExOne
Collaborate. Innovate. Accelerate.

GE Renewable Energy

RENISHAW

CARPENTER
TECHNOLOGY

LAUNCHPOINT
TECHNOLOGIES

Published research results in journal articles and conferences.

(19) **United States**
(12) **Patent Application Publication** (10) **Pub. No.: US 2021/0057149 A1**
Paranthaman et al. (43) **Pub. Date: Feb. 25, 2021**

US 20200188996A1

(19) **United States**
(12) **Patent Application Publication** (10) **Pub. No.: US 2020/0188996 A1**
SETHURAMAN et al. (43) **Pub. Date: Jun. 18, 2020**

Teams are pursuing licensing opportunities through lab partnering services.

Key Takeaways and Closing Remarks

Project Impact:

First steps in transforming design, materials and processes needed for minimizing wind industry's vulnerability to rare-earth supply chain and challenges in lightweighting next-generation wind turbine generators.

- ✓ MADE3D-AML : First-of-its-kind accelerated multimaterial design optimization tool to create 3D-printable lightweight wind turbine generators –**can facilitate new material discovery, optimal combination of critical materials and strengths.**
- ✓ First-of-its-kind AM process: for near-net shaping of reduced rare-earth free magnets with low eddy current losses – **New means to conserve critical materials.**

Project Performance:

- ✓ Project tasks and milestones were met on schedule with minor impacts due to funding rebalance and COVID delays
- ✓ Project resulted in 2-journal review articles, 2-patents and 1-software copyright

Stakeholder Engagement:

- ✓ Project performers are continuing to engage with industry through NDAs, explore partnership opportunities, publish in journals and conferences and file patents.