REACT Program Overview

This program seeks the development of transformational enabling technology solutions with potential for disruptive impact by the reduction or elimination of a dependence on rare-earth materials in emerging clean energy technologies. Specific high-impact application areas of rare-earth containing materials in clean energy technologies are alternatives for high energy density permanent magnets for electric vehicle motors and wind turbine generators. Approaches which establish new technology pathways to achieve systems-level clean energy performance with high efficiency and low cost, while reducing rare-earth material dependency, are of particular interest for funding.

1. BACKGROUND

Rare earth materials consisting of the lanthanide elements (lanthanum, cerium, neodymium, praseodymium, samarium, europium, gadolinium, terbium, dysprosium, erbium, thulium, ytterbium and lutetium, as well as yttrium and scandium) have an increased importance in clean energy applications due to their unique magnetic, optical, and chemical properties.[1,2]

While many rare earth elements are relatively abundant in mineral deposits in the United States and elsewhere in the world, over 95% of the global material production of all rare earth materials currently occurs in China.[3,4] In addition, while some rare earth minerals are mined and processed to rare-earth oxides at locations outside of China, very little commercial separation of rare-earth ore mixtures into specific elements or reduction of rare-earth oxides to metals is performed in the United States. Further, several of the heavy rare-earth elements such as dysprosium, yttrium, europium and terbium are more abundant in geological deposits in Southeastern Asia. Commercially viable rare-earth ore resources outside of this region (including in the United States) are primarily composed of light rare-earth elements (LRE) of cerium, lanthanum, neodymium and praseodymium.

With increased global competition for rare earth materials in emerging clean energy applications, limited availability from a single source presents a "criticality risk" to domestic clean energy technology development.[5,6] Criticality risk is the degree of risk related to potential supply interruption coupled with importance of specific elements for an application.[8] Figure 1 shows the criticality diagram of 14 elements examined in US DOE's Critical Materials Strategy, based on importance to clean energy and degree of supply risk.[9]

---

[1] "Critical Elements for New Energy Technologies: an MIT Energy Initiative Workshop Report" April 29, 2010. web.mit.edu/miteicomm/web/reports/critical_elements/CritElem_Report_Final.pdf (2010)

[2] "Critical Materials Strategy" US Department of Energy, www.energy.gov/news/documents/criticalmaterialsstrategy.pdf (2010)

[3] "Rare Earth Elements-Critical Resources for High Technology" US Geological Service, US Department of Interior, Fact Sheet 087-02 http://pubs.usgs.gov/fs/2002/fs087-02/ (2002)

[4] "The Principle Rare Earth Element Deposits of the United States – A Summary of Domestic Deposits and a Global Perspective" US Geological Service, US Department of Interior, Scientific Investigations Report 2010-5220 http://pubs.usgs.gov/sir/2010/5220/ (2010)

[5] "Minerals, Critical Minerals and the US Economy" National Research Council, National Academies Press www.nap.edu/catalog/12034.html (2008)

[6] "Critical Materials Strategy" US Department of Energy, http://www.energy.gov/news/documents/criticalmaterialsstrategy.pdf (2010)

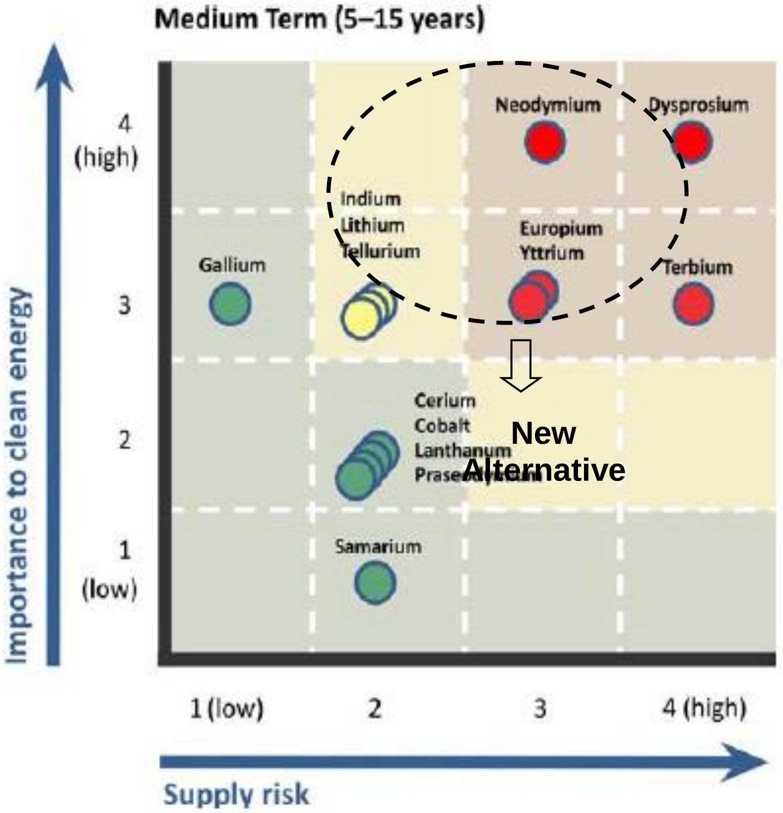

Figure 1: Criticality diagram for elements of importance for emerging clean-energy applications.[9] Neodymium, dysprosium, terbium, europium and yttrium have the greatest importance and risk of supply interruption over the next 5 to 15 years. As such, alternative technology solutions which would lessen the dependence on these materials for energy applications are sought.

The increased demand for rare earth materials in the global energy sector, combined with the potential decreased availability of imports to the United States from worldwide sources, is of concern in the medium term (5-15 years). In particular, supplies of Neodymium (Nd) and Dysprosium (Dy) may become constrained as use of these materials in magnets for clean-energy applications escalates dramatically. Specifically, the highest-known energy density in magnetic materials (in Megagauss Oersted or MGOe) are based on alloys containing Neodymium and Dysprosium, as the anisotropy in their structure combines in specific crystalline configurations to dramatically enhance magnetic coercivity.[7,8] Such high energy density magnets are a critical enabling component technology in several emerging clean energy applications, most notably permanent magnets for vehicle traction drive motors and large direct-drive wind turbine generators.

One response to the shortfall of rare-earth materials is to rely on market forces to encourage private sector expansion of supply and/or the development of new mining and refining facilities, using the currently available state-of-the-art processes, at domestic and global resource locations. However, as shown in Figure 2, rare-earth elements such as Neodymium are likely to experience supply-demand mismatches over the next 5-10 years, even though new rare-earth

---

[7] "Recent Developments in Hard Magnetic Bulk Materials" J. Fidler, T. Schrefl, S. Hoefinger, M.Hajduga, *J. Phys. Condens. Matter*, 16, pS455-S470 (2004)

[8] "Neodymium-Iron-Boron Permanent Magnets" J. Herbst and J. Croat, *Journal of Magnetism and Magnetic Materials*, 100, p57-78 (1991)

processing facilities (from firms such as Molycorp and Lynas) have been publicly announced and are scheduled to commence operation within the next 5 years. Furthermore, new facilities may have less impact on the supply of heavy rare earth elements such as Dysprosium, for which global demand is projected to exceed global supply, since the newly-developed rare-earth resources are expected to have significantly lower HRE concentration than existing overseas ores.[9] In “Fast Cleantech Growth” cases that assume rapid adoption rates of clean energy technologies with high critical material intensity on a global basis, rare earth resources are depleted faster than new supplies and proven reserves can be economically brought into production. In these scenarios, the availability of a reliable rare-earth materials supply chain will become a critical differentiator in manufacturing competitiveness across energy sectors.[10] Therefore, there is a pressing need to develop new technology alternatives that reduce or eliminate the use of rare earth materials in emerging clean energy applications that are of high economic and national importance.

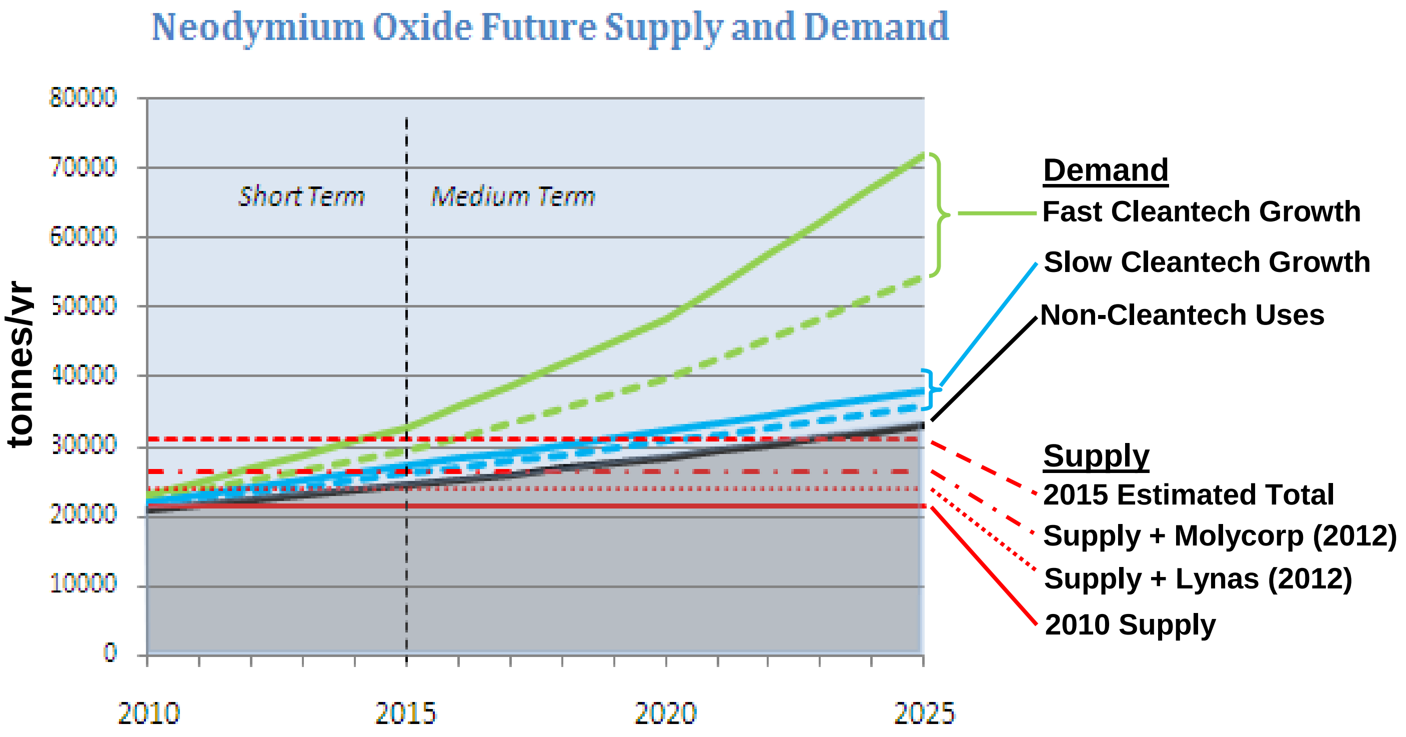

Figure 2: Projected worldwide supply and demand for Neodymium oxide.[12] Even with new commercial production from identified resources, a shortfall will occur in approximately 10 years. Under higher clean energy penetration scenarios, this shortfall is projected in 5 years.

In this program, ARPA-E will focus on developing alternative technologies in two specific clean energy applications that currently have critical dependencies on rare earths: motors for emerging electric vehicles (permanent magnets) and generators for direct-drive wind turbines (permanent magnets).

For each application topic, over-the-horizon system level metrics are defined, with the goal of motivating the development of disruptive enabling component technologies capable of meeting subsequent aggressive system targets with reduced or eliminated rare-earth material content.

---

[9] DOE Critical Materials Strategy, Chapter 7, http://www.energy.gov/news/documents/criticalmaterialsstrategy.pdf (2010)

[10] ”Energy Critical Materials: Securing Materials for Emerging Technologies” American Physical Society Panel on Public Affairs and the Materials Research Society, www.aps.org/policy/popa-reports/ (2011)

Category 1: Technology for motors in cost effective and efficient electric vehicle applications (rare earth magnet alternatives):

For electric vehicle applications, permanent magnet motors couple electric energy to propulsive torque at high efficiency across a broad range of operating conditions at acceptable cost and power density levels for vehicle applications as described below.[11] For similar torque and power ratings, the energy density of permanent magnet motors increases with the energy density of the magnets. For continuous technology advancement, the US Department of Energy's Vehicle Technologies Program (VTP) has focused on a roadmap for reducing cost ($/kW) and increasing specific power (kW/kg) in 30 kW (continuous) / 55 kW (peak) motors over the next decade (see Figure 3).[12] The power and torque in such electric motors is consistent with the requirements for hybrid electric vehicle (HEV) applications, where propulsion combines electric motors and internal combustion engine in a drive-train.[14,15] The rare earth content in a current state-of-the-art permanent magnet motors used in such HEVs is roughly 3-5g of rare earth material per kW of rated peak power.[13,14]

For future electric vehicle (EV) applications in which large vehicle platforms are propelled all-electrically, a motor that provides 100 kW (continuous) / 200 kW (peak) may be required.[15] While costs of energy storage systems will be substantial in these vehicles, the costs of the larger, high-performance motors used in these vehicles could also be a barrier to adoption, particularly if permanent-magnet designs are used. ARPA-E seeks early-stage enabling component-level technology innovations that would have the potential to simultaneously reduce rare earth content, lower cost, and increase performance of motors for next generation electric vehicles. Specifically, ARPA-E aims to enable development of advanced EV motors that eliminate or greatly reduce rare earth content to less than 10% of that used in typical existing permanent magnet motors (not exceeding 0.33 g/kW).

---

[11] "Electrical Machines and Drives for Electric, Hybrid and Fuel Cell Vehicles" Z. Zhu and D. Howe, *Proc. of IEEE*, Vol 95, No 4, p746-765 (2007)

[12] "Multiyear Program Plan: 2011-2015" US Department of Energy, Vehicle Technology Program (2010) http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/vt_mypp_2011-2015.pdf

[13] ARPA-E Calculation for a 2004 Prius: A 55kW permanent magnet motor contains 1.1kg of sintered NdFeB magnet, with a typical rare earth content of 25-30%. This yields a rare earth content of 4.5-5.5g/kW in permanent magnets. Teardown data from: "PM Motor Parametric Design Analyses for a Hybrid Vehicle Traction Drive Application" R. Staunton, S. Nelson, P. Otaduy, J. McKeever, J. Bailey, S. Das, R. Smith *ORNL/TM-2004/217* (2004) www.ornl.gov/~webworks/cppr/y2001/rpt/121559.pdf

[14] ARPA-E Calculation for 2010 Prius: A 60kW permanent magnet motor contains 0.768kg of sintered NdFeB magnet, with a typical rare earth content of 25-30%. This yields a rare earth content of 3.2-3.8-g/kW in permanent magnets. Teardown data from: "Evaluation of the 2010 Toyota Prius Hybrid Synergy Drive System" T. Burress, S. Campbell, C. Coomer, C. Ayers, A. Wereszczak, J. Cunningham, L. Marlino, L. Seiber, H. Lin *ORNL/TM-2010/253* (2011) http://info.ornl.gov/sitres/files/Pub26762.pdf

[15] For comparison, the electric motor in the all-electric Tesla Roadster is rated as 215kW (peak). www.teslamotors.com/roadster/specs

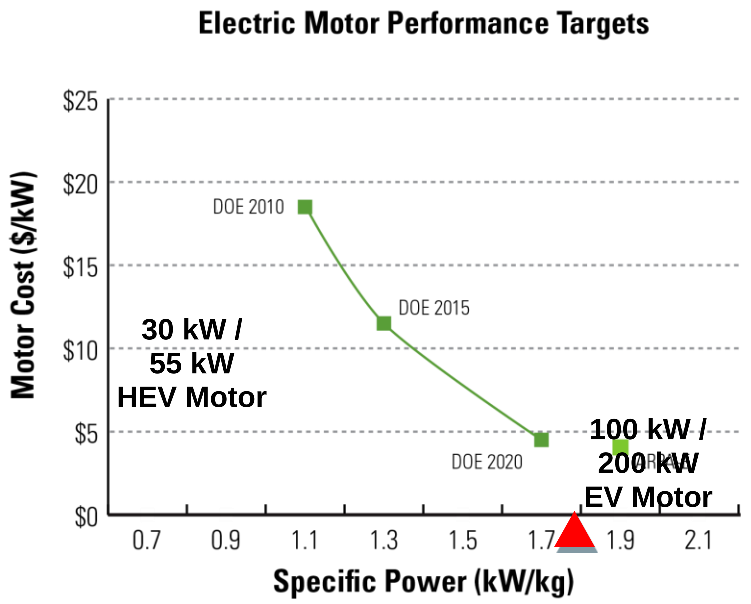

Figure 3: Technology trajectory for electric motors for use in electric vehicles.

ARPA-E is particularly interested in supporting the development of innovative enabling component technologies with broad potential system benefits. Submissions which propose enabling component technology should provide a clear and compelling explanation of how breakthroughs at the component level would have transformational impact at the system level, including the reduction of rare-earth material content. For example, the development of amorphous soft magnetic material formations in complex core structures which would enable low-cost, high efficiency, permanent magnet free induction motors suitable for EV applications.

The system-level goal of reducing rare-earth material content while increasing the power and decreasing cost in electric vehicle motors might be achieved through several technical strategies, including but not limited to: (A) new high energy density, low-rare earth content permanent magnetic materials may be developed through the use of ab-initio computational materials simulation combined with high throughput combinatorial screening of new compositions or structures; (B) non-permanent magnet motors such as induction or reluctance motors leveraging the use of advanced solid-state drive electronics, coupled with advanced high-permeability low-loss soft magnetic materials may be developed; or (C) new approaches to magnetic circuit design based on short range correlation design of magnetic phenomena may be developed[16]. For magnetic materials development, approaches that would potentially eliminate the use of Dysprosium in permanent magnetic materials requiring high operating temperature tolerance are of particular interest. Applications that focus on system-level demonstrations of electric motor concepts based on existing component level technologies but do not include component level technical risk or innovation are of less interest to ARPA-E under this category. Similarly, simulations or assessment studies that do not include demonstration of a new innovative component level technology are not of interest. Finally, concepts which primarily focus on the development of novel power electronics for motor applications would be discouraged from applying as these technologies are currently supported through the ARPA-E Agile Delivery of Electrical Power Technologies (ADEPT) program.[17]

Component-level technologies that, if successfully developed, result in dramatic improvements to system-level functionality are of high interest under this category. Applicants who propose component-level innovations are not necessarily required to demonstrate performance in a full motor prototype as part of this program. However, applicants

---

[16] Fullerton, L., et.al. "Ring Magnet Structure Having A Coded Magnetic Pattern" US Patent 7,755,462 (2010)

[17] ARPA-E Agile Delivery of Electrical Power Technology (ADEPT) program: http://arpa-e.energy.gov/ProgramsProjects/ADEPT.aspx

who are not proposing a quantitatively measurable motor system level demonstration must provide a clear, compelling and quantitative explanation of a new component’s impact on system-level functionality, and must also outline a feasible plan for subsequent transition and demonstration at a system level (including potential system integration partners) in future efforts if initial component development is successful. All applicants are encouraged to include electric motor systems technical partners on their teams to ensure rapid and effective subsequent transition of early stage technologies.

Category 2: Enabling technology for high power generators for direct drive wind turbines (rare earth magnet alternatives)

In direct drive wind turbine generator applications, high-energy-density permanent magnets are used to create high magnetic flux densities to efficiently couple torque to electricity generation, particularly under conditions of high-torque and low rotational speeds. For new, large-scale wind turbine generators (> 4MW), direct drive systems are preferable, as they have the potential to reduce the operation and maintenance cost for traditional gearboxes.[18] Larger direct drive systems are particularly attractive for off-shore wind installations, where access to turbines may be costly and maintenance intervals infrequent. However, in direct drive systems, the generator rotates at the same rate as the wind turbine (typically ~10 RPM), as rotation rate is limited by the linear velocity and related aerodynamics of the blade tips. The high-torque related to the slow generator rotation speed of direct-drive wind-turbines also stresses generator and shaft components to a level exceeding that of conventional steam generation systems.[19] The low rotation speed of direct drive systems necessitates higher magnetic flux density to generate power from the drive shaft.[20] High energy density permanent magnets are thus a critical enabling component in future wind generation systems, with several hundred kilograms of rare earth materials projected for each turbine for large-scale offshore wind.[21,22,23] The increased magnetic field strength greatly increases the dependence on rare-earth materials for electric power as well as the total system mass for permanent magnet direct drive generators at relative to traditional geared wind generators, as shown in Figure 4a.

While the overall goal of this category is to develop disruptive technology pathways to eliminate rare-earth permanent magnet content in large-scale offshore wind turbines, the range of solutions need not be constrained to generator components, and may target any point in the wind turbine system that significantly enables the elimination of rare-earth permanent magnet content. Technology alternatives might include: the development of rare-earth free high energy-density permanent magnetic materials, advanced hydraulic transmission for drive train systems, as well as high-temperature superconductor generators (HTSCG). Based on recent analysis, high-temperature superconducting generators could provide a lower cost relative to permanent magnet or geared systems for high power (>6MW) direct-drive turbines proposed for offshore wind, as shown in Figure 4b.[24]

---

[18] “Advanced Wind Drivetrain Concepts: Workshop Report, June 29-30, 2010” http://www.nrel.gov/docs/fy11osti/50043.pdf

[19] ARPA-E Calculation for Comparison: A 5MW horizontal axis wind turbine at 10 RPM requires a generator shaft torque of 4.8 MNm (Power = Torque*Angular Velocity). By comparison, a 500 MW conventional steam turbine at 3600 rpm generates only a torque of 1.3 MNm.

[20] Voltage generated is proportional to the change in flux ($-d\Phi/dt$) across a coil which is proportional to magnetic field (B) and angular velocity (ω). For direct drive turbines with no gearbox, the low generator rotation speed must be compensated for with higher magnetic field in the generator windings.

[21] Wind Power Monthly, Vol 26, 11 (Nov 2010) p 17.

[22] ARPA-E Calculations of Rare Earth Mass in Wind Turbine Permanent-magnet Generator: For a scaled generator design, 300kg/MW of NdFeB magnet materials with Dysprosium added for elevated temperature tolerance, results in 93kg of Nd/MW (31% Nd by mass) and 6kg of Dy/MW (2% Dy by mass) would be required for a wind turbine generator. A 10MW turbine would require 930 kg (2046 lbs) of Nd and 60kg (132 lbs) of Dy (magnet mass per MW from reference 26, figure 7.10)

[23] “Design of Direct-driven Permanent-magnet Generators for Wind Turbines” Anders Grauers, *Technical Report 292*, Chalmers University of Technology, Goteborg, Sweden webfiles.portal.chalmers.se/et/PhD/GrauersAndersPhD.pdf (1996)

[24] “Comparative Assessment of Direct Drive High Temperature Superconducting Generators in Multi-Megawatt Class Wind Turbines” B. Maples, M. Hand and W. Musial NREL/TP-5000-49086 www.nrel.gov/docs/fy11osti/49086.pdf (2010)

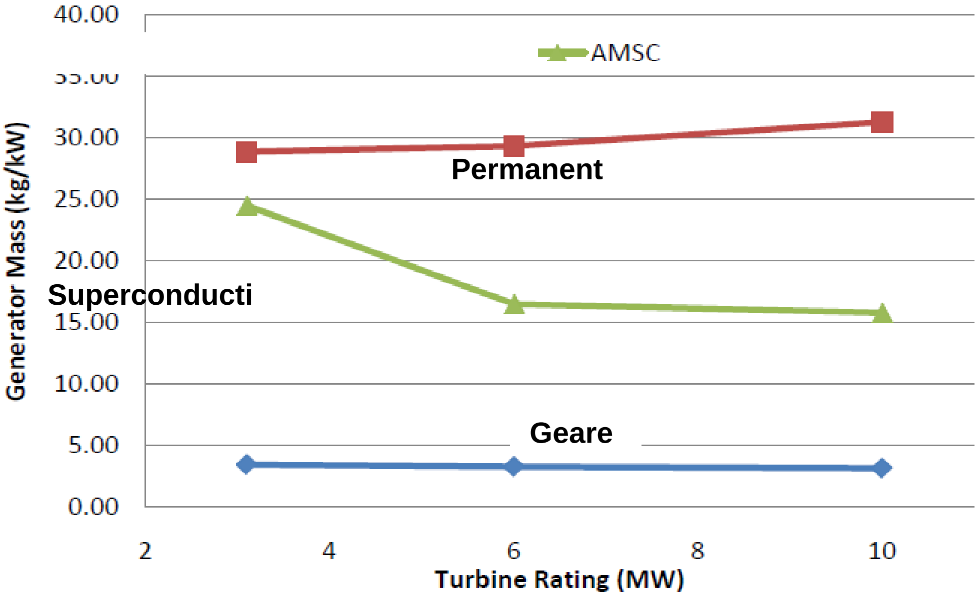

Figure 4a: Wind turbine generator mass for various generator technologies

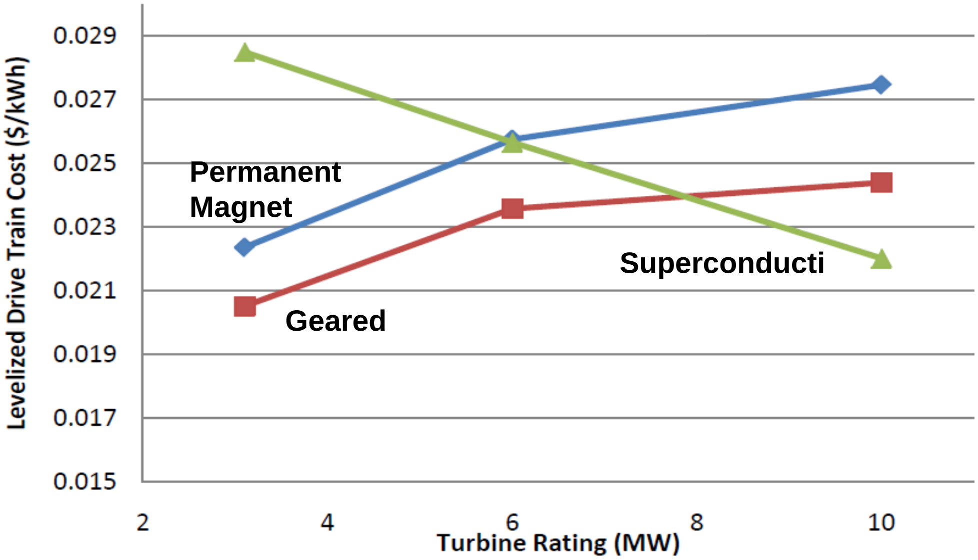

Figure 4b: Wind turbine drive train cost for various generator technologies

To address the challenge of reduced rare-earth magnet materials dependence in large-scale wind generation, ARPA-E is interested in early stage technologies with the potential to achieve a levelized drive train cost of <$0.022/kWh, to be used in wind turbine generators scalable from 6MW to 10MW or larger with zero rare earth content. This target is suitable with the technical requirements for torque (5.0 MNm to >8.8 MNm) and rotation speed (12.3 RPM to 11.5 RPM) of future direct drive wind generation systems.[25] Proposed solutions should be compatible with the size and weight restrictions proposed for off-shore wind turbine systems (tower design and cost) as well as providing >10 year utility scale lifetime, high reliability and reasonable operational costs.

---

[25] "Comparative Assessment of Direct Drive High Temperature Superconducting Generators in Multi-Megawatt Class Wind Turbines" B. Maples, M. Hand and W. Musial NREL/TP-5000-49086 Page 9, Table 1. www.nrel.gov/docs/fy11osti/49086.pdf (2010)

The goal of reducing rare earth materials supply risk for permanent magnets in advanced direct drive wind generators might be achieved through several different technical pathways, including but not limited to[26]: (A) new high energy density non-rare earth containing permanent magnetic materials may be developed, for instance, through the use of high throughput combinatorial synthesis and screening informed by advanced computational models; (B) development of radical new technologies for un-geared hydraulic transmission systems at high torque and power densities; (C) the development of advanced superconducting generators based on scalable low cost, high critical field and high critical current density superconductors or completely new topologies for generating electric power from large scale wind turbines could also be pursued. Early-stage technology development that focuses on the key technical barriers to wind turbine generator systems free of rare-earth magnets are of highest interest to ARPA-E. While technology barriers addressed in this effort may be at the material, component or system level, proposed efforts for advances at the material or component level should clearly and quantitatively identify resultant impact of technology breakthroughs on the system level. However, efforts that primarily consist of simulation and modeling studies and do not contain the demonstration of a high-risk transformational early stage technology are not of interest for this category.

2. PROGRAM OBJECTIVES

The purpose of this funding opportunity is to develop disruptive enabling technology approaches to applications in clean energy systems for electric vehicle motors and direct drive wind generators while simultaneously reducing dependency on rare-earth materials. Such system-level technical breakthroughs are often dependent on the development of completely new enabling component technologies. In this program, ARPA-E seeks the development of new enabling component technologies within the context of advanced and aggressive system level performance requirements. The development of such enabling technologies is intended to set the technology development in new directions to attain the benefits of low-cost, efficient clean energy services with a reduced dependence on rare-earth materials. Diverse teams that include expertise in both advanced materials (such as permanent magnets) and motor design are strongly encouraged.

3. AREAS OF INTEREST

Areas of Particular Interest:

- Early-stage electric motor/generator components that enable reduction or elimination of rare earth materials, including:
    - New high energy density permanent magnets which substantially approach or achieve zero rare-earth content in one or more constituents;
    - Novel soft magnetic materials and components for complex shapes in electric motors and generators;
    - Advanced insulating materials and components for electric motors and generators with high electrical and thermal breakdown tolerance under high operating current and voltage transient conditions; and
    - New superconducting materials and components, particularly for large-scale wind generators.
- Novel demonstration of transformational systems technologies that integrate one or more advanced components to achieve superior performance in electric vehicle or wind generation applications; and
- High- efficiency rare-earth free gearless components and systems for large-scale wind turbine systems.

Areas Specifically Not of Interest:

---

[26] "Advanced Wind Turbine Drivetrain Concepts: Workshop Report" EERE Wind and Water Program, June 29-30, 2010. www.nrel.gov/docs/fy11osti/50043.pdf

- Incremental improvements to, or combinations of, existing products and technologies, wherein no significant advances in understanding or reductions in technical uncertainty are achieved;
- Demonstration projects that do not involve a significant degree of technical risk;
- Simulations or assessment studies that do not include demonstration of new innovative component-level or system-level technology development or demonstration;
- Projects which focus exclusively on innovations in power electronics. This technical area is currently supported by ARPA-E through the Agile Delivery of Electrical Power Technology (ADEPT) program.

Any Concept Papers or Full Applications that focus on “Areas Specifically Not of Interest” will be rejected as nonresponsive and will not be reviewed or considered.

4. TECHNICAL PERFORMANCE TARGETS

Applications will not be considered for funding unless they have a well-justified, realistic potential to meet or exceed all of the Primary Technical Targets by the end of the period of performance for the proposed project. In this program, ARPA-E seeks development of electric motor or generator systems that meet the metrics outlined below, or electric motor or generator components that enable systems to meet the system-level metrics below. Applicants who choose to develop full motor systems must develop a system with sufficient power rating to justify scalability to the targets below. Applicants who choose to focus on development of an advanced component (such as magnetic materials) do not need to deliver a complete motor system in this program. However, these applicants must clearly articulate their assumptions regarding the utilization of the new enabling component technology in a proposed system such that measurement of technical progress during program performance and determination of potential impact in the area of application may be assessed.

Applications will receive favorable consideration if they also meet or exceed at least one of the Secondary Technical Targets. Preference will be given to applications that have a well-justified, realistic potential to meet or surpass most, if not all, of the Secondary Technical Targets.

The Primary Technical Targets and Secondary Technical Targets for this FOA are stated below.

Area 1: Advanced Magnetics for Electric Vehicle Motors

ARPA-E seeks development of motor systems that meet the following metrics, or motor components that enable systems to meet the following electric motor system-level metrics:

a. PRIMARY TECHNICAL TARGETS FOR ELECTRIC VEHICLE MOTORS

ID Number	Category	Value (Units)
1.1.1	SCALABLE TO POWER, CONTINUOUS (PEAK POWER FOR 18 SEC DURATION)	100kW (200kW)
1.1.2	SPECIFIC POWER (PEAK)	>1.9 kW/kg
1.1.3	COST (MOTOR)	<$3/kW
1.1.4	RARE EARTH CONTENT	<0.33g/kW

b. SECONDARY TECHNICAL TARGETS FOR ELECTRIC VEHICLE MOTORS

ID Number	Category	Value (Units)

1.2.1	Efficiency (30%-60% of the rated RPM at 25% rated torque)	>95%

Area 2: Advanced Magnetics for Electric Generators

ARPA-E seeks development of generator systems that meet the following metrics, or generator components that enable systems to meet the following generator level metrics:

c. Primary Technical Targets for Electric Generators

ID Number	Category	Value (Units)
2.1.1	Scalable to Power	>6 MW
2.1.2	Torque	>5MNm
2.1.3	Rare-Earth Permanent Magnet Content	Zero (0 kg/MW)
2.1.4	Cost (LCOE of wind generator drivetrain)	<$0.022/kWh

d. Secondary Technical Targets for Electric Generators

ID Number	Category	Value (Units)
2.2.1	Efficiency (at rated RPM)	>95%
2.2.2	Rotor Hub Speed	Up to 12.3 RPM
2.2.3	Operating Temperature (magnets)	>120 C