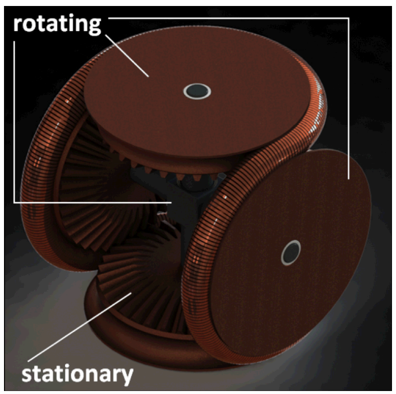
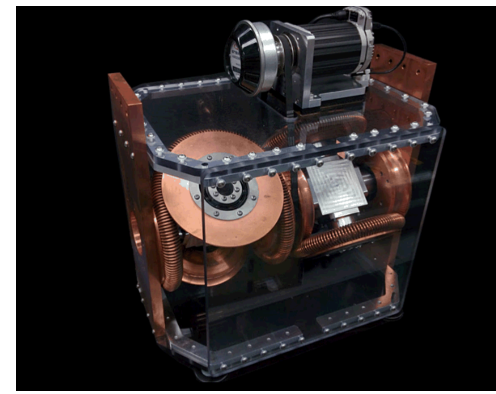
SAND2017-0344PE





Twistact Techno-economic Analysis

January 11th, 2017

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND NO. 2011-XXXXP

Outline

- Project Overview (Brian Naughton)
- Generator Design Analysis (Katherine Dykes)
- LCOE Analysis (Katherine Dykes)
- Supply Chain Analysis (Justin Vanness)
- Conclusions and Discussion

Project Overview

- Sandia team presented Twistact technology to DOE staff in October, 2014
- DOE requested a proposal for SNL & NREL to conduct a techno-economic assessment of the Twistact technology and its potential impact to the wind industry
- A joint proposal was submitted to DOE on February 18th, 2015
- The project was funded in August, 2015 and the work began in FY16 and concluded in Q1 FY17

Project Overview

The project had three primary tasks:

1. Develop LCOE Models for 10 MW PMDD and wire wound, synchronous turbines (NREL lead)
2. Perform LCOE commodity cost sensitivity analysis on generator CAPEX (NREL lead)
3. Evaluate broader impact of supply chain disruption for magnetic material commodities. (SNL lead)

The project deliverables are a summary report (in final draft) and a presentation at DOE HQ (this meeting).

Introduction & Methodology

- To determine the opportunity space of potential benefits of Twistact in terms of cost of energy an analysis was performed on a 500 MW wind plant using three different generator technologies
  - 10 MW Permanent magnet direct drive (PMDD)
  - 10 MW Wire wound synchronous generator (WWSG) with sliprings
  - 10 MW Wire wound synchronous generator with Twistact

- The following models were used for the analysis:
  - Generator designs and corresponding costs where developed using GeneratorSE
  - Wind plant costs were modeled using the NREL Balance-of-system cost model
  - O & M costs were modeled using ECN's O & M tool v4.4
  - Energy production estimates were developed from AWS TruePower's OpenWind

- The 10 MW design was based on DTU's new 10 MW reference design with the following key parameters:
  - Rated torque of 9.94 MNm and a rated rotor speed of 9.6 rpm
  - Overall nacelle mass of 446 tons of which 200 tons was a medium-speed generator

Generator Design Analysis

Design Approach

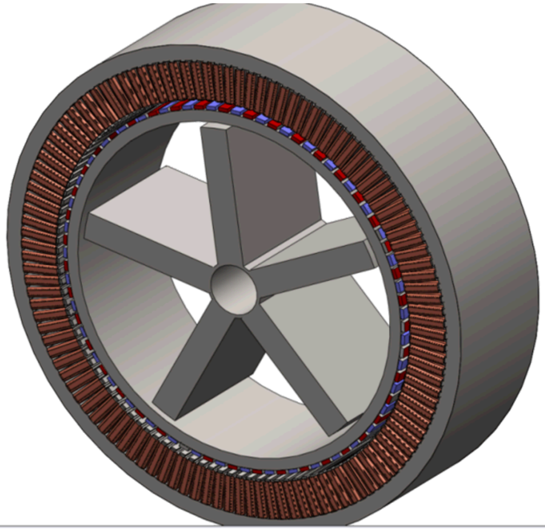
- All designs were optimized using GeneratorSE
  - Minimizes cost for a given efficiency constraint
    - Pareto fronts created; first pass at LCOE uses optimization for minimum efficiency level of 93%
  - Includes both electromagnetic and structural design
    - Electromagnetic design constrained by required output voltage
    - Support design constrained by withstanding air-gap closure from gravity, Maxwell’s stress, and torque as well as deflection limits
  - Design variables depend on machine configuration (PMDD, WWSG)

10 MW PMDD Baseline Design

- Design Variables: air gap radius, stator length, slot height, pole pitch, magnet height, number of arms and arm dimensions

- Key design assumptions / constraints:
  - Targeting a no-load output voltage of 6kV L-L (~3.5kV/ph)
  - Targeting 200 tons based on NTNU design study[1]
  - Peak air-gap flux density not to exceed 1.2T

- Main Results:
  - Air gap diameter : 8.95 m
  - Length : 2.00m
  - Pole pairs : 147
  - Total Mass : 231 tons
  - Structural Mass : 163 tons
  - Generator Efficiency: 93.001%

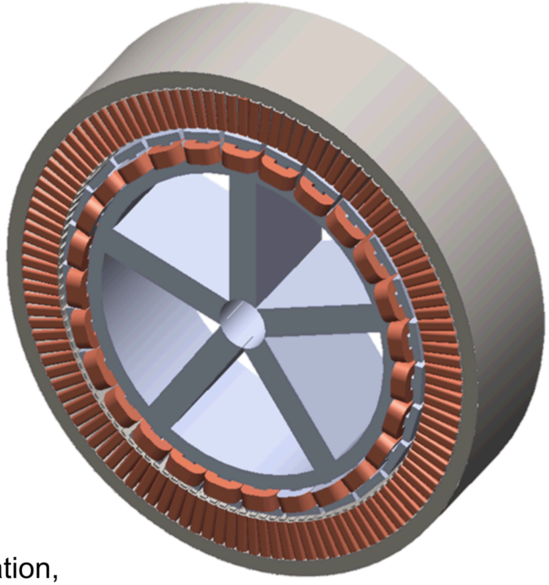


[1] H E Liseth and R Nilssen, *10 MW Reference Wind Turbine* , Department of Electric Power Engineering, NTNU

10 MW Baseline WWSG Design

- Design Variables: air gap radius, stator length, slot height, pole pitch , Field winding turns, Field current, number of arms and arm dimensions

- Key design assumptions / constraints:
  - Targeting 270 tons based on Japanese study comparing PMDD and WWSG[2]
  - Targeting a no-load voltage of ~ 6kV L-L (~3.5kV/phase)
  - Maximum excitation power is <1% of rated power(consistent with normal design practice[3])
  - Brush contact drop ~1 V[4]
- Main Results:
  - Air gap diameter : 8.512 m
  - Length : 1.92m
  - Pole pairs : 67
  - Total Mass : 298.5 tons
  - Structural Mass : 148.93tons
  - Generator Efficiency: 93%



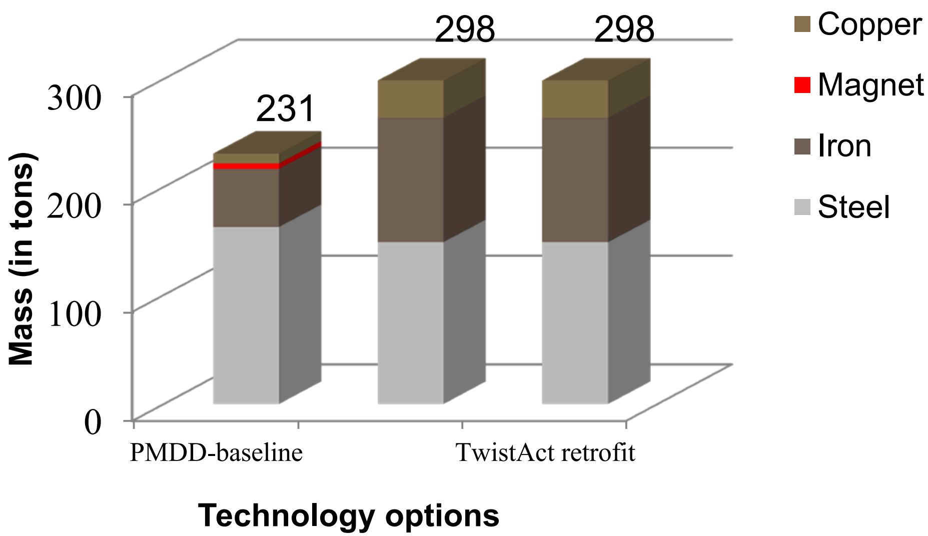
[2] Performance Comparison of 10-MW Wind Turbine Generators With HTS, Copper, and PM Excitation, IEEE Trans. on applied superconductivity, vol. 25, no. 6, 2015. http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=7312921
[3] Ion Boldea, *Electric Generators Handbook*, *Synchronous Generators* (CRC Press, 2015).
[4] http://www.argointl.com/wp-content/uploads/2014/03/necp-How_to_Select_Brushes_for_Motors_and_Generators2.pdf

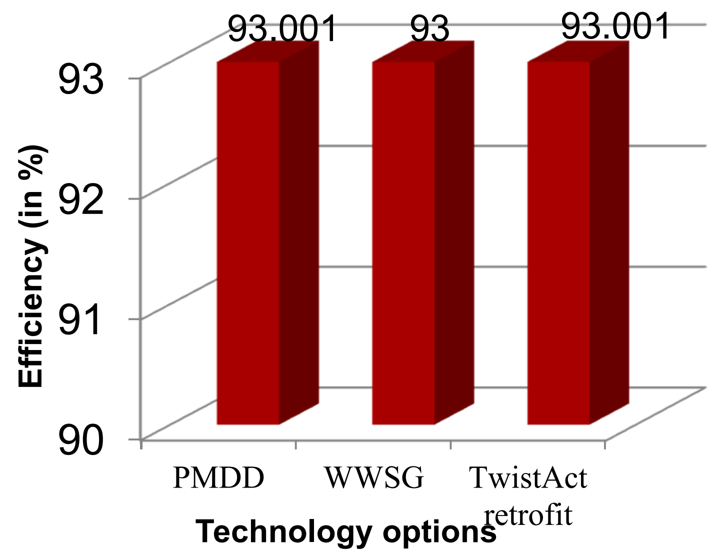
10 MW WWSG with Twistact

- Approach:
  - Keep generator design constant and update loss model of brushes with that of Twistact
    - Produces very minor efficiency gain from 93% to 93.001%- equivalent to PMDD

    *(Brush loss constitutes only a fraction of the total losses)

Design Comparison

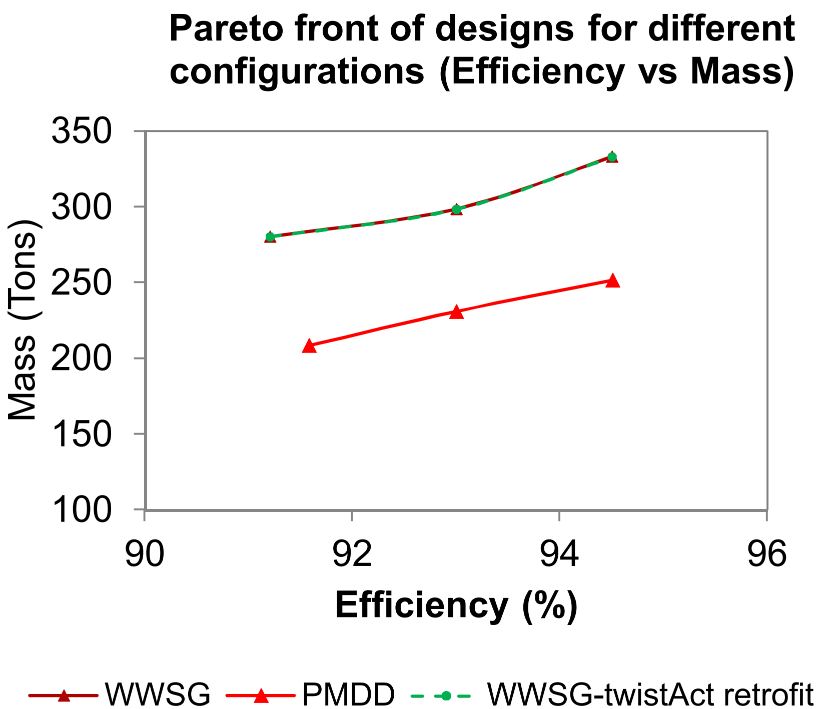


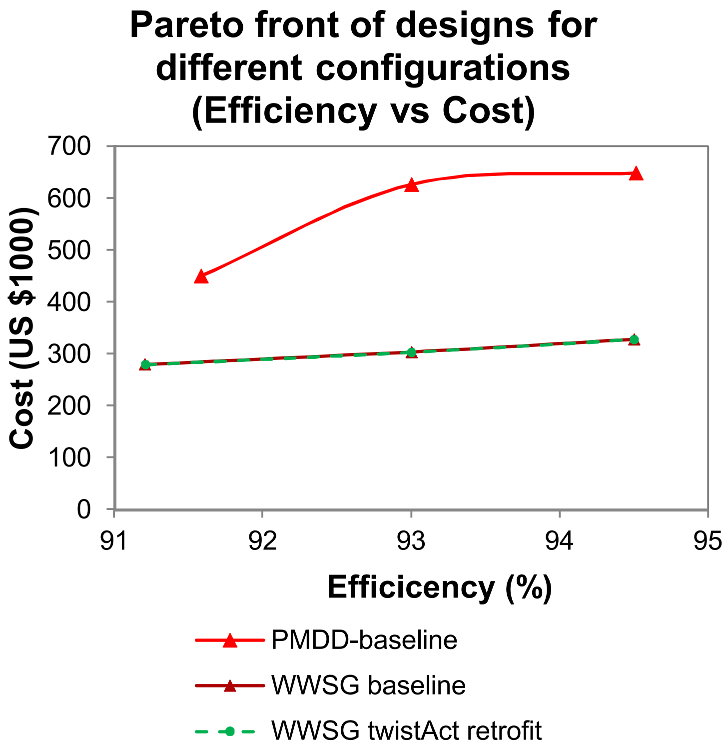


Parameters	PMDD baseline	WWSG-baseline	WWSG-Twistact retrofit
Air gap diameter (m)	8.95	8.51	8.51
Length (m)	2	1.92	1.92
Pole Pairs	146	82	82
Output voltage Vrms	**3318.34**	**3578.12**	**3578.12**
Field current (A)	**-**	**130**	**130**
Number of rotor turns	**-**	**75.7**	**75.7**

Pareto fronts

- Cost optimization by configuration performed for varying efficiency constraints





LCOE Analysis

PMDD Baseline

PMDD Baseline	Mass (t)	Material cost ($/t)	Cost of Materials ($)	Cost of Manufacture ($)
Electrical Steel	53.8	556	29,913	23,503
Magnets	5.0	95,000	471,200	370,229
Copper	9.1	4,786	43,746	34,372
Inactive Material	163.3	501	81,898	64,349
Total	**231.2**	**100,844**	**626,758**	**492,452**
Total system cost ($)	**1,119,210**			

PMDD Baseline O & M	Value	Units
Generator Failures	0.076	Failures/year
Small repair	97.0	%
Major Repair	2.0	%
Major Replacement	1.0	%
Total O & M Cost	62.59	$/kW

PMDD Baseline LCOE	Value	Units
Turbine CapEX	1,203.6	$/kW
O & M Cost	62.59	$/kW
BOS Costs	1,638.9	$/kW
AEP (net)	1,661.6	GWh
LCOE	124.6	$/MWh

Key Assumptions:

- Material cost was found using available material commodity pricing data and historical averages
- A ratio of material cost to finished cost was developed to estimate manufacturing costs
    - Materials account for 56 % of the generator cost
- 97 % of PMDD of failures require small, inexpensive maintenance or repairs

Material Costs Source: Bloomberg, World Bank; O & M and CapEX Sources: ECN O & M Tool v4.4, NREL Offshore Balance of System Model, NREL Cost & Scaling Model, (Carrol, McDonald, & McMillan 2015), (Kate-singoy 2014).

WWSG Baseline

WWSG Baseline	Mass (t)	Material cost ($/t)	Cost of Materials ($)	Cost of Manufacture ($)
Electrical Steel	115.2	556	64,040	39,250
Copper	34.5	4,786	164,982	101,118
Inactive Material	148.9	501	74,672	45,767
Total	**298.6**	**5,844**	**303,694**	**186,135**
Total per unit cost ($)	**489,829**			

WWSG Baseline O & M	Value	Units
Generator Failures	0.123	Failures/year
Small repair	74.0	%
Major Repair	24.0	%
Major Replacement	2.0	%
Total O & M Cost	68.96	$/kW

WWSG Baseline LCOE	Value	Units
Turbine CapEX	1,144.4	$/kW
O & M Cost	68.96	$/kW
BOS Costs	1,638.5	$/kW
AEP (net)	1,661.4	GWh
LCOE	125.6	$/MWh

Key Assumptions:

- Materials account for 62 % of the unit cost for wire wound machines
- Slipring failures are a major driver of maintenance requirements for WWSG's
- Assumes slipring brushes are replaced annually

Material Costs Source: Bloomberg, World Bank; O & M and CapEX Sources: ECN O & M Tool v4.4, NREL Offshore Balance of System Model, NREL Cost & Scaling Model, (Kate-singoy 2014).
Reliability Sources: Reliability of wind turbine subassemblies (Spinato, Tavner, van Bussel, Koutoulakos 2009); Reliability & Availability of Wind Turbine Electrical Components (Tavner, Faulstich, Hahn, van Bussel 2015); Drivetrain Availability in Offshore Wind Turbines (Carroll, McDonald, Feuchtwang, McMillan 2015)

WWSG Twistact Retrofit

WWSG Twistact Retrofit	Mass (t)	Material cost ($/t)	Cost of Materials ($)	Cost of Manufacture ($)
Electrical Steel	115.2	556	64,040	39,250
Copper	34.5	4,786	164,982	101,118
Inactive Material	148.9	501	74,672	45,767
Total	**298.6**	**5,844**	**303,694**	**186,135**
Total per unit cost ($)	**489,829**			

WWSG Twistact O & M	Value	Units
Generator Failures	0.059	Failures/year
Small repair	90.0	%
Major Repair	8.0	%
Major Replacement	2.0	%
Total O & M Cost	62.59	$/kW

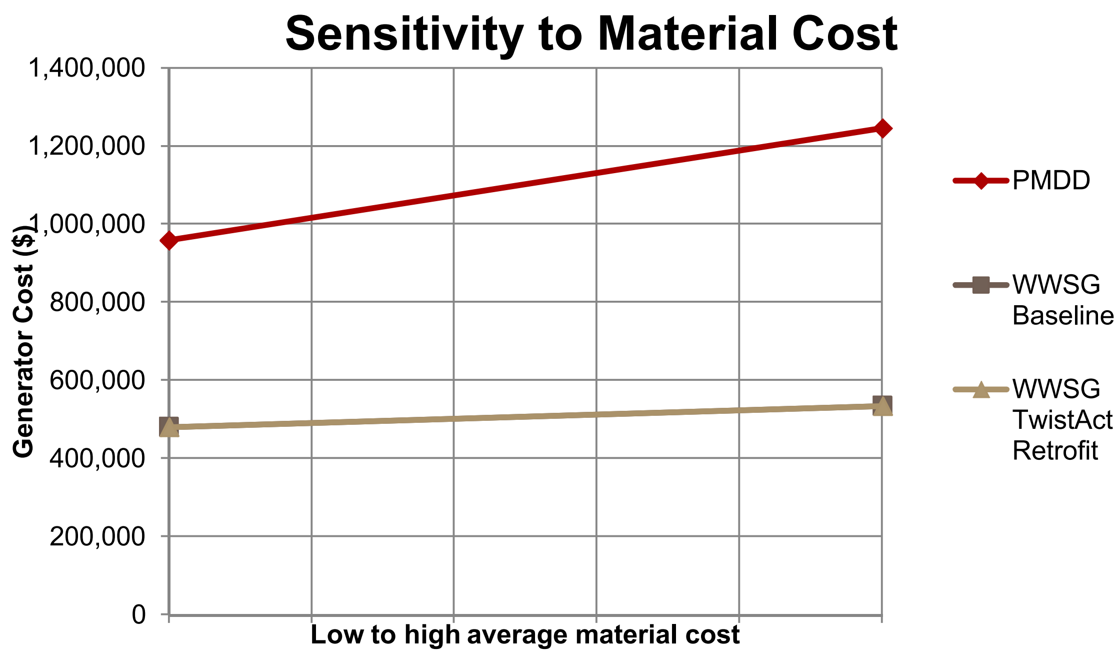
WWSG Twistact Retrofit	Value	Units
Turbine CapEX	1,144.4	$/kW
O & M Cost	62.6	$/kW
BOS Costs	1,638.5	$/kW
AEP (net)	1,661.6	GWh
LCOE	122.4	$/MWh

Key Assumptions:

- Generator design remains the same as the WWSG baseline with only the sliprings being substituted with Twistact
- Cost of Twistact is assumed to be the same as a slipring assembly
- Twistact was not assumed to require preventative maintenance where as preventative annual slipring maintenance was modeled for the baseline

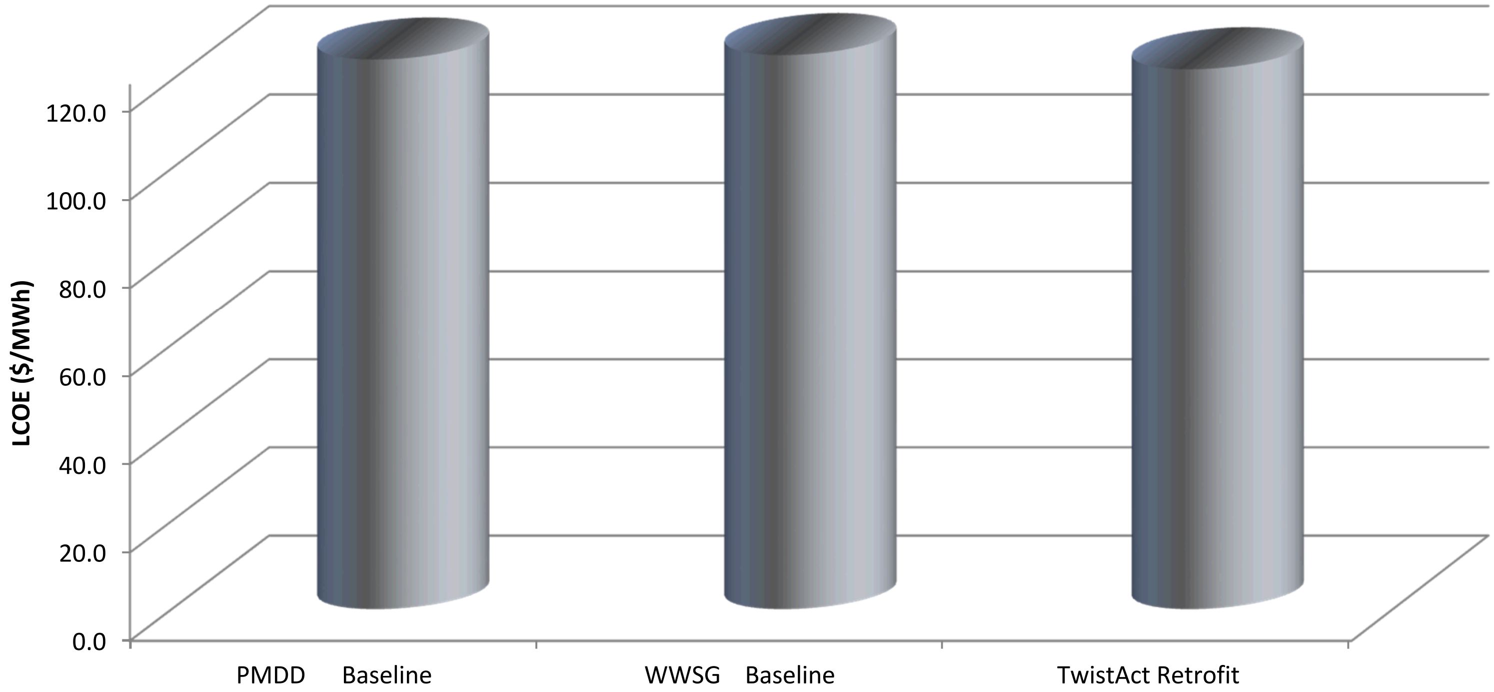
Material Costs Source: Bloomberg, World Bank; O & M and CapEX Sources: ECN O & M Tool v4.4, NREL Offshore Balance of System Model, NREL Cost & Scaling Model, (Carrol, McDonald, & McMillan 2015), (Kate-singoy 2014).

Generator cost sensitivity to material



- PMDD generator cost shows the greatest sensitivity to material cost primarily because of the high variability in magnetic material prices
- WWSG generators show much lower sensitivities to material pricing compared to PMDD generators

Summary & Comparison



Twistact is the lowest cost option for these reasons:

1. Compared to WWSG baseline O&M costs are significantly lower due to absence of sliprings
2. Compared to PMDD baseline the material cost for Twistact is significantly lower because no magnets are required

Summary & Comparison

Twistact Cost Analysis Results	PMDD Baseline	WWSG Baseline	Twistact Retrofit
Turbine CAPEX ($/kW)	1,203.8	1,138.3	1,138.3
O & M Cost ($/kW)	62.59	68.96	62.59
BOS Costs ($/kW)	1,638.9	1,638.5	1,638.5
AEP (net GWh/yr)	1,661.6	1,661.4	1,661.6
LCOE ($/MWh)	124.6	125.6	122.4
LCOE change over baseline PMDD ($/MWh)	-	+1.0	-3.2

- Twistact reduces O&M cost for WWSG's resulting in a small decrease in overall LCOE.
- Results presented assume brush replacement annually. LCOE benefits of Twistact increase over WWSG baseline if brush replacement is more frequent.
- In the event of an increase in magnetic material cost Twistact WWSG's will gain an increased advantage over PMDD (low sensitivity to material cost for WWSGs)
- Conventional wisdom that WWSG mass equates to non-competitive LCOE is incorrect.
- Conventional wisdom that brush/slip-ring technology cannot be used for offshore WWSGs appears to be somewhat dubious.
- **The original proposed value proposition for Twistact technology has been validated.** It eliminates the need for rare earth materials, eliminates both the real and perceived risks of rotary electrical contacts, and incurs no cost or efficiency penalties.

Supply Chain Analysis

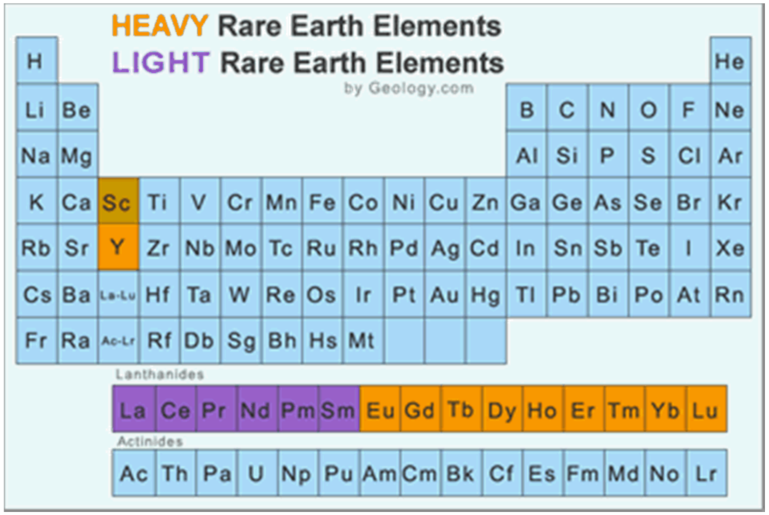
Economic Analysis of Rare Earths

- Quick Introduction to Rare Earths Elements (RREs)
- Economics of Rare Earths
  - Supply Side Influences
  - Demand Side Influences
- Feasibility of Renewable Energy Penetration
- Conclusions

http://geology.com/articles/rare-earth-elements/

Introduction to Rare Earths Elements

- Group of 17 elements split into two groups: **Heavy** and **Light**
- Rare earth elements are not actually rare
  - As abundant as Nickel and Copper but in lower concentrations
  - But they share similar chemical properties that make them difficult to separate
- Exhibit unique physical properties
- Very useful
  - Permanent Magnets
    - Neodymium (Nd) **Light**
    - Dysprosium (Dy) **Heavy**
  - DOE classifies them as "critical" materials

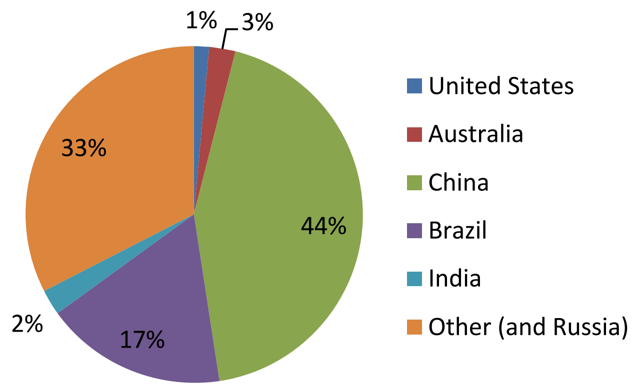


http://geology.com/articles/rare-earth-elements/

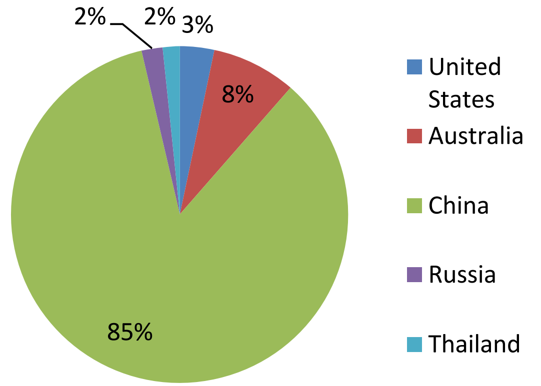
Economic value of REE products at $2 trillion

Supply Economics: Resource Distribution

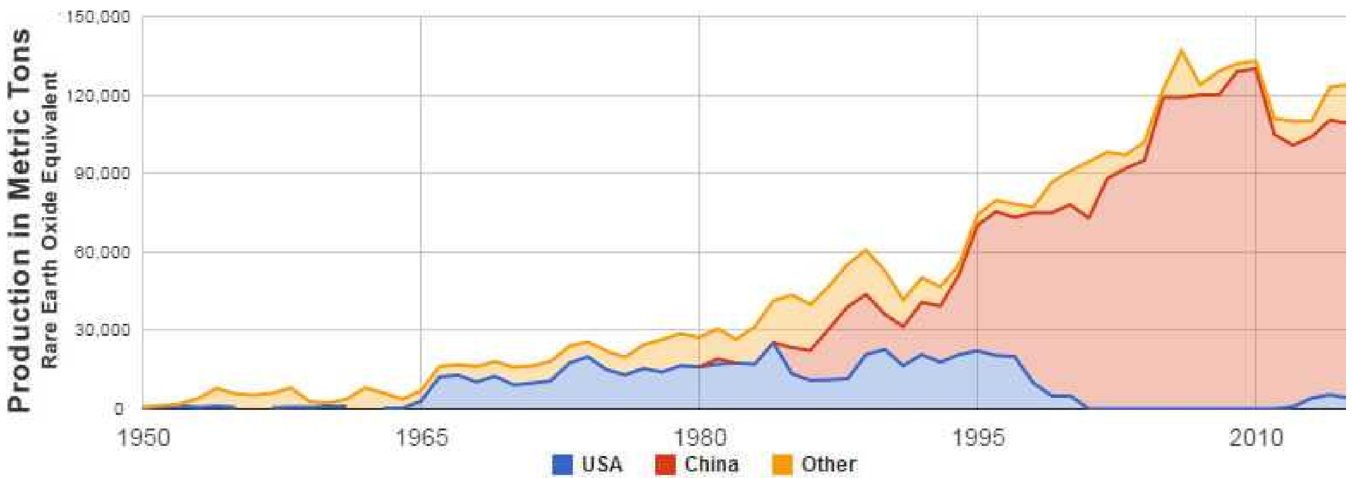
Reserves of Oxide (2015)



Production of Oxide (2015)



Historical Production



China enjoys monopoly of the market

http://geology.com/articles/rare-earth-elements/

Supply Economics: Political Influences

- Export Quotas
- Export Tariffs
- Export Contracts
- Production Quotas
  - Illegal mining
- Export Bans
  - 2010 Japanese-Chinese boat incident

HOME SEARCH The New York Times

GLOBAL BUSINESS

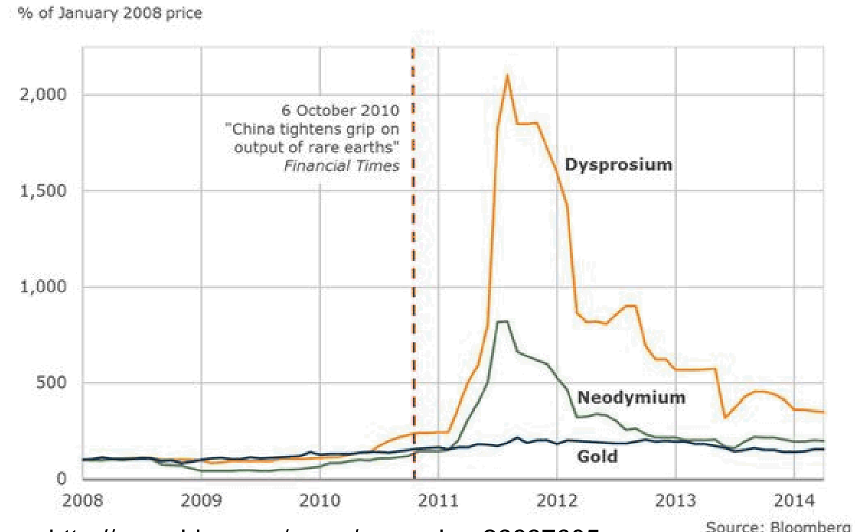
Amid Tension, China Blocks Vital Exports to Japan

By KEITH BRADSHER SEPT. 22, 2010

HONG KONG — Sharply raising the stakes in a dispute over Japan's detention of a Chinese fishing trawler captain, the Chinese government has blocked exports to Japan of a crucial category of minerals used in products like hybrid cars, wind turbines and guided missiles.

http://www.nytimes.com/2010/09/23/business/global/23rare.html

Rare earth metal prices compared with gold



http://www.bbc.com/news/magazine-26687605

Supply Economics: Barriers to Entry

Barriers to opening new mines

- Access to cheap labor in remote mining locations
- Suitable ore grade
- Technical and economic feasibility of processing plants
- Environmental approvals
  - Waste products often contaminated with radioactive Thorium
  - Risks lead to processing in developing nations
    - Ex: Lynas Corp mines in Australia but processes ore in Malaysia

http://ecomerge.blogspot.com/2014/11/rare-earth-mining-and-its-damaging.html

Supply Inelasticity:
Process of opening new mine can take 5 to 12 years

Supply Economics: Increasing Supply

- Research into finding new economical sources
  - Enriched sedimentary marine phosphate deposits
    - 👍 Easy to extract
    - 👍 Minimal radioactive waste
    - 👎 Environmental challenges
    - 👎 Difficulty of marine mining
  - Coal, coal by-products, and fly ash recovery

- Recycling (urban mining)
  - Less than 1% currently recovered
    - Lack of robust recycling programs
    - Difficult to cost effectively extract materials
  - Expected to increase after 2050
    - End of life of products with significant quantity of REEs
    - Improved product design for recycling

Supply Economics: Mitigating Disruptions

- Stockpiling of material
  - Japanese Oil, Gas, and Metals National Corporation holds 42-day stockpile
  - Japanese government mandates companies maintain an 18-day supply
- Long term price agreements
  - Partnership between Siemens and Molycorp in April 2015
  - Molycorp filed for bankruptcy in June 2015


PEGASUS CAPITAL ADVISORS

Approach | Our Team | Investments | Newsroom | Contact Us

Molycorp Chosen to Supply Rare Earths for Use In High-Efficiency Siemens Wind Turbine Generators

April 15, 2015

GREENWOOD VILLAGE, CO (April 15, 2015) – Siemens AG ("Siemens") has selected Molycorp, Inc. (NYSE: MCP) ("Molycorp") to supply rare earth materials over the next 10 years from its Mountain Pass, California facility for incorporation into Siemens' high-efficiency, direct drive wind turbine generators.

http://www.pcalp.com/molycorp-chosen-supply-rare-earths-use-high-efficiency-siemens-wind-turbine-generators/


Bloomberg | Markets | Tech | Pursuits | Politics | Opinion | Businessweek

Molycorp Files for Bankruptcy as Rare-Earth Prices Drop

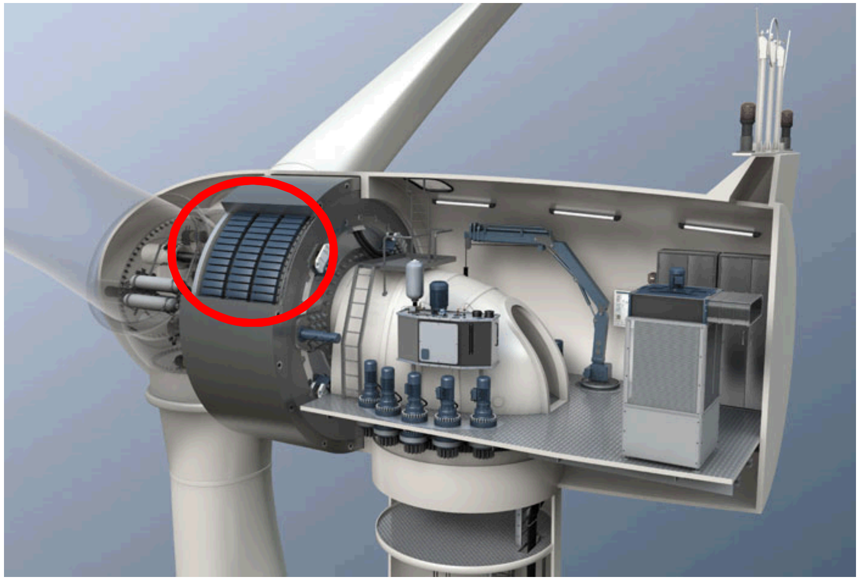
Dawn McCarty and Simon Casey

June 25, 2015, 1:15 AM PDT Updated on June 25, 2015, 6:32 AM PDT

https://www.bloomberg.com/news/articles/2015-06-25/molycorp-files-for-bankruptcy-proposes-debt-restructuring-plan

Demand Economics: Increasing Demand

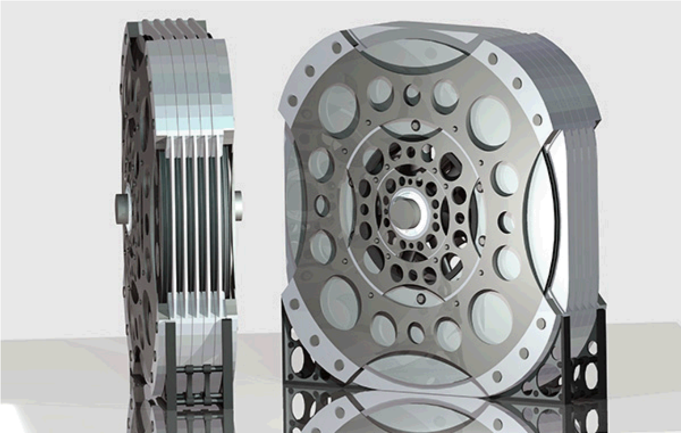
- Highly desirable due to unique physical properties
  - Magnetic
  - Luminescent
  - Electrochemical
- Difficult to substitute
- Significant demand sectors:
  - Electric vehicles and bicycles
  - Computers / electronics
  - Electric motors
  - Audio systems
  - Wind turbines
    - 150 kg/MW of Nd
    - 14 kg/MW of Dy
    - Total cost of permanent magnets: $105,000/MW



https://www.ifm.com/ifmna/web/apps-by-industry/cat_060_010.html

Demand Economics: Reducing Demand

- Particularly important for Dysprosium due to:
  - Higher prices
  - Greater Chinese monopoly on heavy REE's
- Methods for **Reduction**:
  - Direct cooling of magnets (e.g. Siemens)
  - Controlling grain structure during production
  - Use of Samarium-Cobalt permanent magnets
    - Impractical due to high cost of Cobalt



Rendering of GreenSpur generator

- Methods for **Elimination**:
  - Use of electromagnets in place of permanent magnets
  - High temperature super-conducting generators
  - Topologically-optimized generators using ferrite magnets (e.g. GreenSpur)

Feasibility of Renewable Energy Penetration

Goal
Use knowledge of supply and demand constraints to estimate feasibility of Global Renewal Energy Penetration Targets

- Can estimated supply meet estimated demand?
  - Analysis is simplified by not attempting to estimate prices
- How does estimated demand compare to today's global reserves?
- Leveraged article "Exploring rare earths supply constraints for the emerging clean energy technologies and the role of recycling" by Habib and Wenzel, Journal of Cleaner Production, 2014

Feasibility Study Setup: Demand

Renewable Energy Demand Scenarios:

- Three International Energy Agency 2050 Emissions Scenarios
  - Baseline: Business-As-Usual (BAU) doubles the CO_2 rate to 57 Gt/yr by 2050
  - Blue Map: (often called 2˚C scenario) reduces the CO_2 rate to 14 Gt/yr
  - Blue hi REN: reduces annual rate to 12.9 Gt/yr (~75% renewables share)
- One "What If" Scenario of 100% Renewables where 1/3 power is generated by wind

Additional Assumptions:

- Reduction in energy demand for non-BAU scenarios due to increased efficiency by end uses and reduced losses due to smart grid technologies
- Gradual increase in Capacity Factor of Wind Turbines due to improvements in siting and performance-enhancing technologies
- PMDD technology is the only option for offshore wind, with an increased market penetration rate for each scenario
- Lifetime of a wind turbine is 20 years

Demand Assumption for Electric Vehicles, Electric Bicycles, Computers, Electric Motors, Audio Systems, and Others were omitted for brevity

Feasibility Study Setup: Supply

BAU Primary Production Supply

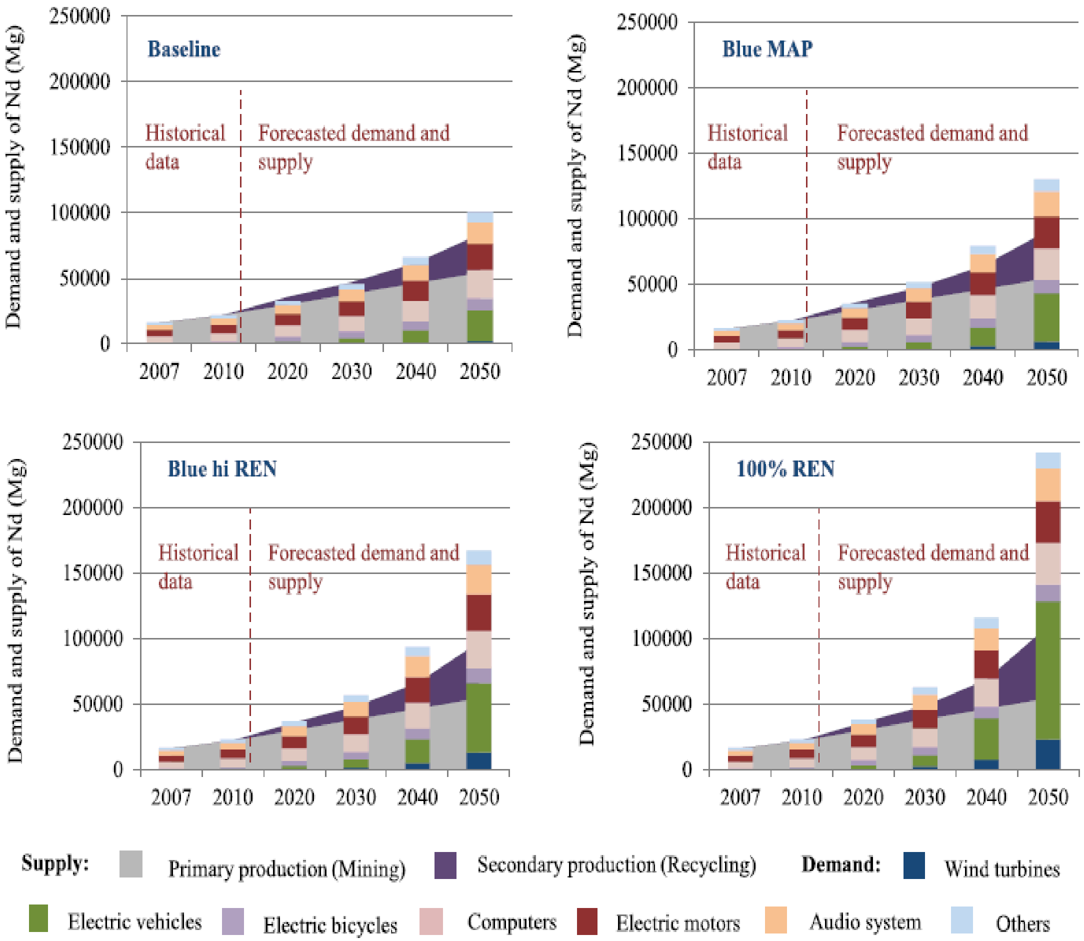
- Application of simple projection of historical mining data
  - Lack of estimate of future potential production in literature
  - Average 813 Mg/yr and 81 Mg/yr increase of Nd an Dy respectively

Secondary Supply (Recycling)

- End-of-lifetime recycling rates achieved by 2050:
  - 90% for wind turbines
  - 70% for electric vehicles
  - 40% for all other uses
- Higher recovery rates for wind turbines and electric vehicles due to higher amounts of easily recoverable materials

Feasibility Study: Nd Results

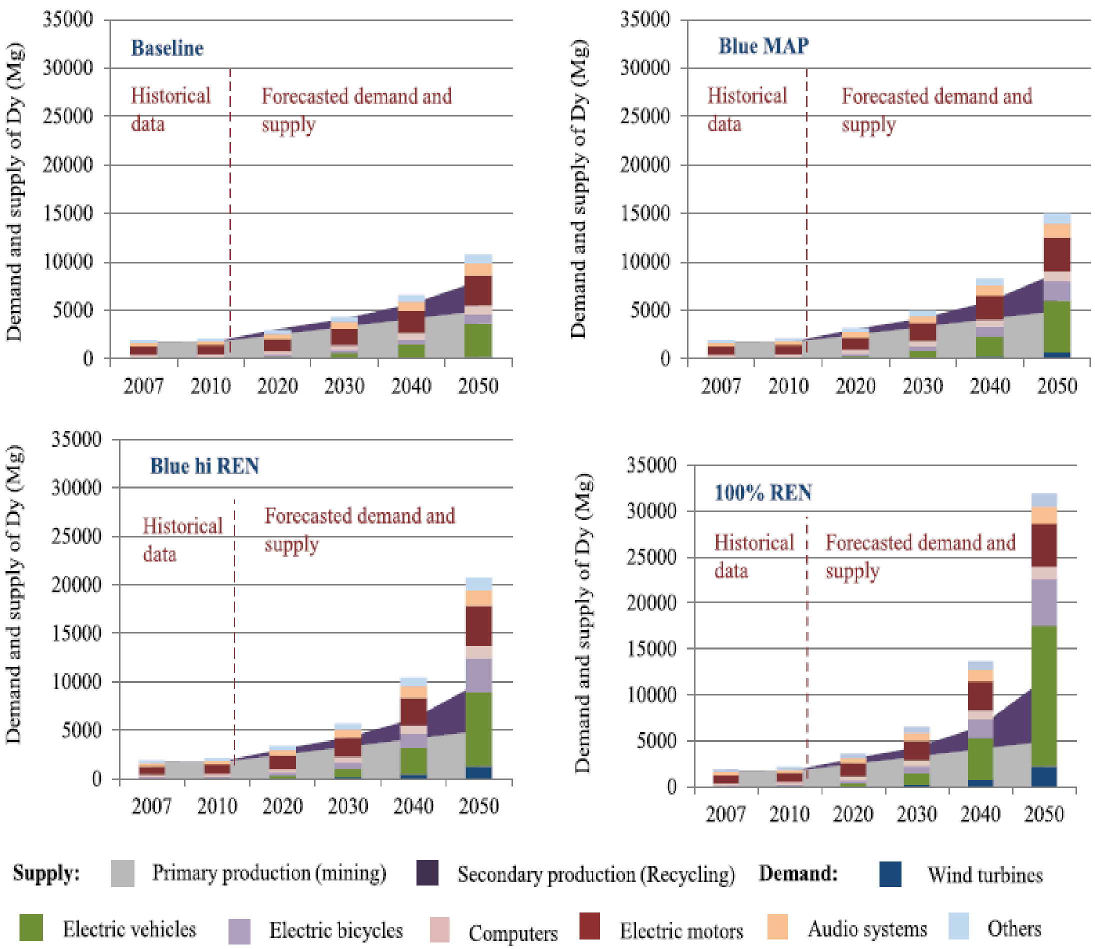
Sandia National Laboratories



Fulfillment of Projected Demand by Projected Supply (2050)

Supply	Baseline	100% REN
Primary Only	54%	23%
Including Secondary	83%	45%

Feasibility Study: Dy Results



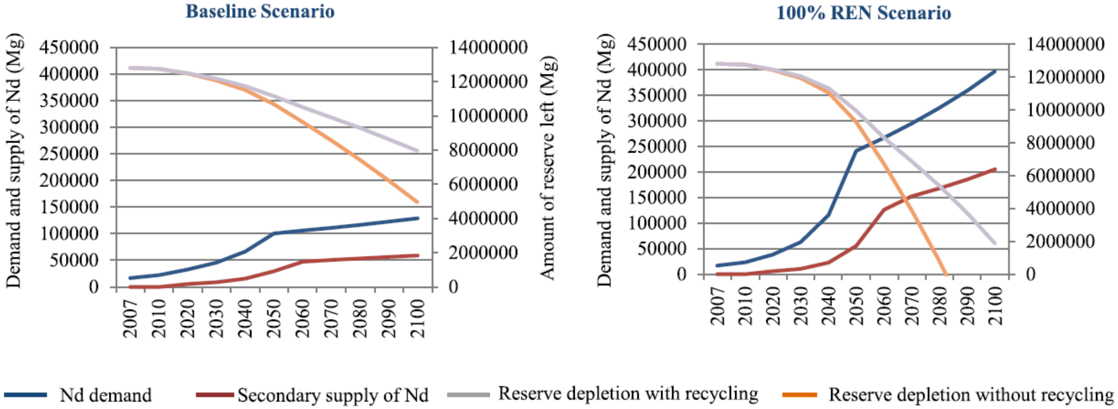
Fulfillment of Projected Demand by Projected Supply (2050)

Supply	Baseline	100% REN
Primary Only	46%	16%
Including Secondary	74%	37%

Feasibility Study: Material Reserves

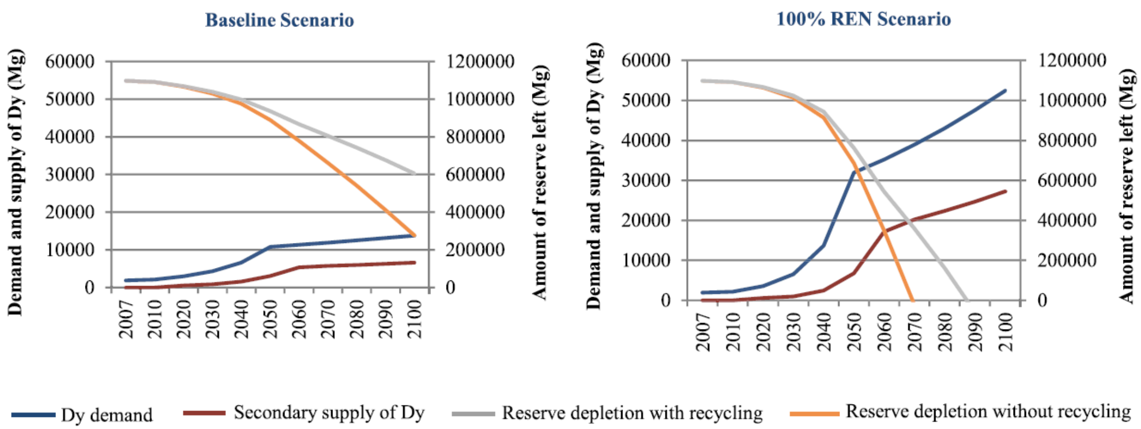
Sandia National Laboratories

Neodymium



Model was extended past 2050 at a stable annual end-use growth rate of 0.5% to 1% for all sectors

Dysprosium



Remaining Reserves$_{2011}$ in 2100 w/ Recycling

Element	Baseline	100% REN
Neodymium	62%	15%
Dysprosium	55%	Depleted by 2090

Note: Reserves will likely grow over time relative to the 2011 reserves due to opening of new mines and improvements in technologies.

Economic Analysis Summary

Sandia National Laboratories

Supply

- Is inelastic due to barriers to entry (5 to 12 years to open mine)
- Low price stability results from market monopoly by China
- Stability can be improved through
  - Researching alternatives technologies
  - Increase in secondary supply
  - Stockpiling
  - Price agreements
  - Diversification of suppliers
- Supplier diversification is unlikely to happen without increase in prices

Demand

- Likely to remain robust due to unique physical properties of elements
- Expected to outpace BAU supply in the next 35 years in all analyzed scenarios

Disclaimer: Predicting the future is difficult. We understand that there are many other factors that influence the market that were not modeled given their unpredictability (regulations, political influences, changes in quotas, new technologies, etc.) Other assumptions, like the proliferation of electric vehicles, were estimated using best available knowledge but may contribute as additional sources of error.

Economic Analysis Conclusions

Sandia National Laboratories

Long term price of REEs is likely to increase due to the anticipated increase in demand led by EVs and the multitude of underlining supply constraints

Higher REE costs will negatively impact the cost competitiveness of PMDD wind turbines in off-shore applications

Perception of price volatility can reduce a company’s willingness to make capital investments needed to increase production, thereby inhibiting growth

Eliminating the need for REEs in direct drive wind turbines without adversely affecting the cost, efficiency, or reliability can:

- Free manufacturers from uncertainty of REE price fluctuations
  - Reduce cost of capital via reduction of risk to ROI
  - Prevention of stranded wind turbine production capacity in the event of price spikes
- Provides an effective deterrent to rare-earth price speculation (proven alternative)

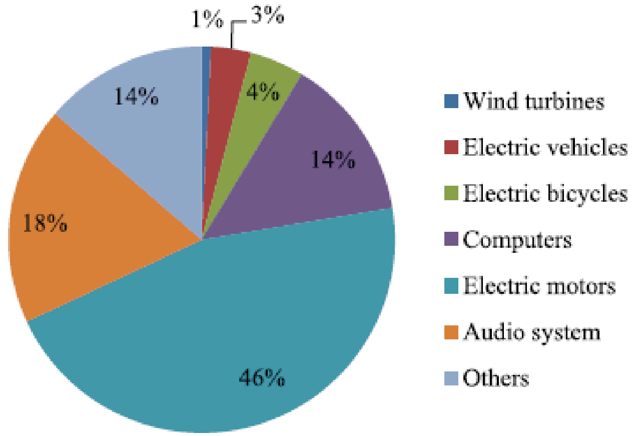
APPENDIX

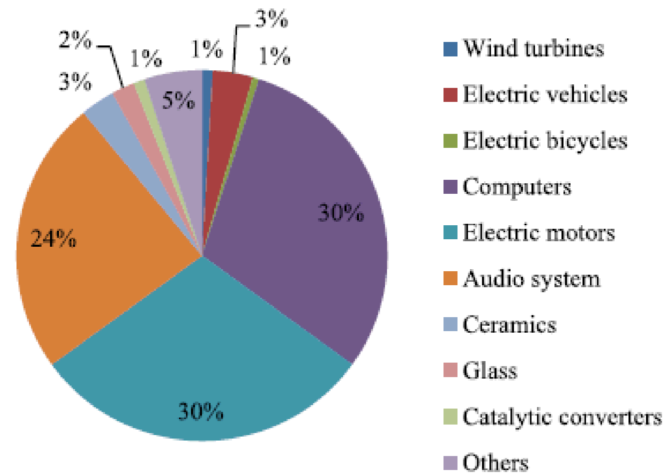
Backup Slides

Scenarios for global electricity demand and estimated share of wind power produced by PMDD wind turbines in 2050

Scenarios	Total electricity demand (TWh)	Share of renewables (%)	Share of wind power (%)	Wind power demand 2050 (TWh)	Market penetration rate of PMDD wind turbines up to 2050 (%)
Baseline	46,186	22	5	2,149	25
Blue MAP	40,137	48	12	4,916	30
Blue hi REN	37,656	75	22	8,193	40
100% REN	37,656	100	33	12,426	50

2010 Dy (left) and Nd (right) End-Use Sector Breakdown





Backup Slides

Demand Assumptions for non-wind REE uses

Electric Vehicles

- Consider NiMH (0.2 kg of Nd) and Li-ion (REE free) batteries, with NiMH phasing out given prevalence of Li-ion
- Electric motor has 0.62 kg of Nd and 0.09 kg of Dy
- 10 year lifespan with 1 battery

Overview of scenarios regarding EVs deployment by 2050.

Scenarios	Passenger vehicles by 2050 (million)	Sales of passenger vehicle in 2050 (million/year)	Market penetration rate of EV/HEV/PHEV by 2050 (%)	Sales of EV/HEV/PHEV in 2050 (million/year)
Baseline	2100	190	20	38
Blue MAP	1800	170	35	60
Blue hi REN	1800	170	50	85
100% REN	1800	170	100	170

Electric Bicycles

- 0.01 kg Dy and 0.09 kg Nd
- 10 year lifespan

Scenarios regarding forecasted demand of electric bicycles by 2050.

Scenarios	Annual growth rate of bicycles (%)	Share of electric bicycles (%)
Baseline	3	19
Blue MAP	3.3	19
Blue hi REN	3.7	19
100% REN	4	19

Other uses

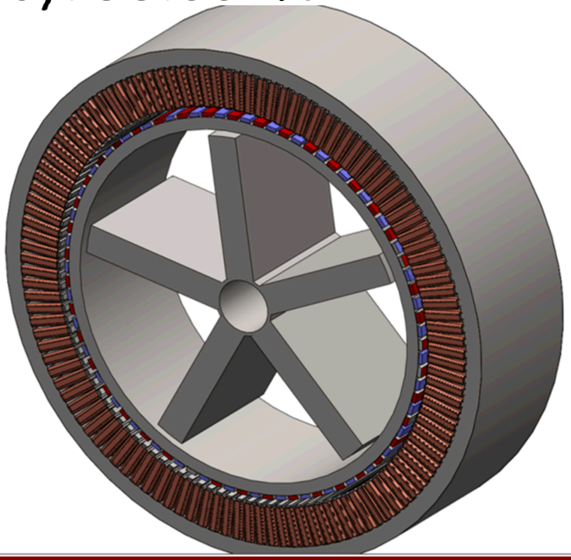
Baseline – 3% annual growth rate
Blue MAP – 3.3 % annual growth rate
Blue hi REN – 3.7% annual growth rate
100% REN – 4% annual growth rate
(based on 3.3% average GDP growth through 2050)
Average lifetime is 10 years

10MW Baseline PMDD

Parameters	Values	Limit	Units
Rating	10.00		MW
Air gap diameter	8.95		m
Overall Outer diameter	9.24		m
Stator length	2.00		m
l/d ratio	0.22	(0.2-0.27)	
Pole pitch	0.22		mm
Stator slot height	95.94		mm
Stator slot width	57.28		mm
Stator tooth width	14.39		mm
Stator yoke height	17.59		mm
Rotor yoke height	87.78		mm
Magnet height	83.09		mm
Magnet width	14.90		mm
Peak air gap flux density	67.16		T
Pole pairs	147		-
Generator output phase voltage	3318.34		V
Generator Output phase current	1004.52		A
Stator resistance	0.14		ohm/ phase
Stator turns	294.00		slots
Conductor cross-section	244.42	5.00	turns
Stator Current density	4.11	3-6	mm^ 2
Specific current loading	31.54	60.00	kA/m
Generator Efficiency	93.00	>93%	%
Total Material Cost	626.86		k$

Main Features

- Air gap diameter : 8.95 m
- Length : 2m
- Pole pairs : 147
- Total Mass : 231 tons
- Structural Mass : 163 tons
- Generator Efficiency: 93.001%

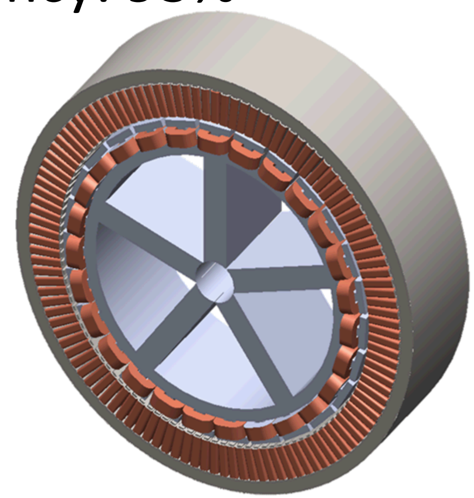


10MW Baseline WWSG

Parameters	Values	Limit	Units
Rating	10.00		MW
Stator Arms	5.00		unit
Air gap diameter	8.51		m
Stator length	1.93		m
l/D ratio	0.23	(0.2-.27)	
Pole pitch	200.00		mm
Stator slot height	66.27		mm
Stator slot width	15.00		mm
Stator tooth width	18.33		mm
Stator yoke height	210.26		mm
Rotor yoke height	210.62		mm
Rotor pole height	140.00		mm
Rotor pole width	140.00		mm
Peak air gap flux density	1.2	1.20	T
Pole pairs	670		-
Generator output phase voltage(rms value)	3578.12		V
Generator Output phase current	958.6		A
Stator slots	804.00		slots
Stator turns	268.00		turns
Stator Current density	298.69	(3-6)	A/mm^2
Specific current loading	3.21	<60	kA/m
Field turns	29.93		turns
Conductor cross-section	130.00		mm^2
Field Current	36.38		A
D.C Field resistance	75.71		ohm
Excitation Power (% of Rated)	0.37	<1%	%
Number of brushes/polarity	2		brushes
Field Current density	2.083	(3-6)	A/mm^2
Generator Efficiency	93.00	>93	turns
Total Cost	263.61		1000$

Main Features

- Air gap diameter : 8.51 m
- Length : 1.92m
- Pole pairs : 67
- Total Mass : 298.5 tons (30% heavie than PMDD)
- Structural Mass : 148.9tons
- Generator Efficiency: 93%

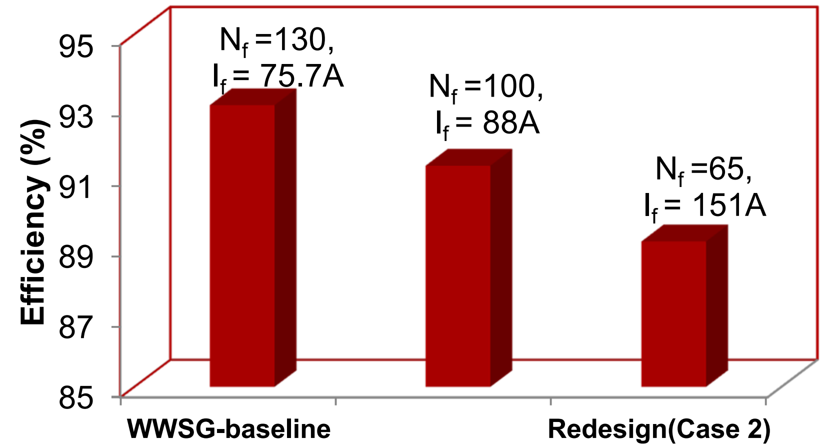


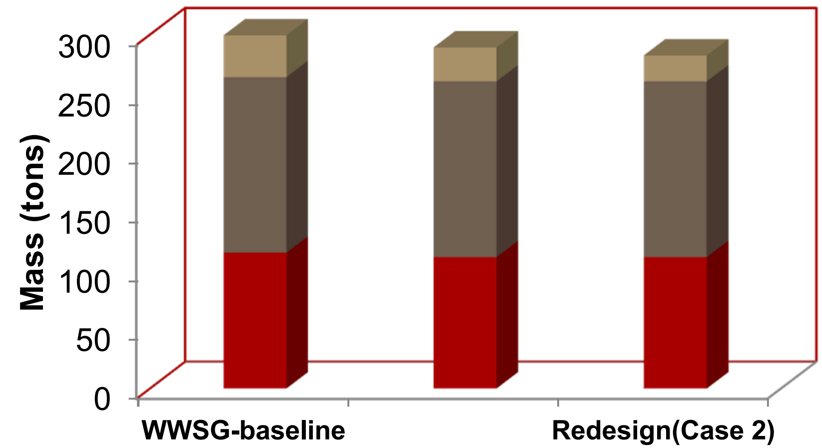
Re-designed 10 MW WWSG with Twi

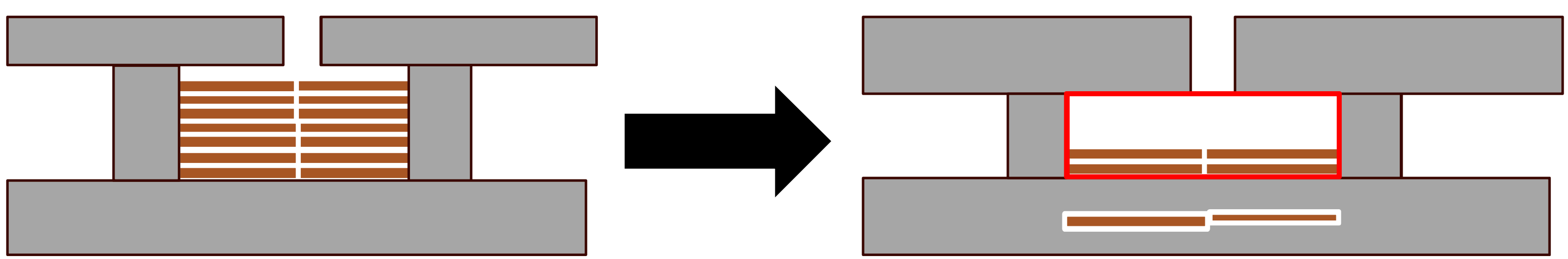
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

- Design variables: same as before plus slot width and height sub-dimensions
- Key Assumptions:
  - Same Stator design and pole pairs as baseline WWSG
  - Same pole core/yoke flux densities, same terminal voltage, effective ampere turns
  - Same conductor cross section in the rotor
  - Halve the number of turns and double the current
  - Current density limited to < 6 A/mm^2
- Main Results:
  - Total Mass : Reduces by 15 tons
    (reduced Copper from 34.4 to 22.53 tons,
    steel from 115 to 111 tons)

Not profitable - Generator Efficiency:89.15% (down from 93.00%)







Slipring Brush Replacement

WWSG Baseline O & M	Brush Replacement Biennially	Brush Replacement annually (baseline)	Brush Replacement Biannually	Units
Generator Failures	0.449	0.821	1.643	Failures/year
Small repair	15.0	8.0	8.0	%
Preventative Repair	83.0	90.0	90.0	%
Major Replacement/Repair	2.0	2.0	2.0	%
Total O & M Cost	65.7	69.0	75.8	$/kW
LCOE	124.6	125.6	127.7	$/MWh

- Brush durability or wear life can have a significant effect on O & M cost for WWSG's
- Retrofitting existing turbines' slipring systems with Twistact has the potential to reduce O & M costs significantly

Reliability Sources: Reliability of wind turbine subassemblies (Spinato, Tavner, van Bussel, Koutoulakos 2009); Reliability & Availability of Wind Turbine Electrical Components (Tavner, Faulstich, Hahn, van Bussel 2015); Drivetrain Availability in Offshore Wind Turbines (Carroll, McDonald, Feuchtwang, McMillan 2015)