The Path to Commercialization through Techno-Economics

NETL

Morgan Summers

April 10, 2018

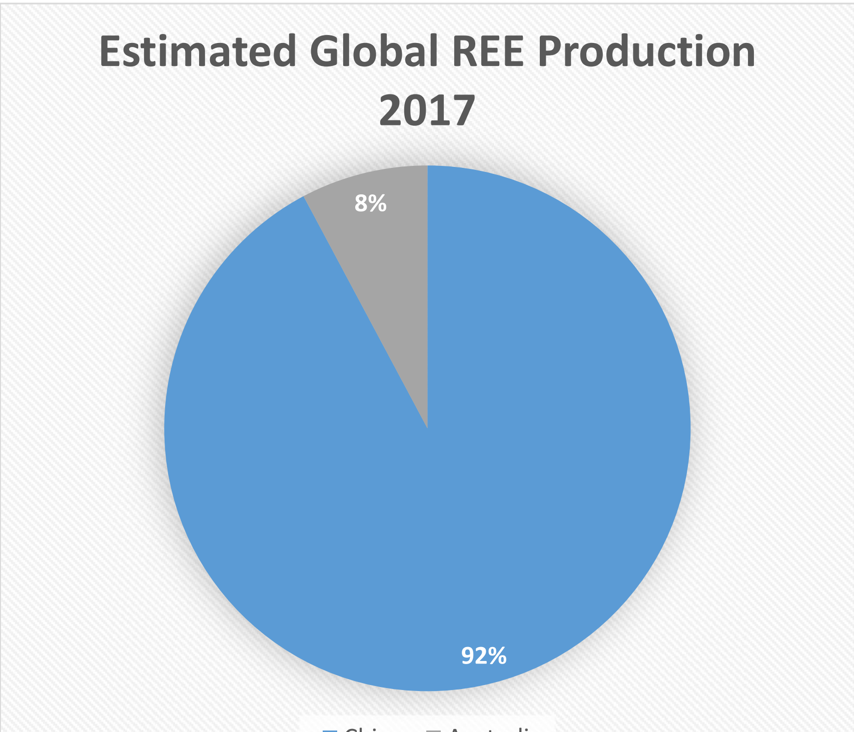
Clockwise from top center: praseodymium, cerium, lanthanum, neodymium, samarium, and gadolinium. (Photo by Peggy Greb)

Overview

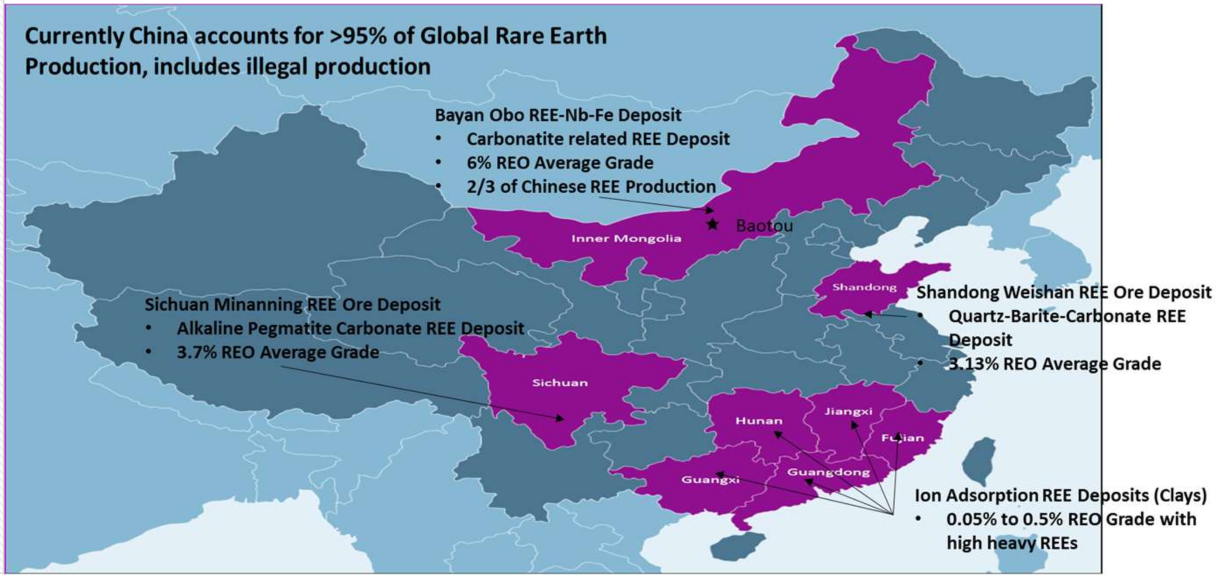
- **Introduction**
- **Program Goals**
- **Techno-Economic Analysis**
  - Benefits of TEA
- **REE Supply Chain**
  - Magnetics Market
  - Production Example
- **Summary**

Introduction

- Total REO Production Estimated at 170,000 tonne/year
- Total REO Demand Estimated at ~150,000 tonne/year
- US accounts for ~11% of Global Demand
- Actual Chinese production >92% including illegal mining

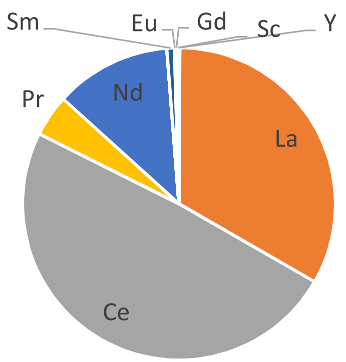


Source: Argus Media

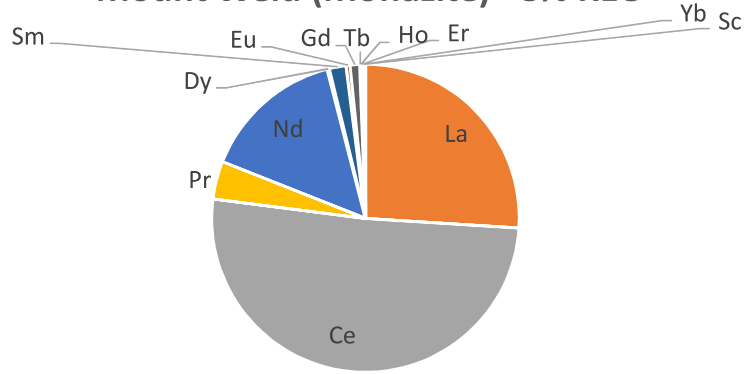


Introduction

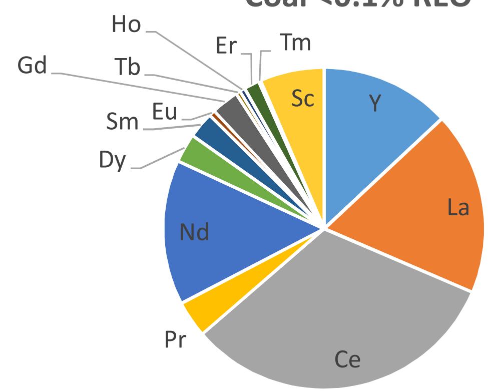
Mountain Pass (Bastnasite) ~8% REO



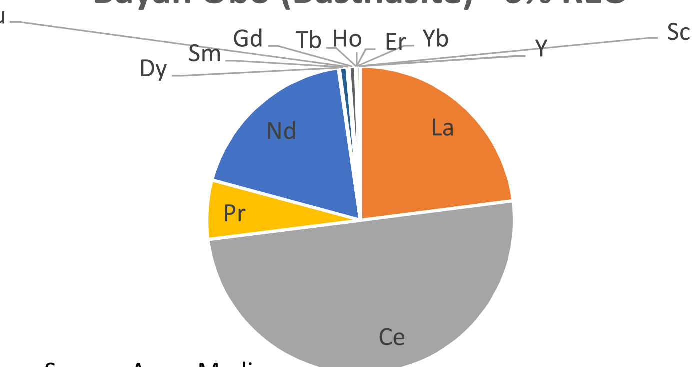
Mount Weld (Monazite) ~8% REO



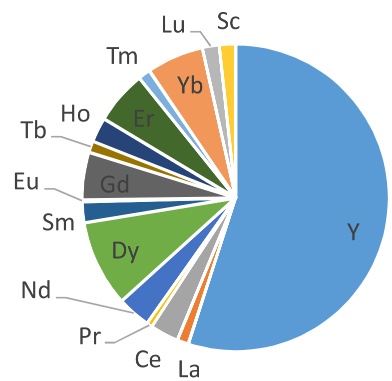
Coal <0.1% REO



Bayan Obo (Bastnasite) ~6% REO



Southeast Guangdong (Xenotime) ~0.5% REO



Source: Argus Media

Program Goals

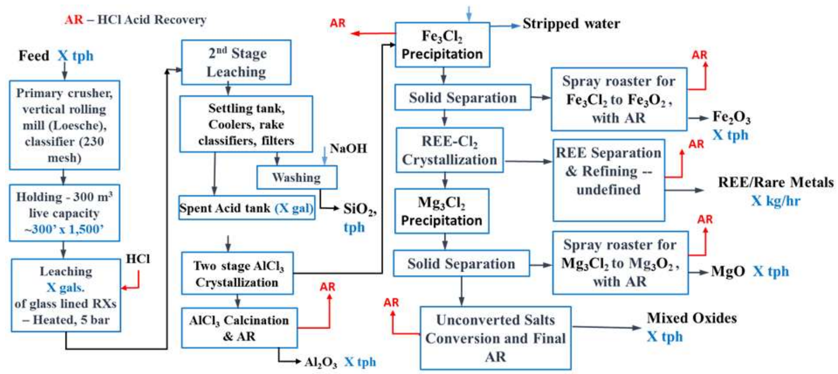
- **Create a domestic source of rare earth elements (REE) to reduce dependence on foreign sources, fortifying national security**
  - **How:** Show that extraction and separation of rare earth elements from coal base sources is **technically** feasible
  - **Impact:** Creates US supply of critical materials, minimal increase in jobs

- **Enable the growth of a commercial domestic REE industry**
  - **How:** Show that extraction and separation of rare earth elements from coal base sources is **economically** feasible
  - **Impact:** Fortifies US supply of critical materials, encourages domestic supply chain development, significant job creation

Techno-Economic Analysis (TEA)

- **TEA – Combines process modeling and engineering design with economic evaluation**
  - Process Flow, Capital and Operating Costs, and Global Finance Assumptions
- **TEA can be applied at any stage in the development of a project**
  - The more defined the project is the more accurate the TEA can be

Project A



Project B

Techno-Economic Analysis (TEA)

- **TEA is a tool used to:**
  - Estimate economic potential
  - Inform environmental impact cost
  - Identify bottlenecks within the process
  - Inform areas of RD&D needs
- **Precautions:**
  - TEA only as good as the technical data on which it is based
  - Important to know the assumptions
    - Financial assumptions
    - Feedstock cost/product price
  - TEA at any stage is still an estimate

Benefits of TEA

- **Determine the economic potential of a project before it is built**
- **Identify steps within the process that could benefit from research and development to improve efficiency or profitability**
- **Used to conduct sensitivity analysis around all aspects of the proposed project**
    - Investigate various financing options
    - Weigh options for dealing with waste
- **Direct jobs can be estimated from operating expenses**
- **Alert the industrial supply chain to a potentially economic project and new source of critical materials**

Downstream Supply Chain

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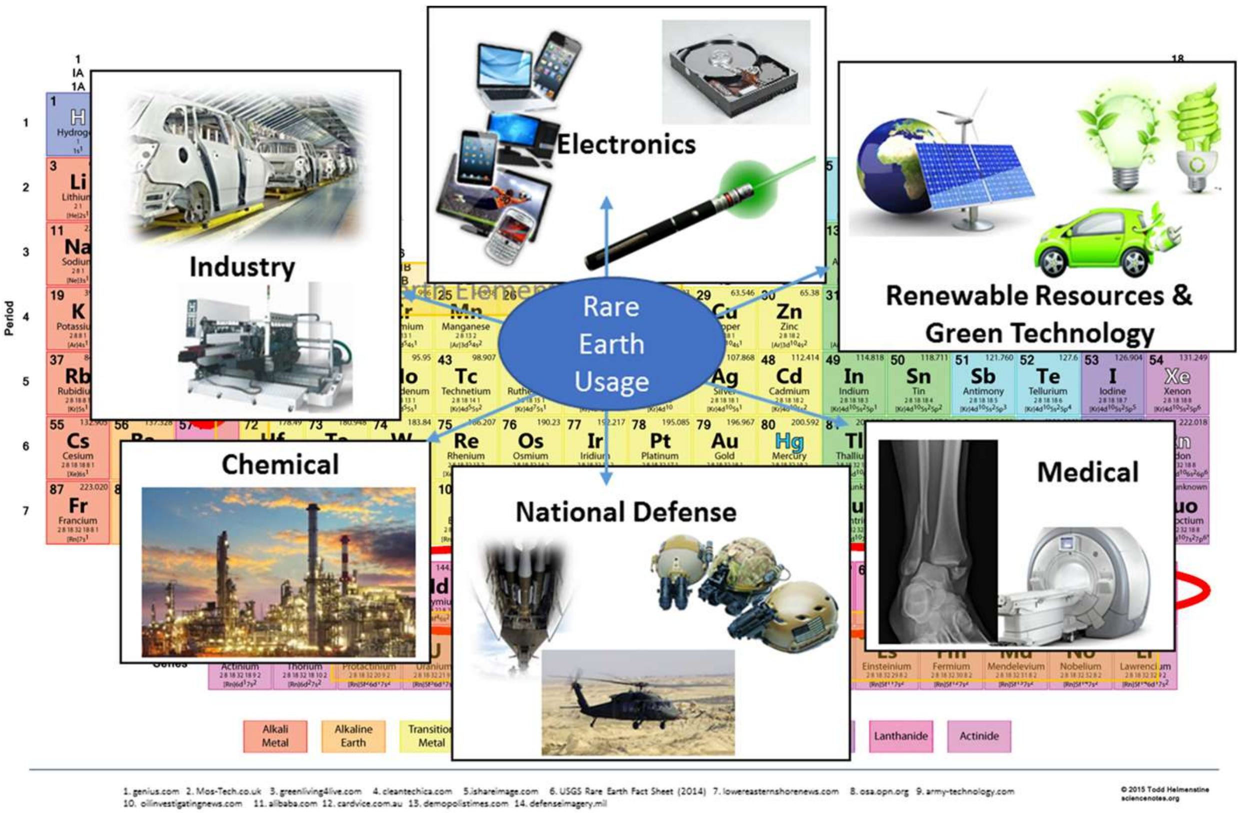
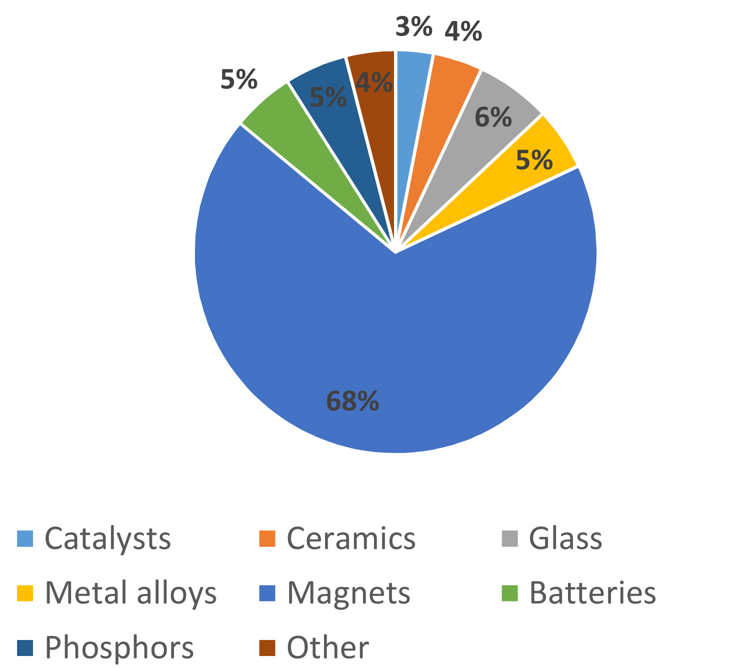
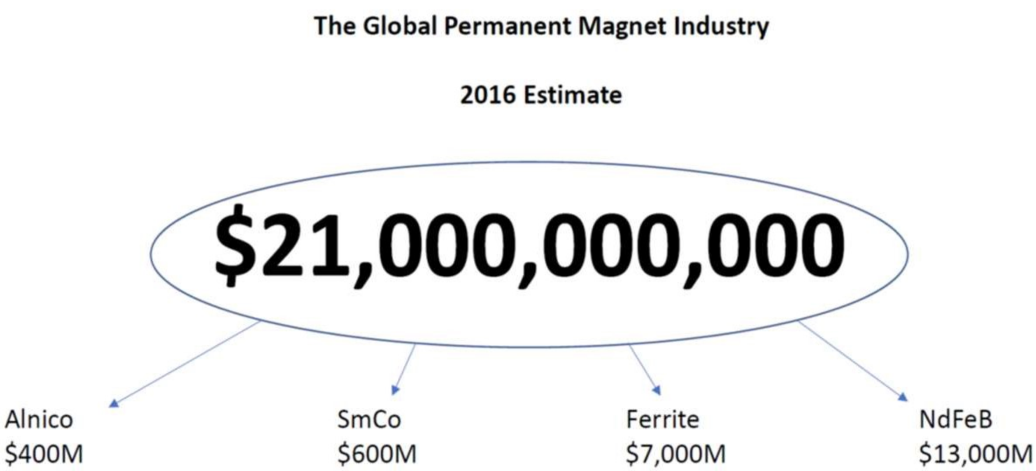


2017 Estimated REO Consumption by Industrial (Value)



Source: Argus Media

Magnetics Market



Source: Magnetics Conference 2018

"The Global Market for Magnets and Magnetic Materials Should Reach $34.9 Billion in 2017 and $51.7 Billion by 2022, Increasing at a CAGR of 8.2%"

Magnets and Magnet Materials: Global Markets, BCC Research

Magnet Production Example

Capacity of Theoretical Magnet Facility		
	Tonnes/Month	Tonnes/Year
Minimum	50	600
Maximum	200	2,400

Approximation of NdFeB Magnet Composition			
	%	Tonnes/year (Min.)	Tonnes/year (Max.)
Nd	30	180	720
Fe	67	402	1,608
Dy	1	6	24
Tb	0.5	3	12
B	1	6	24
Nb	0.5	3	12

Magnet Production Example

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Distribution of REEs in Coal	
	Coal Arithmetic mean (ppm) (g/tonne)
Sc	4.20
Y	8.50
La	12.00
Ce	21.00
Pr	2.40
Nd	9.50
Sm	1.70
Eu	0.40
Gd	1.80
Tb	0.30
Dy	1.90
Ho	0.35
Er	1.00
Tm	0.15
Yb	0.95
Lu	0.14

Capacity of Theoretical Magnet Facility		
	Tonnes/Month	Tonnes/Year
Minimum	50	600
Maximum	200	2,400

Required Coal to Meet Nd Need per Year		
	MMT of Coal Min.	MMT of Coal Max
100% REE Recovery	18.9	75.8
50% REE Recovery	37.9	151.6

REEs Produced from Coal (Tonnes)		US Demand for REE 2015 (Tonnes)
Min	Max	
1,235	4,941	~16,000

Historic US Coal Production	
	MMT of Coal
2008 (peak)	1,063
2016	661

Source: EIA Annual Coal Report

Summary

- **TEA:**
  - Is a great tool for developers to utilize during the early stages of a project to accelerate commercialization
  - Assumptions used within the TEA should be scrutinized by reviewers and made transparent by developers
  - Can aid in meeting both program goals of fortifying national security and enabling a domestic commercial REE industry
- **A commercial domestic REE industry can not live in a vacuum, needs a portion of the supply chain**


Questions?
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Back-up Slides

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Comparison of Materials

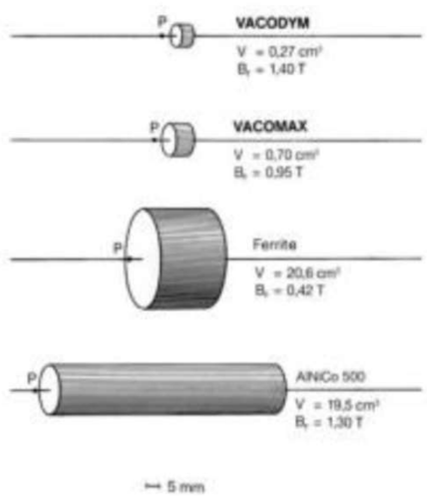

Fig. 5:
Example illustrating the volume reduction achieved with VACODYM and VACOMAX: each magnet is designed to produce a field of 100 mT at the reference point P = 5 mm from the surface of the pole

Source: VAC Magnet Catalog

Permanent Magnets

	Ferrite	Alnico	SmCo		NdFeB	
Property	Ceramic 8	Alnico 5	1-5	2-17	Bonded	Sintered
B_r (kG)	4.0	12.5	9.0	10.4	6.9	13.4
α (%/°C)	-0.18	-0.02	-0.045	-0.035	-0.105	-0.12
$(BH)_{max}$ MGOe	3.8	5.5	20	26	10	43
H_{ci} (kOe)	3.3	0.64	30	25	9	15
β (%/°C)	+0.4	-0.015	-0.3	-0.3	-0.4	-0.6
H_s (kOe)	10	3	20	30	35	35
T_c (°C)	460	890	727	825	360	310

Notes: The quantity α is the reversible temperature coefficient of B_r. (20 °C to 100 °C minimum)
The quantity β is the reversible temperature coefficient of H_{ci}. (20 °C to 100 °C minimum)
The field required to saturate the magnet is H_s.

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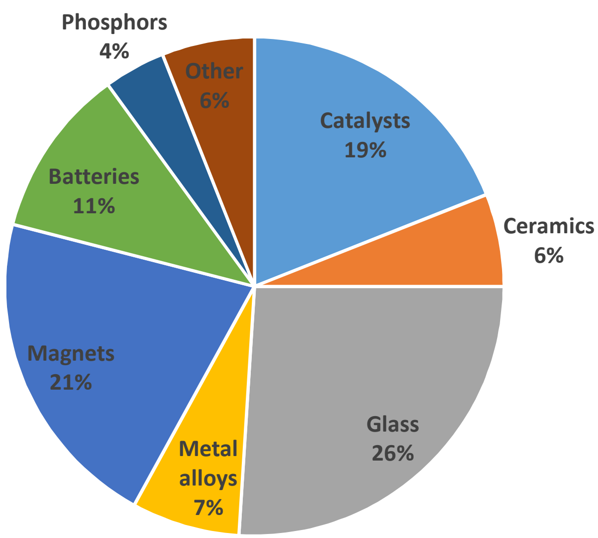
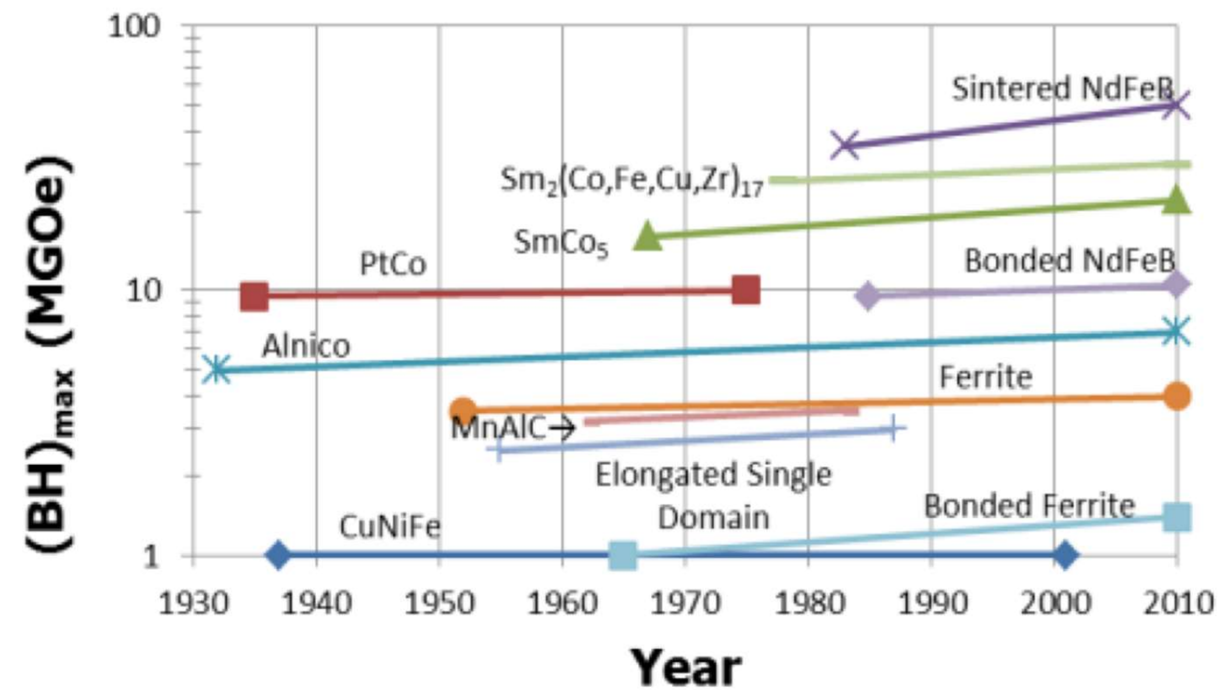
2017 Estimated REO Consumption by Industrial (Volume)

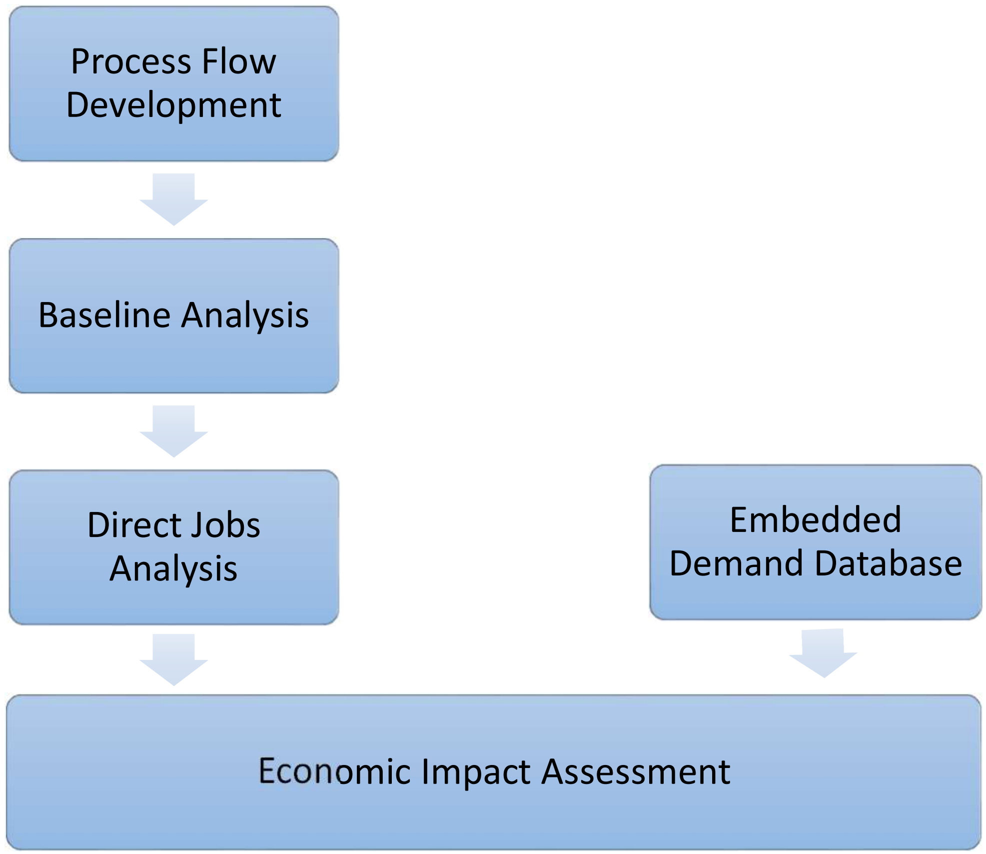


History of Permanent Magnets

Permanent Magnets 1930 to 2010



SEA Task Summary



Techno-Economic Analysis

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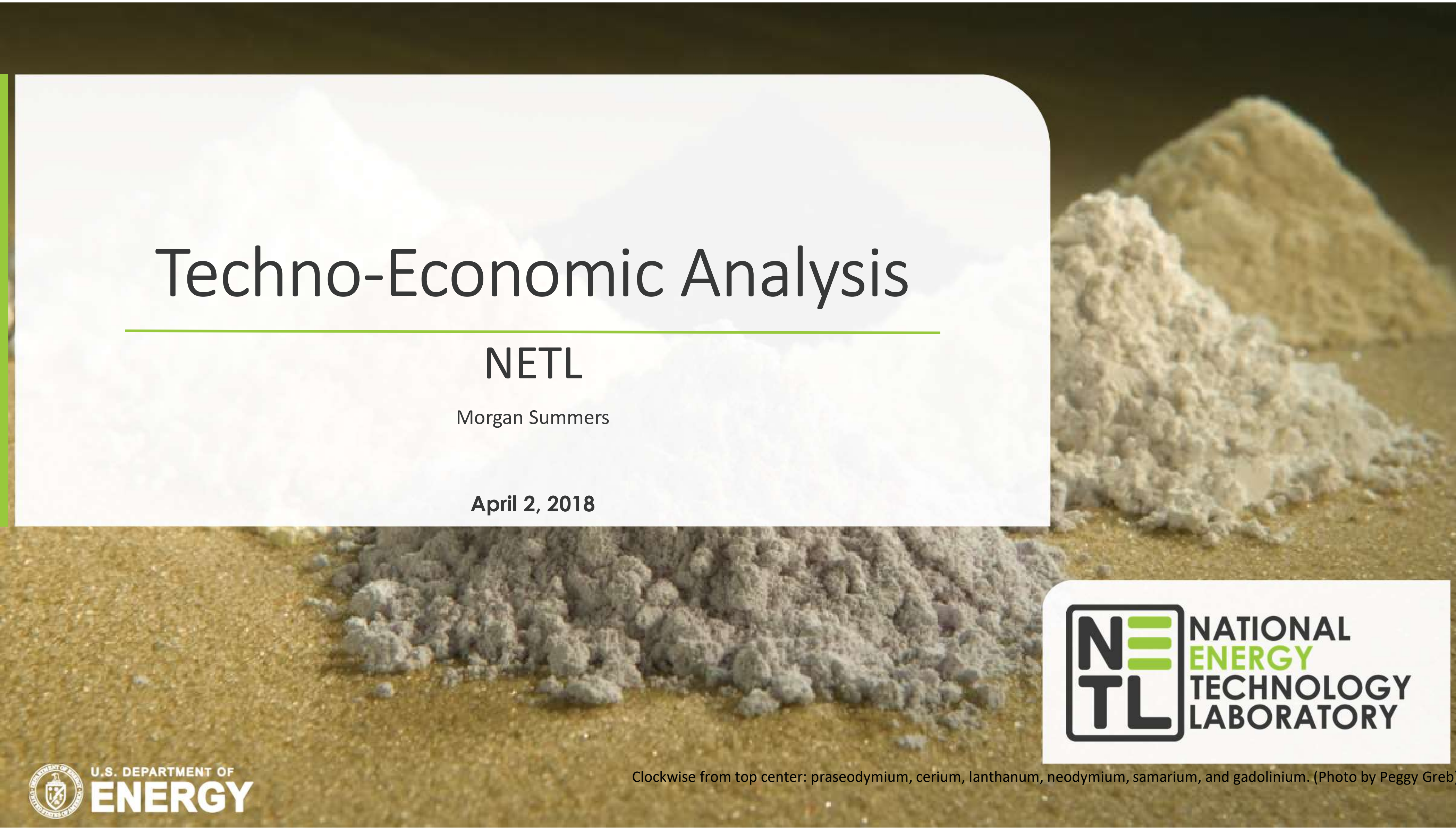
April 2, 2018



Clockwise from top center: praseodymium, cerium, lanthanum, neodymium, samarium, and gadolinium. (Photo by Peggy Greb).

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U.S. DEPARTMENT OF ENERGY

Overview

- **FOA Guidelines**
- **AACE Guidelines**
  - Class Estimates
- **TEA Requirements**
  - Levels of Capital Cost
  - Capital Cost Contingency
  - Operating and Maintenance (O&M) Costs
  - Fixed Assumptions for TEA

FOA Guidelines – Appendix B

- **The updated Technical-Economic Feasibility Study Report to be provided with the Renewal Application package should estimate the cost and performance of the project at the scale that is being proposed for Phase 2. This analysis does not have to show, nor is it expected, that the project will be economic at the proposed scale. The intent is to identify economic and performance hurdles at the onset of the project with the intent to identify improvement strategies over the course of Phase 2. A fully functional interactive Excel spreadsheet model with no locked or hidden cells should be included with the updated Technical-Economic Feasibility Study Report.**
- **All Renewal Applications proposing the installation of an AOI 2 Phase 2 <u>pilot scale</u> facility should include a design estimate with adequate detail to be classified as an AACE Class 3 estimate. This estimate is intended to serve as a pre-FEED level estimate for the proposed project so that construction can begin shortly after any Phase 2 award.**
- **All Renewal Applications proposing the installation of an AOI 1 bench-scale facility should include a design estimate equivalent to an AACE Class 4 estimate. This is also to ensure that installation can begin shortly after any Phase 2 award. See estimate guidelines here, http://www.aacei.org/toc/toc_18R-97.pdf.**

FOA Guidelines – Appendix B

- **The estimate should include at a minimum —**
  - Detailed Block flow diagrams identifying all major process equipment and/or steps with as much fidelity as possible (for example grinding/crushing, floatation …)
  - Material and energy balances around the complete plant and all major pieces of equipment or process areas, including all heating and cooling duties and electric power requirements.
  - Vendor quotes for specific pieces of equipment should be used, and reported, whenever possible
  - Complete stream tables showing operating pressures, temperatures, compositions, and enthalpies for all streams entering or leaving major process equipment.
  - Economic analysis providing a detailed code of accounts for the capital cost estimate, similar to Table 1.
- **Estimates prepared by the technology developer for equipment and consumables unique to the process being developed.**
  - If possible, capital cost estimates for unique equipment should be made based on similar equipment that may exist for other type processes.
  - If equipment analogs do not exist for unique equipment, the developer should do a bottom-up estimate of the unique equipment.
- **Operating and maintenance (O&M) costs should be itemized lists, similar to Table 2, detailing costs for:**
  - Fixed operating costs (annual operating labor, maintenance labor, support labor),
  - Variable O&M cost:
    - Maintenance material cost
      - All consumables: water, chemicals (each itemized individually), initial fills, waste disposal (individually itemized), and fuel or feedstock costs (if applicable)

AACE Estimate Classification Matrix

	Primary Characteristic	Secondary Characteristic			
Estimate Class	Level of Project Definition	End Usage	Methodology	Expected Accuracy Range	Preparation Effort*
Class 5	0% to 2%	Concept Screening	Capacity Factored, Parametric Models, Judgment, or Analogy	L: -20% to -50% H: +30% to +100%	1
Class 4	1% to 15%	Study or Feasibility	Equipment Factored or Parametric Models	L: -15% to -30% H: +20% to +50%	2 to 4
Class 3	10% to 40%	Budget, Authorization, or Control	Semi-Detailed Unit Costs with Assembly Level Line Items	L: -10% to -20% H: +10% to +30%	3 to 10
Class 2	30% to 70%	Control or Bid/Tender	Detailed Unit Cost with Forced Detailed Take-Off	L: -5% to -15% H: +5% to +20%	4 to 20
Class 1	50% to 100%	Check Estimate or Bid/Tendor	Detailed Unit Cost with Detailed Take-Off	L: -3% to -10% H: +3% to +15%	5 to 100

AACE International Recommended Practice No. 18R-97

*Typical degree of effort relative to least cost index of 1 (If the range index value of 1represents 0.005% of project costs, then an index value of 100 represents 0.5%. Estimate preparation effort is highly dependent upon the size of the project and the quality of estimating data and tools.

Class Estimates

CLASS 4

"Typically, engineering is from 1% to 15% complete, and would comprise at a minimum the following: plant capacity, block schematics, indicated layout, process flow diagram for main process systems, and preliminary engineered process and utility equipments lists." - AACE

- **Corresponding accuracy range of -15% to +50%**

CLASS 3

"Typically, engineering is from 10% to 40% complete, and would comprise at a minimum the following: process flow diagrams, utility flow diagrams, preliminary piping and instrument diagrams, plat plan, developed layout drawings and essentially complete engineered process and utility equipment lists."-AACE

- **Corresponding accuracy range of -10% to +30%**

Techno-Economic Analysis Requirements

- **Plant Boundary**
- **Assumed Plant Life**
- **Capital Costs**
  - Level of Capital Cost
  - Contingencies (Project and Process)
- **Operating Costs**
- **Global Economic**

Levels of Capital Cost

process equipment
supporting facilities
direct and indirect labor

$\Big\}$ **BEC**

EPC contractor services
process contingency
project contingency

$\Big\}$ **TPC**

pre-production costs
inventory capital
financing costs
other owner's costs

$\Big\}$ **TOC**

escalation during capital expenditure period
interest on debt during capital expenditure period

$\Big\}$ **TASC**

Bare Erected Cost
Total Plant Cost
Total Overnight Cost
Total As-Spent Cost

BEC, TPC and TOC are all "overnight" costs expressed in constant dollars.

TASC is expressed in mixed-year current dollars, spread over the capital expenditure period.

Capital Cost Contingencies

AACE Definition of Contingency

- **"an amount added to an estimate to allow for additional costs that <u>experience shows will likely be required</u>. This may be derived either through statistical analysis of past project costs, or by applying experience gained on similar projects. Contingency usually does not include changes in scope or schedule or unforeseeable major events such as strikes or earthquakes (AACE 1998).**

O&M Costs

Fixed Operating and Maintenance (O&M) Costs	Variable Operating and Maintenance (O&M) Costs
Annual Operating Labor Cost	Maintenance Material Cost
Maintenance Labor Cost	Consumables
Administrative & Support Labor	Water
Property Taxes and Insurance	Chemicals
	Waste Disposal
	By-Products and Emissions

Fixed Assumptions for TEA

Table 3: Simplified Market Prices (Dec. 2016)	
LIGHT RARE EARTH METALS	US$/kg
Lanthanum metal ≥ 99%	7
Lanthanum Oxide ≥ 99.5%	2
Cerium metal ≥ 99%	7
Cerium Oxide ≥ 99.5%	2
Praseodymium metal ≥ 99%	85
Praseodymium Oxide ≥ 99.5%	52
Neodymium metal ≥ 99.5%	60
Neodymium Oxide ≥ 99.5%	42
Samarium metal ≥ 99.9%	7
HEAVY RARE EARTH METALS	US$/kg
Europium Oxide ≥ 99.99%	150
Gadolinium metal 99.9%	55
Gadolinium Oxide ≥ 99.5%	32
Terbium metal ≥ 99.9%	550
Terbium Oxide ≥ 99.5%	400
Dysprosium metal ≥ 99%	350
Dysprosium Oxide ≥ 99.5%	230
Erbium metal ≥ 99.9%	95
Erbium Oxide ≥ 99.5%	34
Yttrium metal ≥ 99.9%	35
Yttrium Oxide ≥ 99.99%	6
Scandium metal 99.9%	15,000.00
Scandium Oxide ≥ 99.95%	4,200.00
Mischmetal ≥ 99%	6
Source:	mineralprices.com

Table 4: Global Economic Assumptions	
Parameter	Value
TAXES	
Income Tax Rate	38% Effective (34% Federal, 6% State)
Capital Depreciation	20 years, 150% declining balance
Investment Tax Credit	0%
Tax Holiday	0 years
CONTRACTING AND FINANCING TERMS	
Contracting Strategy	Engineering Procurement Construction Management (owner assumes project risks for performance, schedule and cost)
Type of Debt Financing	Non-Recourse (collateral that secures debt is limited to the real assets of the project)
Repayment Term of Debt	10 years
Grace Period on Debt Repayment	0 years
Debt Reserve Fund	None
ANALYSIS TIME PERIODS	
Capital Expenditure Period	1 – 3 years
Operational Period	20 years
Economic Analysis Period (used for IRROE)	21 or 23 Years (capital expenditure period plus operational period)
TREATMENT OF CAPITAL COSTS	
Capital Cost Escalation During Capital Expenditure Period (nominal annual rate)	3.6%[1]
Distribution of Total Overnight Capital over the Capital Expenditure Period (before escalation)	3-Year Period: 10%, 60%, 30%
Working Capital	zero for all parameters
% of Total Overnight Capital that is Depreciated	100% *(this assumption introduces a very small error even if a substantial amount of TOC is actually non-depreciable)*
ESCALATION OF OPERATING REVENUES AND COSTS	
Escalation of Product Price (revenue), O&M Costs, Fuel Costs (nominal annual rate)	3.0%[2]
EXAMPLE FINANCING SCENARIO	
Debt/Equity Ratio	50%
Internal Rate of Return on Equity (IRROE)	20%
Interest Rate	6%