Economic Feasibility of Rare Earth Element Extraction from Wyoming Coal Ash/Char

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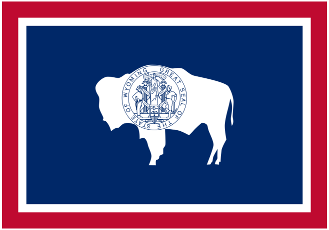
Background

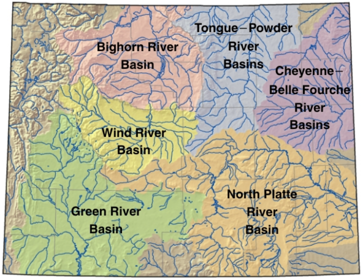
- Wyoming: largest producer of coal in U.S.[1]
- Coal on the decline
  - Market effects
  - Regulatory changes [2]
- Diversification $\Rightarrow$ REE extraction from coal ash?
  - Increased global demand
  - China dominates market



[1] (*EIA*, 2016)
[2] (*Godby et al.*, 2015)

REE Extraction Potential

- Taggart et al. (2016) sampled 3 ash sources:
  - Appalachian
  - Illinois
  - Powder River Basin (PRB)
- Results:
  - PRB: lowest average total REE content
  - PRB: highest extractable REE content



Objective

Analyze economic feasibility of RE extraction from coal ash through two economic models:

- Open-pit RE mine
- Coal stations

Open-Pit Mine Overview

- Small-tonnage RE mine built from scratch
- Significant start-up costs
  - Capital cost of mining
  - Capital cost of refining
- Estimates from the literature:
  - Camm, 1991
  - MIT, “Opening new mines” study
  - MIT, “Green refinement” study
- SRK Consulting’s Mountain Pass Report
  - Mine-to-oxide operating cost:
    1.17 US$ per lb TREO

Open-Pit Mine Results

Initial Mining Capital Cost $\approx$ \$127 million

Initial Refining Capital Cost $\approx$ \$100 million

Annual Mining Operating Cost $\approx$ \$5.5 million

Annual Refining Operating Cost $\approx$ \$387 million

Annual Revenue $\approx$ \$265 million

$\Rightarrow$ **Large, negative net present value (NPV)**

$\approx$ **-\$1.9 billion**

Coal Stations Overview

- Powder River Basin (PRB)
  - Laramie River
  - Dave Johnston
  - WyoDak
  - Dry Fork
- Green River Basin (GRB)
  - Jim Bridger
  - Naughton
- Data on RE concentrations in coal ash (in ppm) [3]
  - FA, BA, and FA+BA (LA)

[3] Estimates provided by J.F. McLaughlin and D.A. Bagdonas

Model Setup: Revenue

- Ash sources:
  - Ash generated daily (rate)
  - Existing landfill (stock)
- Rate Ash Calculations
  - ppm $\Rightarrow$ % concentration $\Rightarrow$ multiplied by ash production rate

    $\Rightarrow$ converted to oxide volume
- Stock Ash Calculations
  - Landfill ash completely refined by last year of operation
  - Same conversion to oxide form

Volume per year $=$ rate per year $+$ fraction of stock refined per year

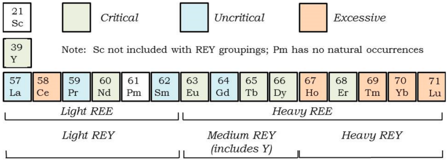
TREO Volumes

Stations		Low Ash Estimate		High Ash Estimate		Average Ash Estimate	
		TREO (lbs/year) 70% yield	TREO (lbs/year) 100% yield	TREO (lbs/year) 70% yield	TREO (lbs/year) 100% yield	TREO (tons/year) 70% yield	TREO (lbs/year) 100% yield
Powder River Basin	Laramie River*	26225	37464	62940	89914	44582	63689
	Dave Johnston	278504	397863	278504	397863	278504	397863
	WyoDak	80476	114965	109277	156110	94876	135538
	Dry Fork	108360	154800	151408	216297	129884	185548
Green River Basin	Jim Bridger*	108685	155264	260844	372634	184764	263949
	Naughton*	26176	37394	26176	37394	26176	37394

Table 1: Yearly TREO Volumes

Model Setup: Revenue

- Obtained average prices of REs using:
  - Argus Media Service *MetalPrices.com*
  - USGS Rare Earths Minerals Yearbook
- Multiplied volume per year by average price
- Summed revenue of all REs
  - OMITTED EXCESSIVE REs
- Used 70% recovery rate [4]
  - Heated nitric acid digestion
- Assuming 95% of product is sold



[4] as found by Taggart et al. when testing PRB ash

Coal Station Revenues

Stations		Low Ash Estimate		High Ash Estimate		Average Ash Estimate	
		Annual Revenue ($/year) 70% Yield	Annual Revenue Critical REE Only ($/year) 70% Yield	Annual Revenue ($/year) 70% Yield	Annual Revenue, Critical REE Only ($/year) 70% Yield	Annual Revenue ($/year) 70% Yield	Annual Revenue, Critical REE Only ($/year) 70% Yield
Powder River Basin	Laramie River*	$ 889,710	$ 651,846	$ 2,135,303	$ 1,564,431	$ 1,512,506	$ 1,108,139
	Dave Johnston	$ 2,475,429	$ 1,808,298	$ 2,475,429	$ 1,808,298	$ 2,475,429	$ 1,808,298
	WyoDak	$ 1,296,431	$ 955,055	$ 2,273,576	$ 1,677,264	$ 1,785,004	$ 1,316,159
	Dry Fork	$ 1,123,246	$ 828,597	$ 2,620,777	$ 1,933,426	$ 1,872,011	$ 1,381,012
Green River Basin	Jim Bridger*	$ 3,444,956	$ 2,445,598	$ 8,267,894	$ 5,869,434	$ 5,856,425	$ 4,157,516
	Naughton*	$ 772,678	$ 562,380	$ 772,678	$ 562,380	$ 772,678	$ 562,380

Table 2: Yearly Revenue by Station

Model Setup: Costs

- Cost of RE extraction from coal ash

  $\Rightarrow$ largely undocumented
- Initial investment: lower
- Breakeven ash-to-oxide unit operating costs

  $\Rightarrow$ using NPV equation

Model Setup: NPV

$$NPV_i = \left[\frac{1-\rho^{n+1}}{1-\rho}\right] \pi_{it} - FC_i$$

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R_{it} = annual revenue

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w^k = breakeven unit cost parameter

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Q_{it}^k = volume of ash refined

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w^k = breakeven unit cost parameter

Q^k_{it} = volume of ash refined

FC_i = initial investment costs

Maximum Initial Investment

Assuming absence of operating costs:

$$FC_i^{max} = \left[\frac{1-\rho^{n+1}}{1-\rho}\right] R_{it}.$$

- Choose level of investment below maximum
  $\Rightarrow$ allows for operating costs
- Value set at \$15 million[5]

[5] for all stations besides Naughton

Maximum Initial Investment

Comparison of Coal Stations		Max Initial Capital Cost ($) Low Ash Estimate	Max Initial Capital Cost ($) High Ash Estimate	Max Initial Capital Cost ($) Average Ash Estimate
Powder River Basin	Laramie River*	$ 11,773,959	$ 28,257,501	$ 20,015,730
	Dave Johnston	$ 32,758,555	$ 32,758,555	$ 32,758,555
	WyoDak	$ 17,156,304	$ 30,087,332	$ 23,621,818
	Dry Fork	$ 14,864,453	$ 34,682,013	$ 24,773,233
Green River Basin	Jim Bridger*	$ 45,588,769	$ 109,413,046	$ 77,500,907
	Naughton*	$ 10,225,222	$ 10,225,222	$ 10,225,222

Table 3: Maximum Initial Investment by Station

Zooming in on the Unit Cost Parameter

Recall:

$$C_{it} = \text{annual costs} = w^k Q_{it}^k$$
$$w^k = \text{breakeven unit cost parameter}$$
$$Q_{it} = \text{volume of ash refined}$$

To calculate the breakeven unit cost:

$$w^k = \frac{R_{it} - \frac{FC_i}{\left[\frac{1-\rho^{n+1}}{1-\rho}\right]}}{Q_{it}^k}.$$

2 variants:

1. Input alternative ($k = ash$)
2. Output alternative ($k = TREO$)

Zooming in on the Unit Cost Parameter

- Recall, from SRK Mountain Pass Report:

  mine-to-oxide operating cost = $1.17 per pound TREO

- Ash-to-oxide operating cost:

  ash already partly refined

$\Rightarrow$ **ash-to-oxide operating cost** $<$ **mine-to-oxide operating cost**

Zooming in on the Unit Cost Parameter

Stations		Low Ash Estimate		High Ash Estimate		Average Ash Estimate	
		Breakeven Ash-to-Oxide Unit Cost ($/lb ash)	Breakeven Ash-to-Oxide Unit Cost ($/lb TREO) 70% yield	Breakeven Ash-to-Oxide Unit Cost ($/lb ash)	Breakeven Ash-to-Oxide Unit Cost ($/lb TREO) 70% yield	Breakeven Ash-to-Oxide Unit Cost ($/lb ash)	Breakeven Ash-to-Oxide Unit Cost ($/lb TREO) 70% yield
Powder River Basin	Laramie River*	$ (0.0016)	$ (9.2957)	$ 0.0027	$ 15.92	$ 0.0014	$ 8.50
	Dave Johnston	$ 0.0033	$ 4.8184	$ 0.0033	$ 4.82	$ 0.0033	$ 4.82
	WyoDak	$ 0.0008	$ 2.0247	$ 0.0031	$ 10.43	$ 0.0023	$ 6.87
	Dry Fork	$ (0.0001)	$ (0.0945)	$ 0.0038	$ 9.82	$ 0.0026	$ 5.69
Green River Basin	Jim Bridger*	$ 0.0032	$ 21.2676	$ 0.0041	$ 27.35	$ 0.0038	$ 25.56
	Naughton*	$ 0.0001	$ 0.6502	$ 0.0001	$ 0.65	$ 0.0001	$ 0.65

Table 4: Breakeven Unit Cost for Each Station

Notice: higher breakeven unit cost is better!

Analysis - NPV

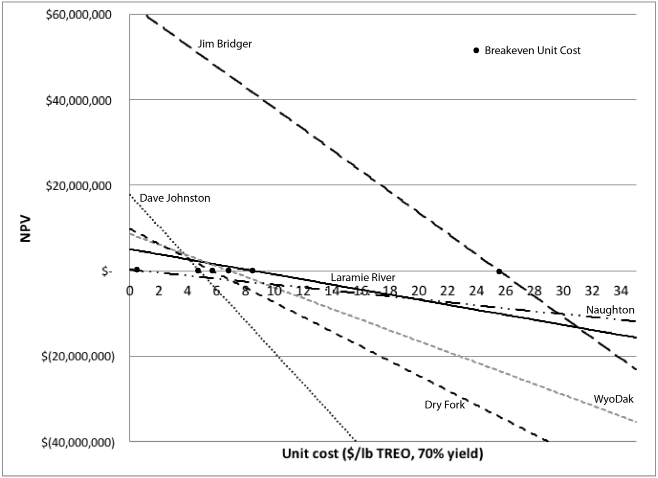

Figure 1: NPV over Unit Cost by Station

Conclusion

- Open-pit mine:
  - Building mine from ground up $\Rightarrow$ infeasible
  - Refinement of REEs $\Rightarrow$ expensive
- RE extraction from coal ash:
  - Lack of estimates in literature
  - Model finds breakeven unit costs

    $\Rightarrow$ Promising results when compared to
    \$1.17 Mountain Pass value
  - Big assumptions on initial capital costs

Conclusion

- If coal stations operate under breakeven unit costs:

  refinement of REs from coal ash $\Rightarrow$ feasible

- Implications for Wyoming:
  1. Potential source of revenue
  2. Reduction in waste material

     $\Rightarrow$ reduction in environmental damage

Conclusion

Questions

???

References

- Camm, T. (1991). Simplified cost models for prefeasibility mineral evaluations. Retrieved from http://pubs.usgs.gov/usbmic/ic-9298/html/cammfrms.htm.
- Godby, R., Coupal, R., Taylor, D., and Considine, T. (2015). The Impact of the Coal Economy on Wyoming. *Center for Energy Economics and Public Policy, Department of Economics and Finance, University of Wyoming*.
- MIT (n.d.a). Green refinement: increasing efficiency and decreasing cost and environmental damage of rare earth refinement. Retrieved from: http://web.mit.edu/12.000/www/m2016/finalwebsite/solutions/greenrefining.html.
- MIT (n.d.b). Opening new mines: the process of mining REEs and other strategic elements. Retrieved from: http://web.mit.edu/12.000/www/m2016/finalwebsite/solutions/newmines.html.

References (continued)

- SRK (2010). Technical economic model for the mountain pass re-start project. Retrieved from: http://www.sec.gov/Archives/edgar/data/1489137/000095012310065239/d74323fwfwp.htm.
- Taggart, R., Hower, J., Dwyer, G. and Hsu-Kim, H. (2016). Trends in the rare earth element content of U.S.-based coal combustion fly ashes. *Environmental Science & Technology*.
- *U.S. Energy Information Administration*. (2016). Wyoming: State Profile and Energy Estimates.