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 ⇒ % concentration ⇒ multiplied by ash production rate
    ⇒ 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

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

Table 1: Yearly TREO Volumes
Model Setup: Revenue

- Obtained average prices of REs using:
  - Argus Media Service \textit{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

## Table 2: Yearly Revenue by Station

<table>
<thead>
<tr>
<th>Stations</th>
<th>Low Ash Estimate</th>
<th></th>
<th>High Ash Estimate</th>
<th></th>
<th>Average Ash Estimate</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Annual Revenue</td>
<td>Annual Revenue</td>
<td>Annual Revenue</td>
<td>Annual Revenue</td>
<td>Annual Revenue</td>
<td>Annual Revenue</td>
</tr>
<tr>
<td></td>
<td>($/year) 70% Yield</td>
<td>Critical REE Only</td>
<td>($/year) 70% Yield</td>
<td>Critical REE Only</td>
<td>($/year) 70% Yield</td>
<td>Critical REE Only</td>
</tr>
<tr>
<td>Powder River Basin</td>
<td>$889,710</td>
<td>$651,846</td>
<td>$2,135,303</td>
<td>$1,564,431</td>
<td>$1,512,506</td>
<td>$1,108,139</td>
</tr>
<tr>
<td>Laramie River*</td>
<td>$2,475,429</td>
<td>$1,808,298</td>
<td>$2,475,429</td>
<td>$1,808,298</td>
<td>$2,475,429</td>
<td>$1,808,298</td>
</tr>
<tr>
<td>Dave Johnston</td>
<td>$1,296,431</td>
<td>$955,055</td>
<td>$2,273,576</td>
<td>$1,677,264</td>
<td>$1,785,004</td>
<td>$1,316,159</td>
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<tr>
<td>WyoDak</td>
<td>$1,123,246</td>
<td>$828,597</td>
<td>$2,520,777</td>
<td>$1,933,426</td>
<td>$1,872,011</td>
<td>$1,381,012</td>
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<tr>
<td>Dry Fork</td>
<td>$3,444,956</td>
<td>$2,445,598</td>
<td>$8,267,894</td>
<td>$5,869,434</td>
<td>$5,856,425</td>
<td>$4,157,516</td>
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<tr>
<td>Green River Basin</td>
<td>$772,678</td>
<td>$562,380</td>
<td>$772,678</td>
<td>$562,380</td>
<td>$772,678</td>
<td>$562,380</td>
</tr>
<tr>
<td>Jim Bridger*</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Naughton*</td>
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</tbody>
</table>

*Projected values
Model Setup: Costs

- Cost of RE extraction from coal ash
  ⇒ largely undocumented
- Initial investment: lower
- Breakeven ash-to-oxide unit operating costs
  ⇒ using NPV equation

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

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

\( i = \text{station} \)
Model Setup: NPV

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

i = station

\[ t = year \]
Model Setup: NPV

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

i = station

t = year

$$\rho = \text{discount factor} = \frac{1}{1+r}$$
Model Setup: NPV

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

\( i = \text{station} \)

\( t = \text{year} \)

\( \rho = \text{discount factor} = \frac{1}{1+r} \)

\( r = \text{interest rate} \)
Model Setup: NPV

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

\( i = \text{station} \)
\( t = \text{year} \)
\( \rho = \text{discount factor} = \frac{1}{1+r} \)
\( r = \text{interest rate} \)
\( \pi_{it} = \text{profit} = R_{it} - C_{it} \)
Model Setup: NPV

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

i = station

t = year

\( \rho \) = discount factor = \( \frac{1}{1+r} \)

r = interest rate

\( \pi_{it} \) = profit = \( R_{it} - C_{it} \)

\( R_{it} \) = annual revenue
Model Setup: NPV

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

i = station

t = year

\( \rho = \text{discount factor} = \frac{1}{1+r} \)

r = interest rate

\( \pi_{it} = \text{profit} = R_{it} - C_{it} \)

\( R_{it} = \text{annual revenue} \)

\( C_{it} = \text{annual cost} = w^k Q^k_{it} \)
Model Setup: NPV

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

i = station

t = year

\( \rho = \) discount factor \( = \frac{1}{1+r} \)

r = interest rate

\( \pi_{it} = \) profit \( = R_{it} - C_{it} \)

\( R_{it} = \) annual revenue

\( C_{it} = \) annual cost \( = w^k Q^k_{it} \)

\( w^k = \) breakeven unit cost parameter
Model Setup: NPV

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

i = station

t = year

\[ \rho = \text{discount factor} = \frac{1}{1+r} \]

r = interest rate

\[ \pi_{it} = \text{profit} = R_{it} - C_{it} \]

\[ R_{it} = \text{annual revenue} \]

\[ C_{it} = \text{annual cost} = w^k Q_{it}^k \]

\[ w^k = \text{breakeven unit cost parameter} \]

\[ Q_{it}^k = \text{volume of ash refined} \]
Model Setup: NPV

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

\( i = \text{station} \)

\( t = \text{year} \)

\( \rho = \text{discount factor} = \frac{1}{1+r} \)

\( r = \text{interest rate} \)

\( \pi_{it} = \text{profit} = R_{it} - C_{it} \)

\( R_{it} = \text{annual revenue} \)

\( C_{it} = \text{annual cost} = w^k Q_{it}^k \)

\( w^k = \text{breakeven unit cost parameter} \)

\( Q_{it}^k = \text{volume of ash refined} \)

\( FC_i = \text{initial investment costs} \)
Maximum Initial Investment

Assuming absence of operating costs:

\[ FC_{i}^{\text{max}} = \left[ \frac{1 - \rho^{n+1}}{1 - \rho} \right] R_{it}. \]

- Choose level of investment below maximum
  \[ \Rightarrow \text{allows for operating costs} \]
- Value set at $15 million\(^5\)

\(^5\)for all stations besides Naughton
## Maximum Initial Investment

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

Table 3: Maximum Initial Investment by Station
Zooming in on the Unit Cost Parameter

Recall:

\[ C_{it} = \text{annual costs} = w^k Q^k_{it} \]

\[ w^k = \text{breakeven unit cost parameter} \]

\[ Q_{it} = \text{volume of ash refined} \]

To calculate the breakeven unit cost:

\[ w^k = \frac{R_{it} - \frac{FC_i}{1 - \rho^n + 1}}{Q^k_{it}}. \]

2 variants:

1. Input alternative \((k = \text{ash})\)
2. Output alternative \((k = \text{TREO})\)
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

⇒ ash-to-oxide operating cost < mine-to-oxide operating cost
### Zooming in on the Unit Cost Parameter

Table 4: Breakeven Unit Cost for Each Station

<table>
<thead>
<tr>
<th>Stations</th>
<th>Low Ash Estimate</th>
<th>High Ash Estimate</th>
<th>Average Ash Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Breakeven Ash-to-Oxide Unit Cost ($/lb ash)</td>
<td>Breakeven Ash-to-Oxide Unit Cost ($/lb TREO) 70% yield</td>
<td>Breakeven Ash-to-Oxide Unit Cost ($/lb ash)</td>
</tr>
<tr>
<td>Powder River Basin</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Laramie River*</td>
<td>$0.0016</td>
<td>$9.2957</td>
<td>$0.0027</td>
</tr>
<tr>
<td>Dave Johnston</td>
<td>$0.0033</td>
<td>$4.8184</td>
<td>$0.0033</td>
</tr>
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<td>WyoDak</td>
<td>$0.0008</td>
<td>$2.0247</td>
<td>$0.0031</td>
</tr>
<tr>
<td>Dry Fork</td>
<td>$0.0001</td>
<td>$0.0945</td>
<td>$0.0038</td>
</tr>
<tr>
<td>Green River Basin</td>
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<td>Jim Bridger*</td>
<td>$0.0032</td>
<td>$21.2676</td>
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<td>Naughton*</td>
<td>$0.0001</td>
<td>$0.6502</td>
<td>$0.0001</td>
</tr>
</tbody>
</table>

Notice: higher breakeven unit cost is better!
Figure 1: NPV over Unit Cost by Station
• **Open-pit mine:**
  - Building mine from ground up ⇒ infeasible
  - Refinement of REEs ⇒ expensive

• **RE extraction from coal ash:**
  - Lack of estimates in literature
  - Model finds breakeven unit costs
    ⇒ 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


References (continued)

