

# Recovering rare earth metals from waste

**Eric Williams\***, **Gabrielle Gaustad**<sup>○</sup>,  
**Saptarshi Das\***, **Alex Leader\***

\* Rochester Institute of Technology

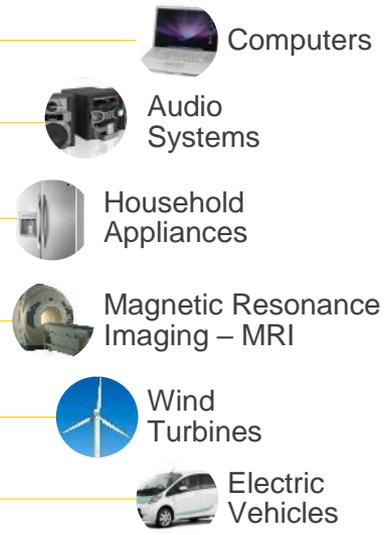
○ Alfred University



# In brief: production and use of rare earth elements

## Rare Earth Elements (REEs)

- ▶ Few substitutes
- ▶ Over 97% produced in China
- ▶ <1% are recycled
- ▶ Energy and resource intensive to produce
- ▶ Utilized by existing and emerging technologies (including clean energy technologies)



hydrogen 1 1.0079																	helium 2 4.0026																														
lithium 3 6.941	beryllium 4 9.0122																	neon 10 20.180																													
sodium 11 22.990	magnesium 12 24.305																	argon 18 39.948																													
potassium 19 39.098	calcium 20 40.078	scandium 21 44.956	titanium 22 47.867	vanadium 23 50.942	chromium 24 51.996	manganese 25 54.938	iron 26 55.845	cobalt 27 58.933	nickel 28 58.693	copper 29 63.546	zinc 30 65.38	gallium 31 69.723	germanium 32 72.64	arsenic 33 74.922	selenium 34 78.96	bromine 35 79.904	krypton 36 83.798																														
rubidium 37 85.468	strontium 38 87.62	yttrium 39 88.906	zirconium 40 91.224	niobium 41 92.906	molybdenum 42 95.96	technetium 43 98	ruthenium 44 101.07	rhodium 45 102.91	nickel 46 106.42	silver 47 107.87	cadmium 48 112.41	indium 49 114.82	tin 50 118.71	antimony 51 121.76	tellurium 52 127.60	iodine 53 126.90	xenon 54 131.29																														
cesium 55 132.91	barium 56 137.33	lanthanum 57 138.91	hafnium 72 178.49	tantalum 73 180.95	tungsten 74 183.84	rhenium 75 186.21	osmium 76 190.23	iridium 77 192.22	platinum 78 195.08	gold 79 196.97	mercury 80 200.59	thallium 81 204.38	lead 82 207.2	bismuth 83 208.98	polonium 84 [209]	astatine 85 [210]	radon 86 [222]																														
francium 87 [223]	radium 88 [226]	actinium 89 [227]	rutherfordium 104 [261]	bohrium 105 [262]	seaborgium 106 [266]	bohrium 107 [264]	hassium 108 [277]	meitnerium 109 [266]	darmstadtium 110 [271]	roentgenium 111 [272]																																					
<table border="1"> <tr> <td>lanthanum 57 138.91</td> <td>cerium 58 140.12</td> <td>praseodymium 59 140.91</td> <td>neodymium 60 144.24</td> <td>promethium 61 [145]</td> <td>samarium 62 150.36</td> <td>europtium 63 151.96</td> <td>gadolinium 64 157.25</td> <td>terbium 65 158.93</td> <td>dysprosium 66 162.50</td> <td>holmium 67 164.93</td> <td>erbium 68 167.26</td> <td>thulium 69 168.93</td> <td>ytterbium 70 173.05</td> <td>lutetium 71 174.97</td> </tr> <tr> <td>actinium 89 [227]</td> <td>thorium 90 232.04</td> <td>protactinium 91 231.04</td> <td>uranium 92 238.03</td> <td>neptunium 93 [237]</td> <td>plutonium 94 [244]</td> <td>americium 95 [243]</td> <td>curium 96 [247]</td> <td>berkelium 97 [247]</td> <td>californium 98 [251]</td> <td>einsteinium 99 [252]</td> <td>fermium 100 [257]</td> <td>mendelevium 101 [258]</td> <td>nobelium 102 [259]</td> <td>lawrencium 103 [262]</td> </tr> </table>																		lanthanum 57 138.91	cerium 58 140.12	praseodymium 59 140.91	neodymium 60 144.24	promethium 61 [145]	samarium 62 150.36	europtium 63 151.96	gadolinium 64 157.25	terbium 65 158.93	dysprosium 66 162.50	holmium 67 164.93	erbium 68 167.26	thulium 69 168.93	ytterbium 70 173.05	lutetium 71 174.97	actinium 89 [227]	thorium 90 232.04	protactinium 91 231.04	uranium 92 238.03	neptunium 93 [237]	plutonium 94 [244]	americium 95 [243]	curium 96 [247]	berkelium 97 [247]	californium 98 [251]	einsteinium 99 [252]	fermium 100 [257]	mendelevium 101 [258]	nobelium 102 [259]	lawrencium 103 [262]
lanthanum 57 138.91	cerium 58 140.12	praseodymium 59 140.91	neodymium 60 144.24	promethium 61 [145]	samarium 62 150.36	europtium 63 151.96	gadolinium 64 157.25	terbium 65 158.93	dysprosium 66 162.50	holmium 67 164.93	erbium 68 167.26	thulium 69 168.93	ytterbium 70 173.05	lutetium 71 174.97																																	
actinium 89 [227]	thorium 90 232.04	protactinium 91 231.04	uranium 92 238.03	neptunium 93 [237]	plutonium 94 [244]	americium 95 [243]	curium 96 [247]	berkelium 97 [247]	californium 98 [251]	einsteinium 99 [252]	fermium 100 [257]	mendelevium 101 [258]	nobelium 102 [259]	lawrencium 103 [262]																																	

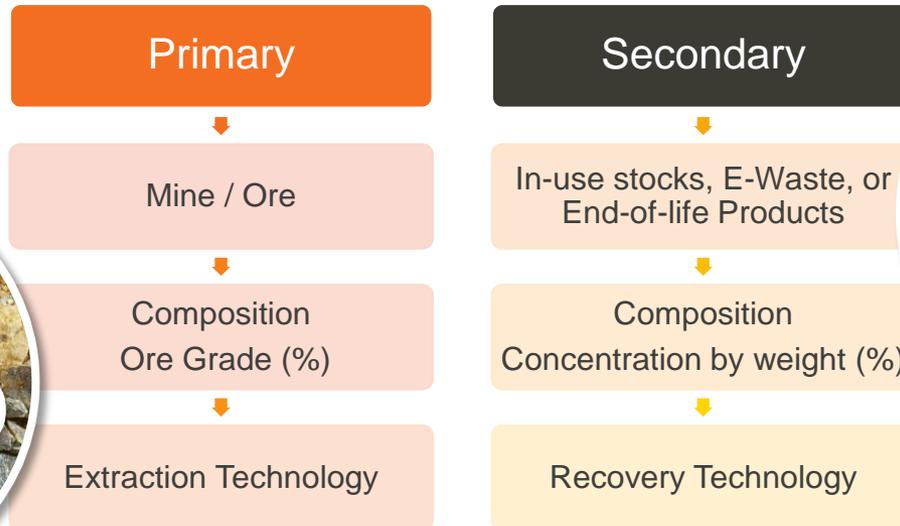
(US DOE 2011, EU 2014, Reck and Graedel 2012, Zaimes et al 2014)

# Societal Risks for Rare Earth Metals

- ▼ **Supply risk:** “critical” to many high tech industries, could easily become a tool/victim in trade wars.
- ▼ **Environmental risk:** little data on impacts of primary production, but technically difficult (REEs are chemically similar) leads to high chemical and energy use.

# Possible solution: recover REEs from wastes (secondary source)

- ▼ Increase supply, nations with lots of REE-containing wastes could become major producers
- ▼ Recycling is **usually** more environmental friendly than making from primary ores.



VS.

# Possible sources of REE from wastes

## Coal Combustion Products (CCPs)

- ▼ Ash byproducts of energy production from coal
- ▼ Current end of life – impounding, concrete, structural fill, road base
- ▼ Also contain heavy metals



## Industrial byproducts and wastes

- ▼ Phospho-gypsum
- ▼ Dross/slag
- ▼ Red mud



## Electronic waste

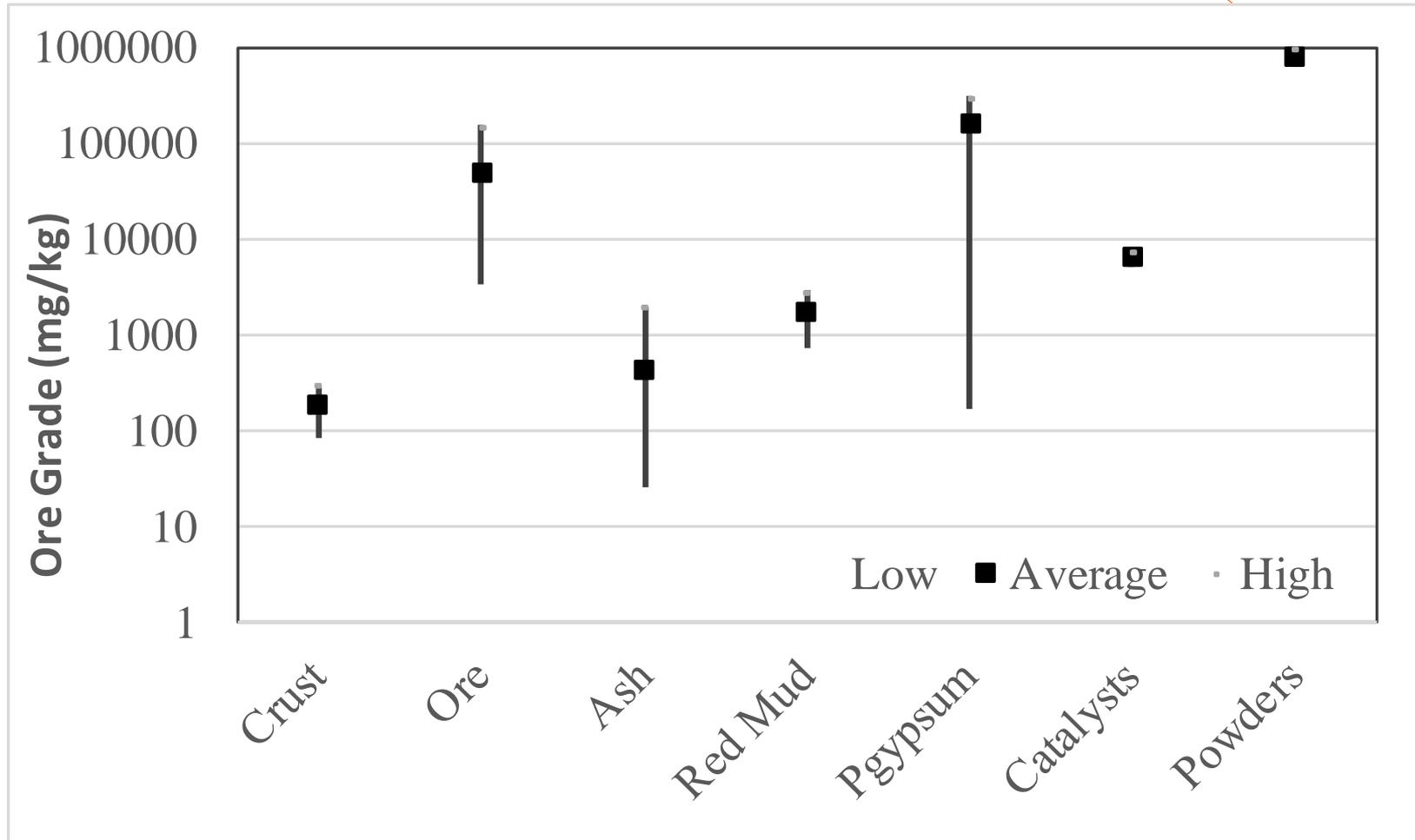
- ▼ Phosphors from LED, LFL
- ▼ NiMH batteries
- ▼ Laptops, desktops
- ▼ Cellphones
- ▼ Speakers



# Two approaches to better understand potential of recovering REEs from waste

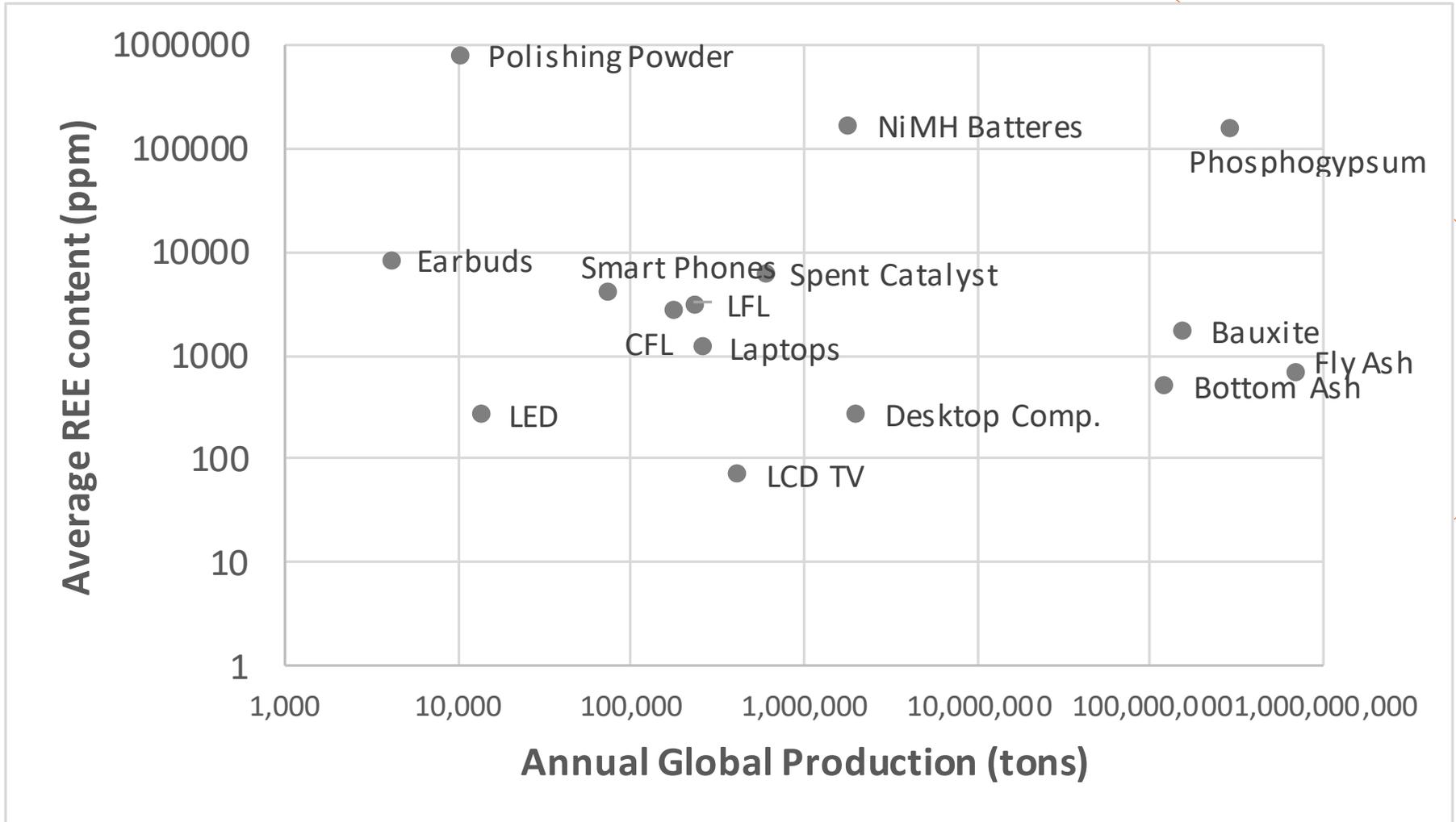
1. Characterize how much REE is in different waste streams (tons) and how likely is it be to easy to extract (grade). Compare with REE production and demand.
2. Techno-economic analysis to estimate potential profitability and emissions from lab scale processes.

“Ore” grade or quality of resource:  
What is the concentration of REEs in  
wastes versus earth sources?

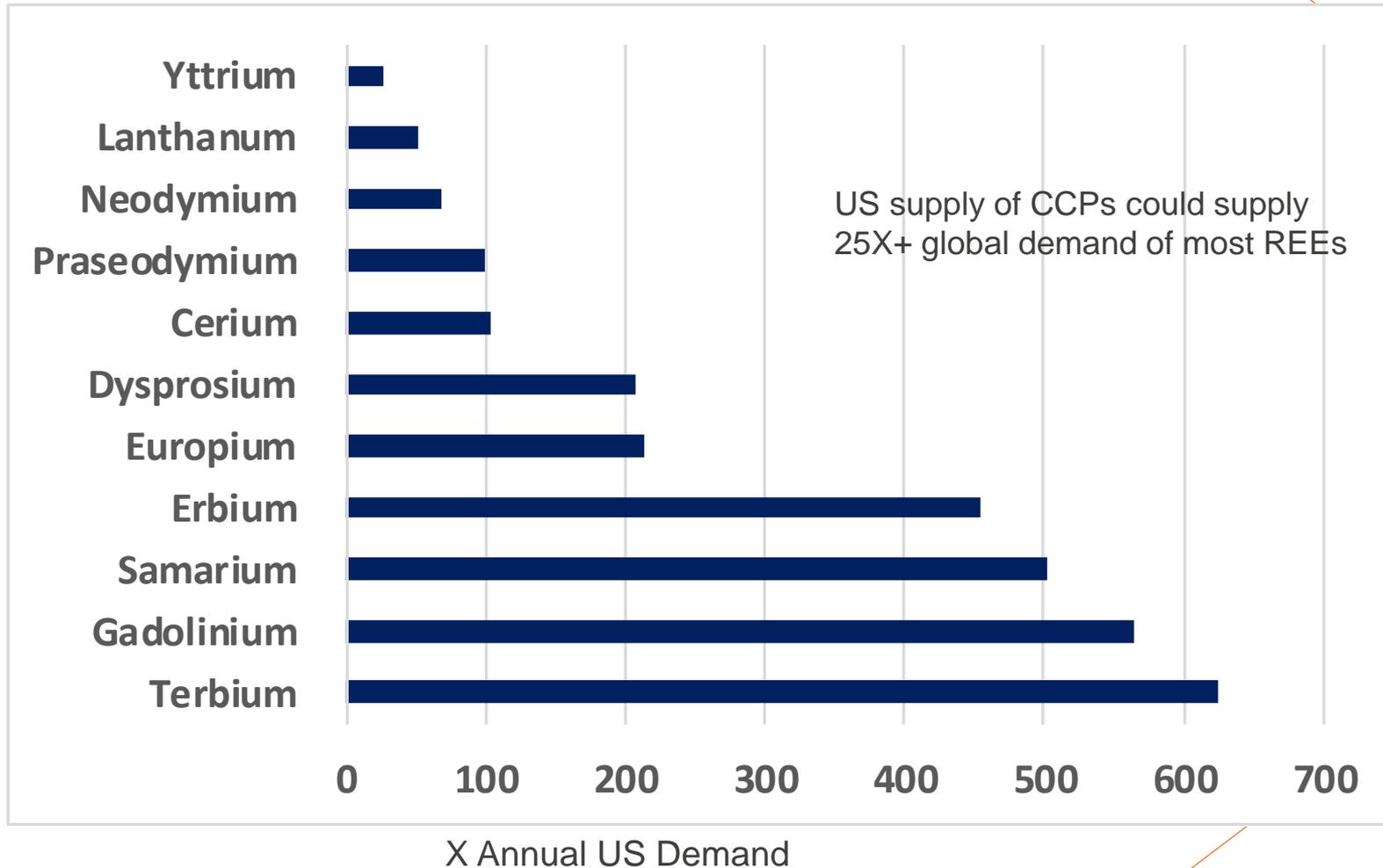


G. Gaustad, E. Williams, and A. Leader (2019). under review

# Quantity and Quality in Context



# Could REE from coal combustion products meet current and future REE demands?



Yes in principle, but at what **cost**?

# Lots of lab-scale extraction studies

Technology	REE source	Reference
acid leaching	fluorescent lamps	tian 2016
dense medium centrifugation	fluorescent lamps	hirajima 2005
flotation separation	fluorescent lamps	hirajima 2005, otsuki 2008
L-L extraction	fluorescent lamps	mei 2009, Meor 2013
hydrometallurgy	fluorescent lamps	rabah 2008, de michelis 2011
photocatalytic extraction	fluorescent lamps	wu 2013
ionic liquid extraction	fluorescent lamps	yang 2012, 2013
supercritical extraction	fluorescent lamps	shimizu 2005
alkaline roasting	fluorescent lamps	wu 2014

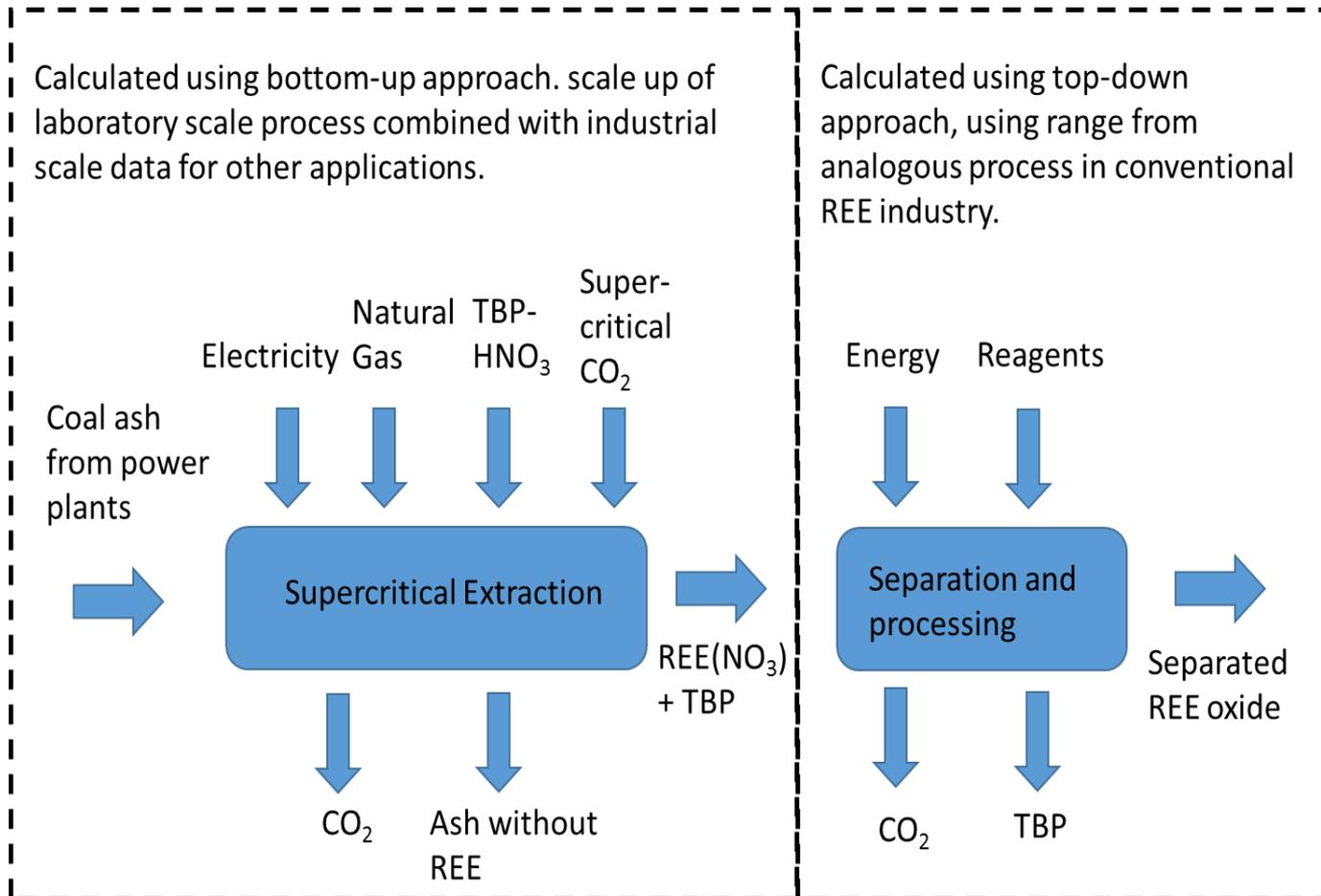
Result:  
Range of yields  
Quantified inputs

Technology	REE source	Reference
hydrometallurgy	NiMH batteries	Rodrigues 2010
hydrogen decrepitation	magnets	Walton 2015
pyrometallurgy	magnets	Okabe et al 2003
ionic liquid/solvent extraction	magnets	Vander Hoogerstraete et al 2013

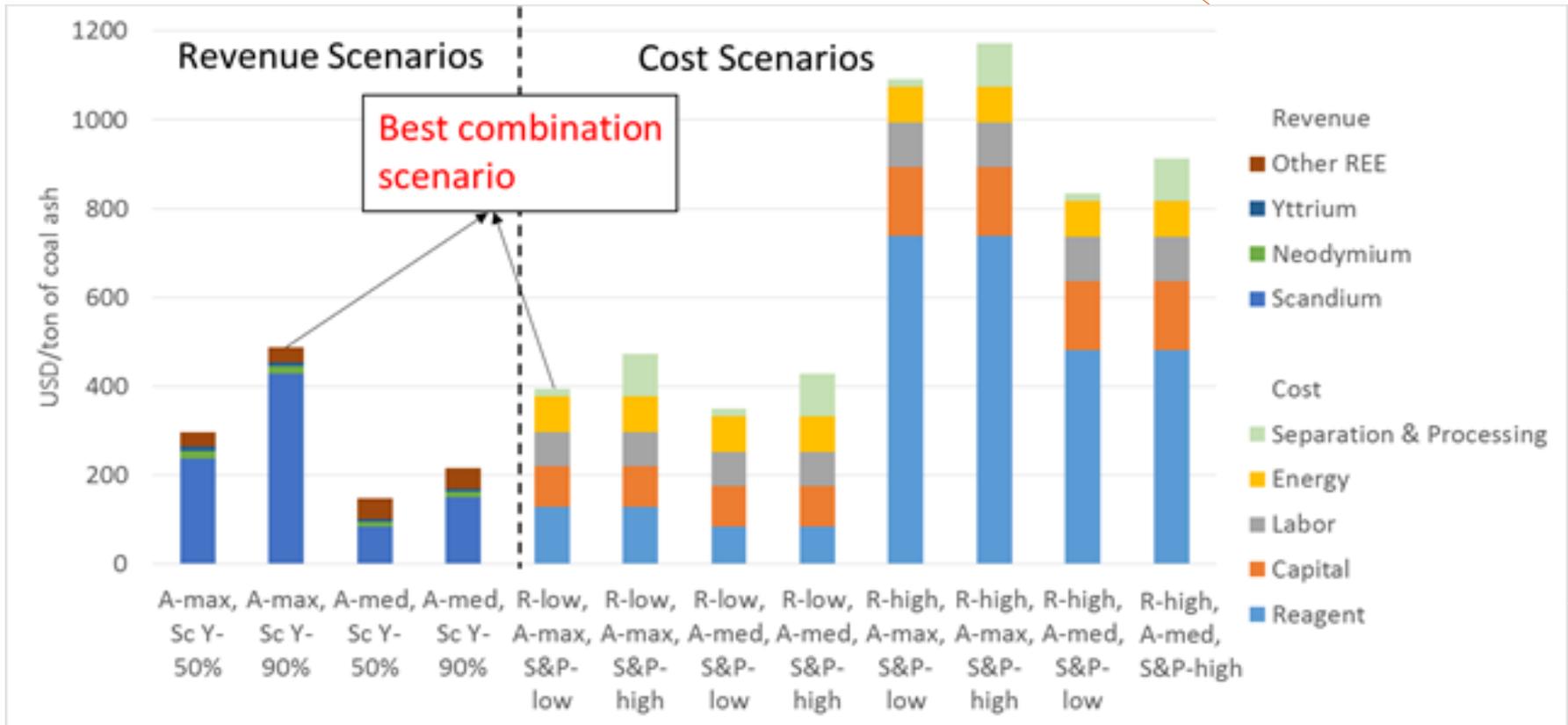
Technology	REE source	Reference
acid leaching	coal ash	Peiro and Mendez 2013
ion exchange	coal ash	Chi et al 2013, Rozelle et al 2016
bio-leaching	coal ash	Kermer et al 2016
supercritical extraction	coal ash	Duan 2012, Samsonov 2007, Shimizu 2005, Sawada 2004

How much would scaled-up versions **cost**?

# Lab results can inform economic feasibility: example assessing recovery from coal ash



# Economic feasibility?



A = REE content of ash, Sc Y = Scandium yield, R = Reagent use, Reagents = CO<sub>2</sub>, TBP, HNO<sub>3</sub>, S&P = Separation and processing

S. Das, G. Gaustad, A. Sekar, E. Williams Techno-economic analysis of super-critical extraction of rare earth elements from coal ash. Journal of Cleaner Production. (2019)

# Conclusions

- ▼ Path to economically feasible recovery of REEs from wastes are not yet clear.
- ▼ Our work suggests:
  - / Focus attention on technologies for waste streams with **potential for large supply**
  - / Content of high value REEs (like scandium) is promising, **but risk of price crash if supply increases**
  - / Early on need to think about recycling reagents and/or using inexpensive ones

Thank you for your attention!

[exwgis@rit.edu](mailto:exwgis@rit.edu)