NATIONAL ENERGY TECHNOLOGY LABORATORY

Critical Materials for SOFC

Impact on SOFC Cost

Presented by Jan Thijssen of J. Thijssen, LLC, subcontractor to Leonardo Technologies, Inc., under NETL Contract DE-FE0004002

Acknowledgement

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Critical Materials for SOFC

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Agenda

1	Background, Objective, and Approach
2	Use of Critical Materials in SOFC
3	Availability of Relevant Materials
4	Impact on SOFC Cost
5	Conclusions

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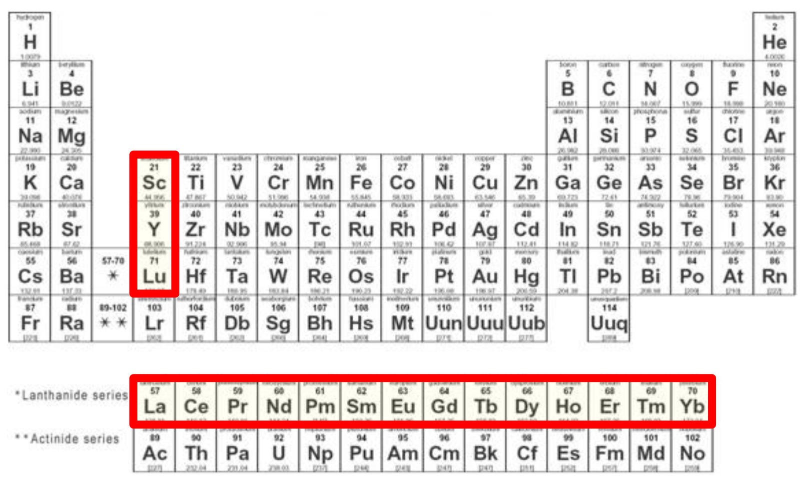
Background Rare Earth Definition

Rare earth elements are yttrium, scandium, lutetium, and the lanthanides.

- **Discovered in 1787**
- **Not that rare (~10-20 ppm) but disperse**
- **Common uses:**
  - Displays (Y)
  - Glass (Ce)
  - Refining (Ce, La)
  - Magnets (Pr, Nd)



Background Rare Earth in Energy Technologies

Rare earth elements are critical to a number of advanced energy technologies, including SOFC.

CLEAN ENERGY TECHNOLOGIES AND *COMPONENTS*

		Solar Cells	Wind Turbines	Vehicles		Lighting	SOFC
	MATERIAL	*PV films*	*Magnets*	*Magnets*	*Batteries*	*Phosphors*	
Rare Earth Elements	Lanthanum				●	●	●
	Cerium				●	●	●
	Praseodymium		●	●	●		
	Neodymium		●	●	●		
	Samarium		●				○
	Europium					●	
	Terbium					●	
	Dysprosium		●	●			
	Yttrium					●	●
	Scandium						○

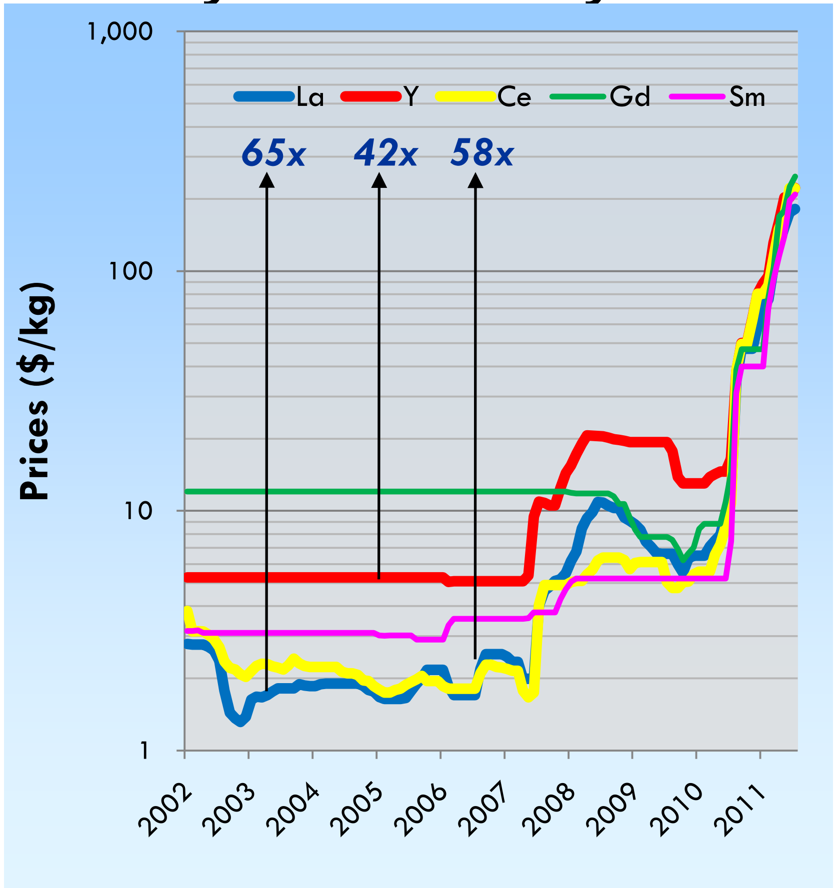
● Used ○ Considered

Source: DOE Critical Materials Strategy

Background Rare Earth Element Prices

Recent increases in rare earth element prices are among the steepest of any commodity.

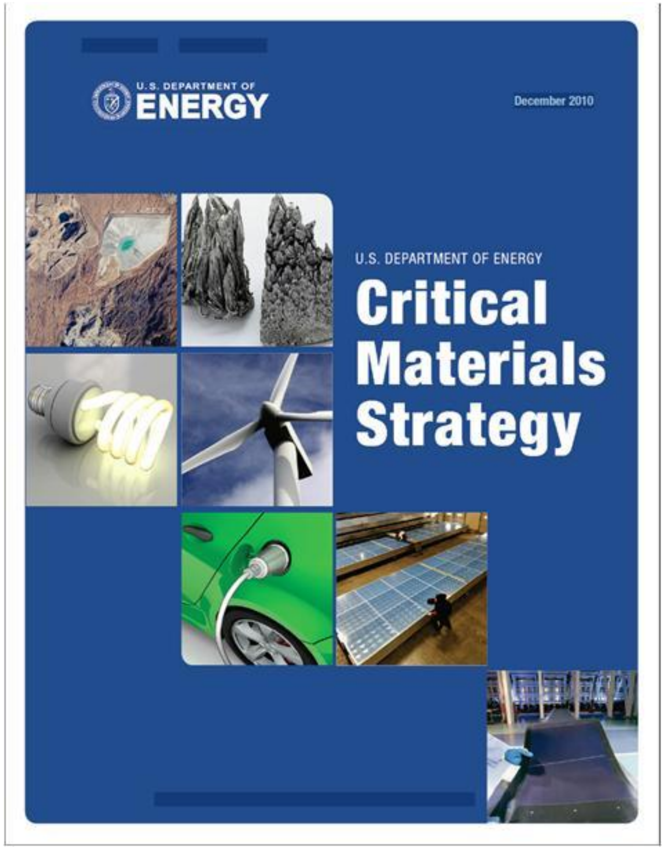
- **Prices of REEs have risen by ~40-60x**
- **Most of this is driven by China's policy:**
  - September 2009: exports to be reduced to 35 kton/yr
  - End of 2010: exports reduced to 14 kton/yr



Background DOE Critical Materials Review

DOE recognizes that certain materials with limited availability are critical for new energy technologies.

- **May 2010: DOE issues RFI on critical materials**
- **December 2010: Critical Materials Strategy Published**
- **RFI for updated information in 2011**
- **NETL wanted to understand the role of and impact of SOFC**



Objective

NETL wanted to understand the impact of REE markets on SOFC commercialization and *vice versa*.

- **What is the use of REE in SOFC**
  - Current use
  - Potential reductions, including alternatives
- **Impact on market demand**
- **Impact of REE prices on SOFC cost**

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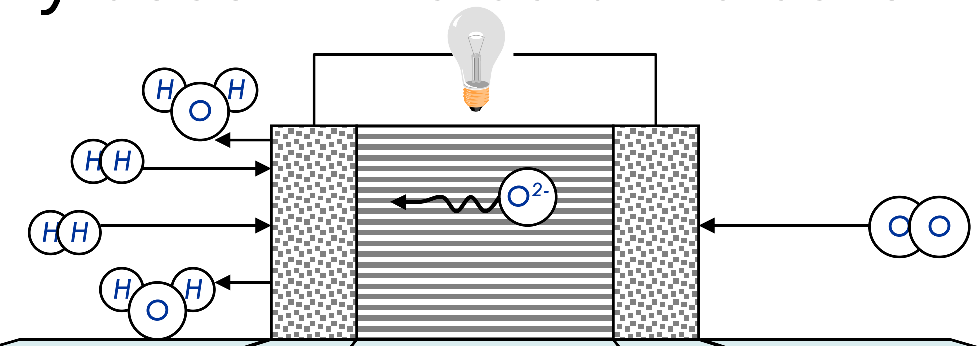
REE Use in SOFC REE Use in Cells

REE are core to the function of SOFC, with primary uses in the ceramic cells.



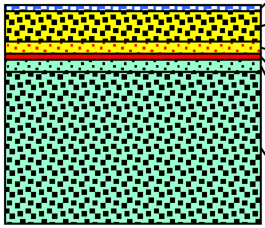
Function	Fuel Supply	Anode	Electrolyte	Cathode	Oxygen Supply
Thickness (μm)		100 - 1000	5 - 100	50 - 1200	
Material		Nickel – YSZ cermet	YSZ or ScSZ	LSM, LSC, LSCF, often composite with YSZ	
REE Used		Y	Y, Sc	La, Y	

Ce, Sm, and Gd are used in SDC, GDC interlayers

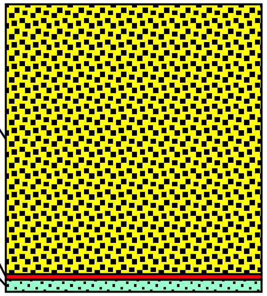
REE Use in SOFC   REE Use in Current SOFC

REE use for production of current planar SOFC amounts to around 35 g/kW.

Planar



Tubular



	Planar Anode-Supported	Tubular Cathode Supported
Material *(Layer Thickness in μm)*		
Cathode Contact Layer	**LSC** (10)	NA
Cathode Current Collector	**LSCF** (30)	LSM (1200)
Cathode Interlayer	**GDC / SmDC** (5)	NA
Electrolyte	**YSZ** (8)	YSZ (20)
Anode Active Layer	**Ni-YSZ** (25)	Ni-YSZ (100)
Anode Support	**Ni-YSZ** (600)	NA
Typical Cell Performance *(W/cm^2)*		
Cell-Performance²	0.4	0.2
Typical Critical Material Content *(mg/cm^2, g/kW, measured as metals)*		
Lanthanum	4, **9.5**	200, 1400
Yttrium	10, **21**	2.9, 19
Cerium	1, **2**	-
Gadolinium/Samarium	<0.3, **<0.6**	-

REE Use for SOFC Use of Scandia

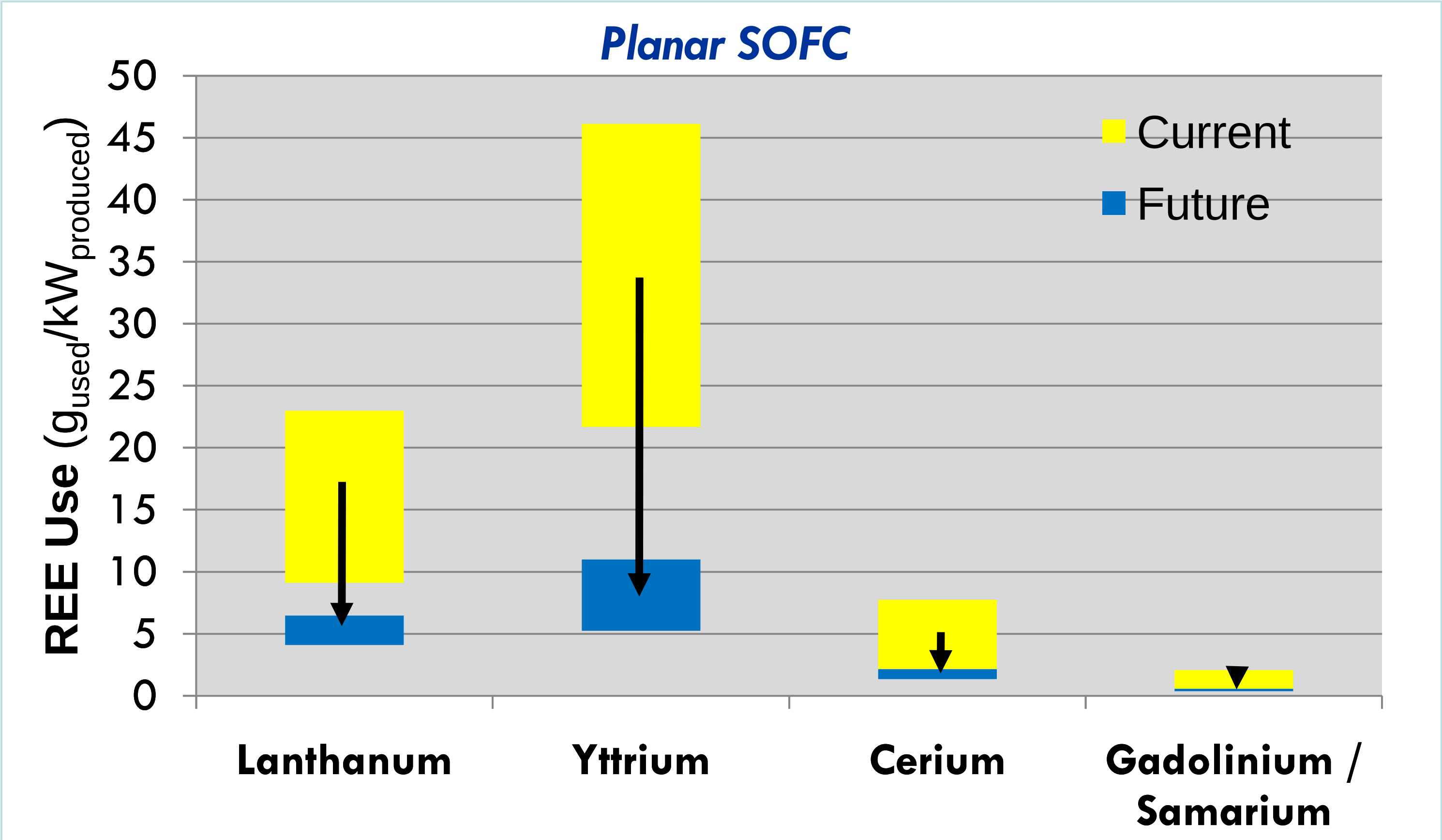
Some stack designs use scandia in the SOFC electrolyte to enhance performance.

- **Scandia can be substituted for yttria to enhance performance**
- **Use is typically limited to the electrolyte (high cost of scandia)**
- **Use per kW is similar to yttria, ranging from 8-100 g/kW, depending on stack design**
- **SECA teams have shown that high performance can be achieved without the use of scandia**

REE Use in SOFC

Potential for Future Reduction in REE Use

Reductions in layer thickness and improvements in power density could reduce REE use by ~60-70%.



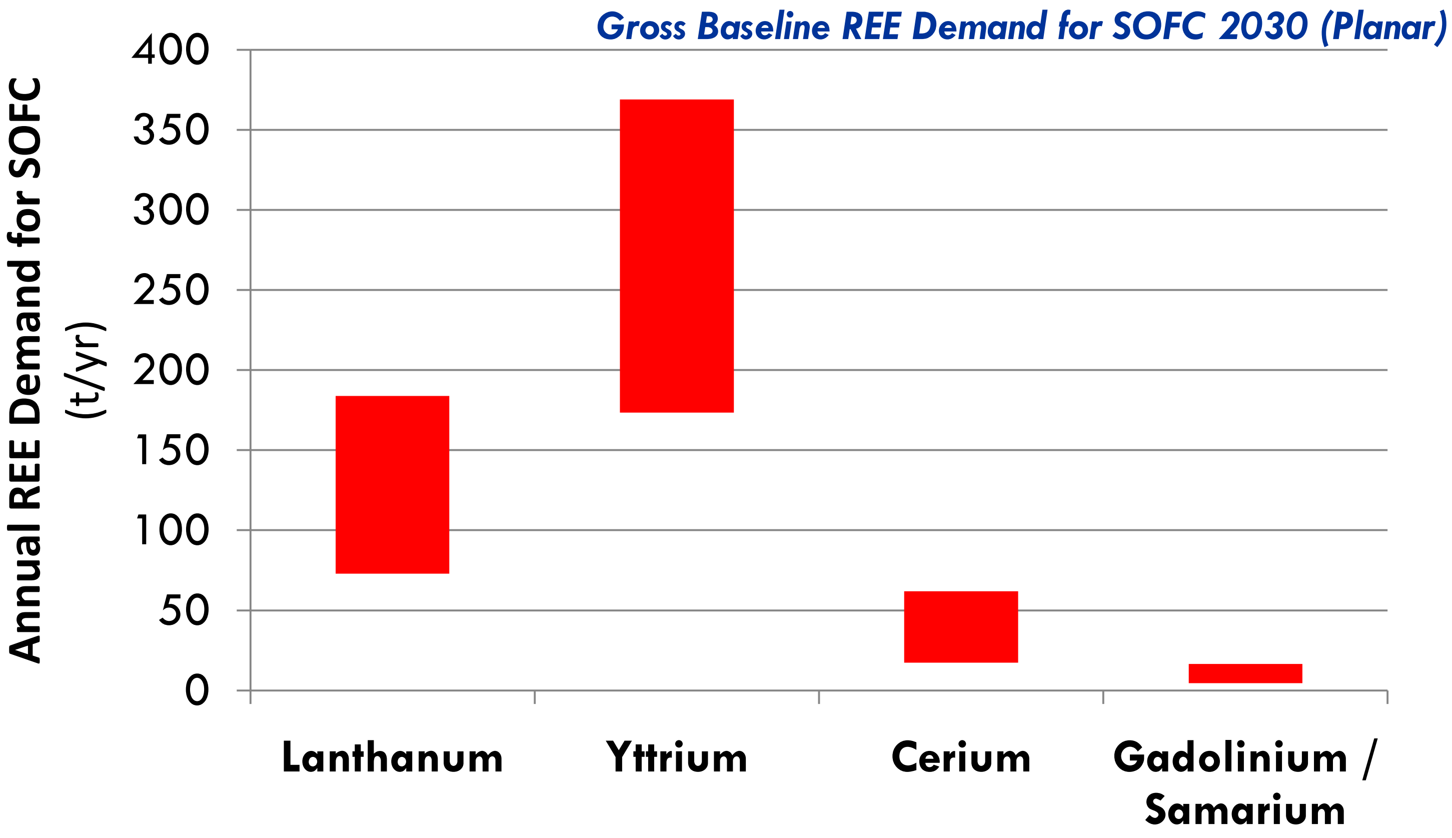
REE Use for SOFC Analysis Approach

We considered three scenarios to evaluate SOFC-driven REE demand.

- **SOFC market based on NETL NEMS projections:**
  - Cumulative installed based 15 GW in 2030
  - Annual capacity addition ~3-5 GW/yr by 2030
  - Stack recycling at end of life (increasing from 3-5 yrs)
- **3 scenarios:**
  1. Baseline: NEMS 2030, new capacity + replacement, no recycling
  2. Recycling: NEMS 2030, new capacity + replacement – 85% recycling
  3. Long-term demand: steady state, 100% of today's coal capacity, 10 yr life, 90% recycling

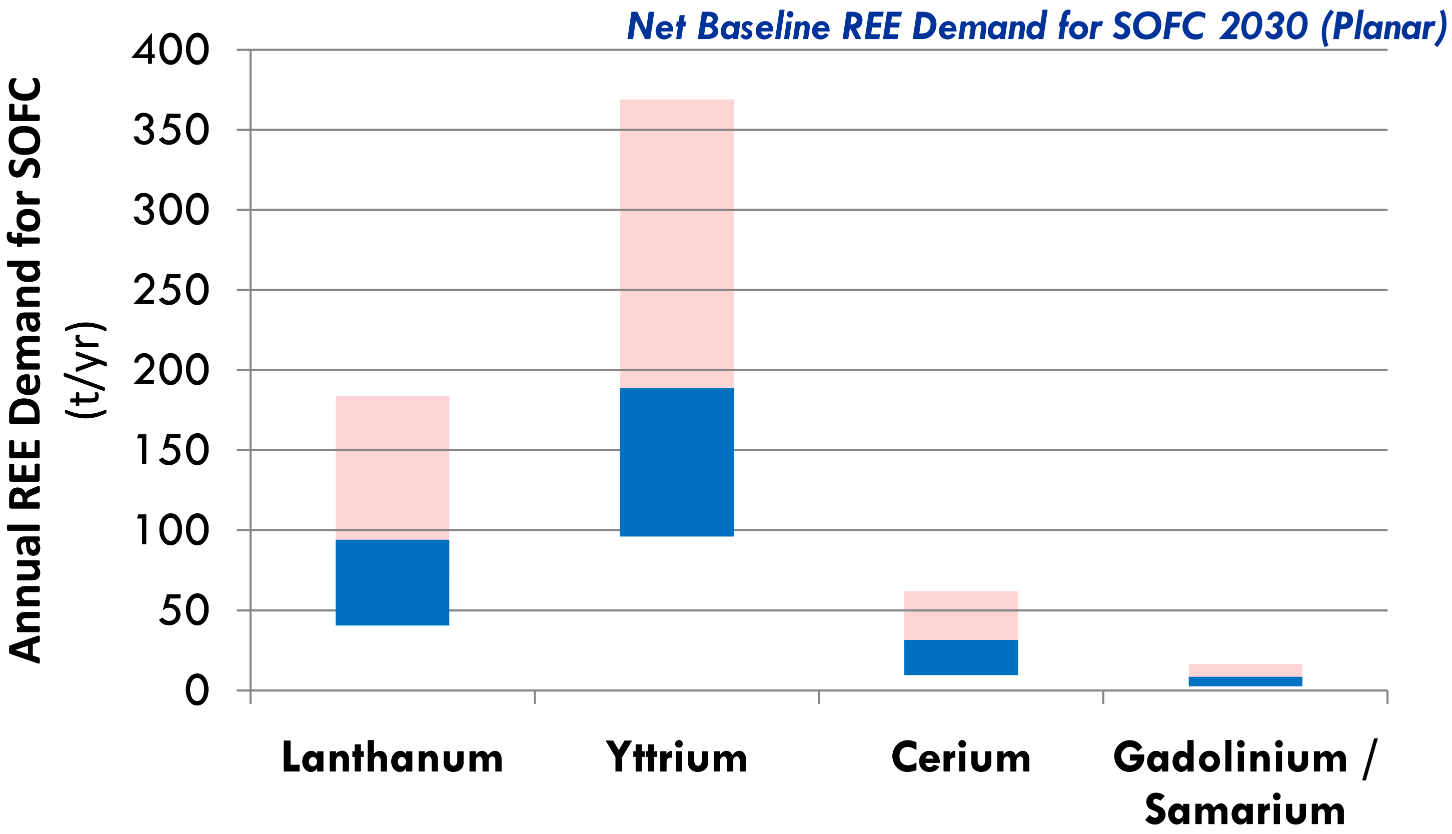
REE Use for SOFC Scenario 1: Baseline 2030

Total baseline REE demand for 2030 is projected to be about 300-700 t/yr.



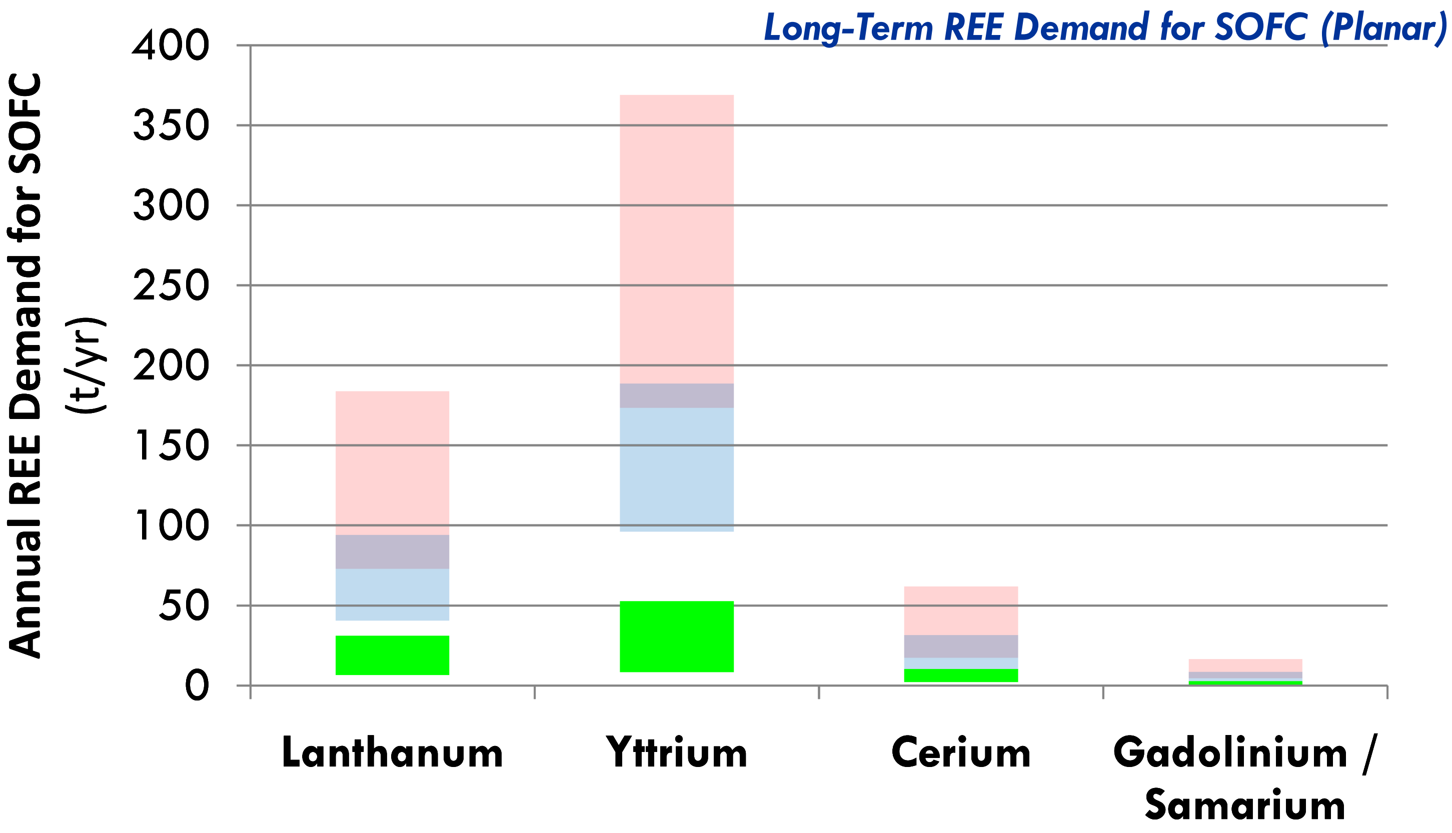
REE Use for SOFC   Scenario 2: 2030 Recycling

Recycling would reduce demand by roughly 50%.



REE Use for SOFC Scenario 3: Long-Term Demand

Long-term steady-state demand would be ~80% below 2030 baseline demand.



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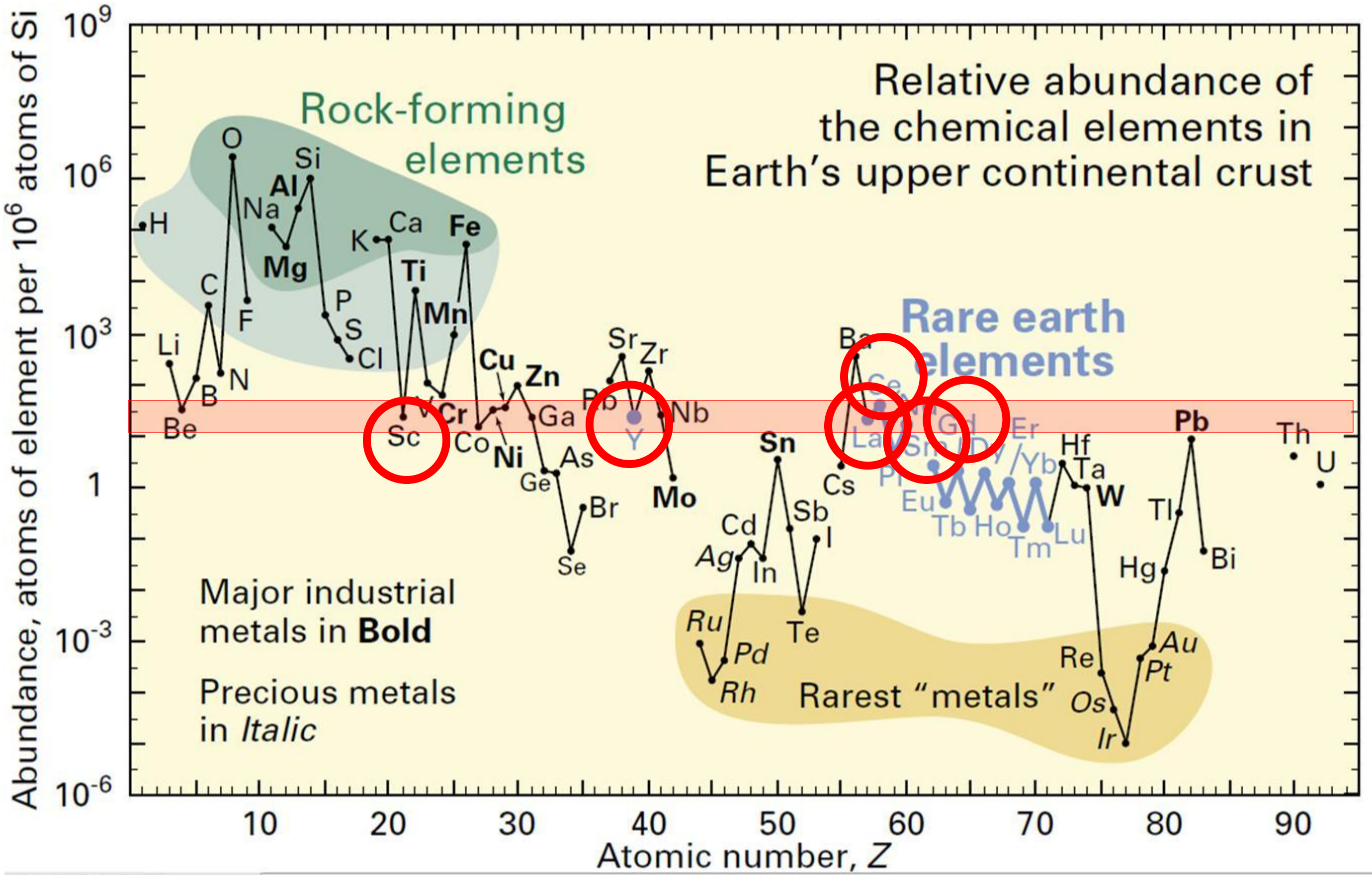
REEE Availability REE Abundance

REE are as abundant (~20 ppm) as many transition metals (Ni, Co, Cr), but much more disperse.



REE Availability

Major REE Use for SOFC

SOFC-driven demand would be small compared with either 2010 production or reserves.

	Content of SOFC	SOFC-Driven Net Demand*	Production (2010)	Estimated Reserves	Projected Production (2015)
	g/kW	t/yr (2030)	t/yr	T	t/yr
Yttria	21	173	9,000	540,000	10,000
Lanthanum Oxide	9.2	73	34,000	>10 million	50,000
Ceria	<3	<20	50,000	~50 million	79,000

** Figures for baseline scenario, no recycling*

SOFC Demand is unlikely to fundamentally change REE markets.

REE Availability

Minor REE Use for SOFC

Sm/Gd use for SOFC would have little impact too, but scandia demand could overwhelm production.

- **Demand for Sm / Gd (for interlayers) would be small compared with either production or reserves:**
  - About 0.3 - 2% of current production
  - Reserves represent >1,000 yrs of current production
- **Scandia demand could far outstrip current production:**
  - Current prices for scandia are >$2000/kg
  - Demand for SOFC could be 10-50x current production
  - It would require new reserves and production capacity
  - Scandia is not produced with other REE & more expensive to refine

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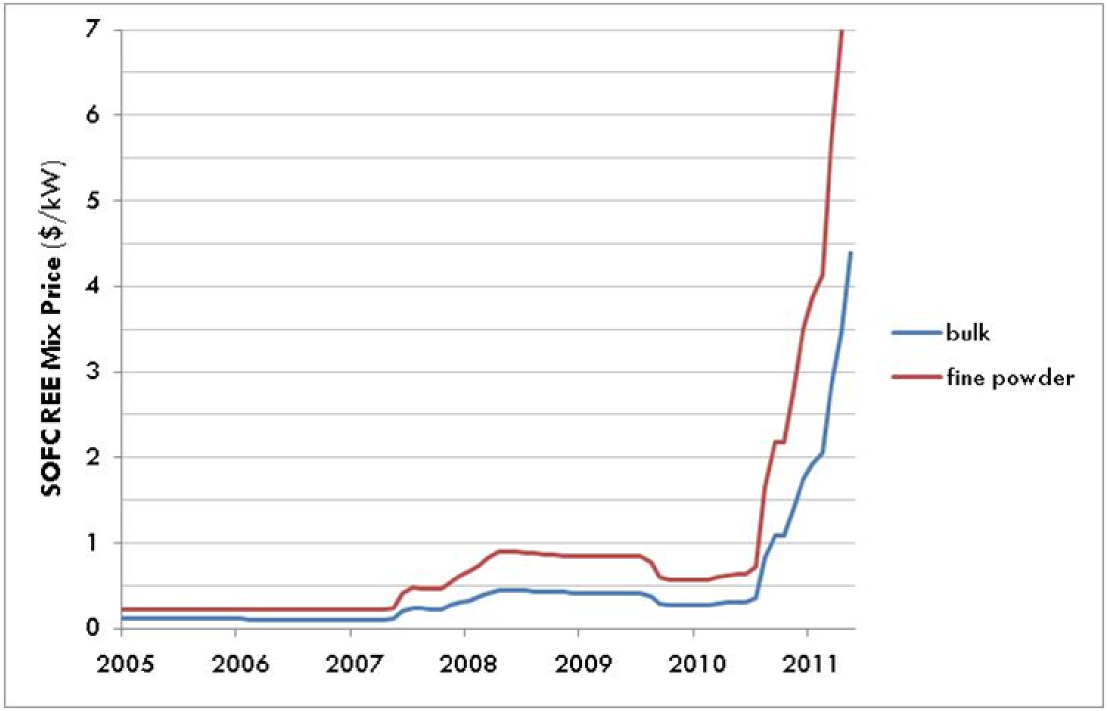
Impact on SOFC Cost Results

Impact of REE cost on SOFC direct manufactured cost remains <$10/kW.



REE cost has no significant impact on SOFC viability.

Impact on SOFC Cost   Other Considerations

For most other stack architectures, results would be similar, except for cathode-supported stacks.

- **REE use varies significantly for other stack architectures, but overall impact is mostly modest**
- **Except cathode-supported stack architectures:**
  - Large amount of La-based cathode as cell support
  - REE amount >40x higher than for planar cells
  - Cost impact of current prices is prohibitive
- **Most industry insiders project:**
  - Ample reserves outside of China will be tapped (e.g. Mountain Pass California)
  - Prices will come down in 1-3 yrs (Goldman Sachs)

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Conclusions (1)

While REE are crucial to SOFC performance, their cost will not affect SOFC viability.

- **A few REEs, notably Y, La, and Ce, are crucial to SOFC performance**
- **Ongoing R&D is already significantly reducing the amounts of REE required for SOFC**
- **Impact of REE prices on SOFC cost, even at today's prices, would be less than $10/kW**

Conclusions (2)

REE demand for SOFC will not significantly impact the market for REEs.

- **REE demand for SOFC is small compared with production rate or reserves, even if all coal-based power were replaced by SOFC**
- **High performance can be achieved without the use of scandia, a high cost raw material**
- **Experts suggest that current high prices are not sustainable, and prices will likely drop in 1-3 yrs**

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