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Solid Oxide Fuel Cells and Critical Materials: A Review of Implications

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Summary

The US DOE has identified a number of materials that are both used by clean energy technologies and are at risk of supply disruptions in the short term. Several of these materials, especially the rare earth elements (REEs) yttrium, cerium, and lanthanum were identified by DOE as critical (USDOE 2010) and are crucial to the function and performance of solid oxide fuel cells (SOFCs)[1]. In addition, US DOE has issued a second Request For Information regarding uses of and markets for these critical materials (RFI;(USDOE 2011)). This report examines how critical materials demand for SOFC applications could impact markets for these materials and *vice versa,* addressing categories 1,2,5, and 6 in the RFI.

Category 1– REE Content of SOFC Yttria (yttrium oxide) is the only critical material (as defined for the timeframe of interest for SOFC) used in SOFC[2]. Yttrium is used as a dopant in the SOFC's core ceramic cells. . In addition, continuing developments in SOFC technology will likely further reduce REE demand for SOFC, providing credible scope for at least an additional 50% reduction in REE use if desirable.

Category 2 – Supply Chain and Market Demand SOFC developers expect to purchase yttrium as high-purity yttria powder when SOFC are commercialized: little if any vertical integration of SOFC producers is expected. The amounts of this yttria powder (And other potentially-critical materials) used in state-of-the-art SOFC are modest (Table 1), representing less than 1% of SOFC weight. Yttrium demand for SOFC applications is also expected to be modest when compared with current and projected yttrium production and reserves, representing less than 0.5% of current production. As such the successful commercialization of SOFC by itself is unlikely to put significant pressure on critical materials markets.

Table 1 Overview of SOFC-Driven REE Demand, REE Production and Reserves

	Content of SOFC	SOFC-Driven Net Demand[3]	Production (2010)	Estimated Reserves	Projected Production (2015)
	g/kW	t/yr (2030)	t/yr	T	t/yr
Yttria	21	40	9,000	540,000	10,000

Category 5 – Energy Technology Transitions and Emerging Technologies Unless dramatic further increases in REE occur, the cost of REE and other critical materials is not expected to

[1] In the production of SOFC, REEs may be used as metals, oxides, or salts. However, for consistency and to avoid confusion, they will be expressed as elements throughout this paper.

[2] The implications for other REE's and materials on DOE's original list (but not deemed critical for the medium term in the 2010 CMS) for SOFC (including lanthanum, cerium, gadolinium, scandium, samarium, and cobalt) are discussed in the body of the report.

[3] Assuming annual SOFC production of 4 GW/yr of new capacity plus 4 GW/yr of stack replacements assuming 90% REE recycling.

pose a barrier to the commercialization of SOFCs. Markets have seen a dramatic increase in the prices for yttrium from less than $5/kg in 2006 to $160/kg in recent months. Nevertheless, the cost of yttrium for SOFC amounts to less than $10/kW[4]. While significant, this is a small fraction of overall SOFC manufactured cost, representing less than 10% of the SOFC stack module cost, about 3% of the SOFC module in powerplants, and less than 1% of installed SOFC powerplant capital cost. The combined impact of first cost and stack replacement would contribute about $1/MWh or less to the levelized cost of electricity (LCOE) of SOFC powerplants. This is well within the margin of error of the overall LCOE estimate (total projected LCOE for SOFC is around $80/MWh). Still, a further 5x increase in yttrium price could impede SOFC commercialization, but it appears that long-term such increase may be unlikely.

Category 6 – Recycling Opportunities Spent SOFC stacks and production waste will likely be recycled for their metal and REE content, which would further reduce REE demand for stack replacements by 80-90%.

In summary, critical REE demand for SOFC applications is not likely to substantially impact overall supply – demand balances for REEs marked as critical or near-critical by DOE. And while recent price increases clearly affect the production and O&M cost for SOFC systems, plausible fluctuations in REE prices are not likely to fundamentally alter the economic viability of SOFC in power generation applications, unless REE prices experience another dramatic increase.

[4] These figures assume April, 2011 yttria prices and today's SOFC technology

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Introduction & Background

In its Critical Materials Strategy (CMS, (USDOE 2010))The US Department of Energy (DOE) has recognized that several emerging energy technologies rely to varying degrees on the unique properties of several critical materials, including rare earth elements (REEs)[5], Cobalt, Gallium, Indium, Lithium, and Tellurium. To evaluate the implications of dramatic changes in market conditions since the publication of the data on which the CMS was based, DOE recently issued a second Request for Information (RFI, (USDOE 2011), initial RFI in 2010 (DOE 2010)).

The US DOE (the Office of Fossil Energy through the National Energy Technology Laboratory, primarily) has supported Solid Oxide Fuel Cell (SOFC) development for years, most recently through its Solid State Energy Conversion Alliance (SECA) progam (Surdoval, Singhal et al. 2000; Vora 2010). Partly due to this support, SOFC technology now appears to be nearly ready for commercialization, with some companies now projecting initial commercial products to be available over the next five years (Delphi 2009; Lim 2010). Several materials used in SOFC are found on the initial list of potentially-critical materials DOE identified in its CMS. First, SOFCs rely on unique properties of several REEs, especially in their core components: the ceramic cells. These multi-layer ceramic cells contain several REEs or REE-based components. Almost all SOFC designs contain yttrium (yttrium oxide, yttria, is used as a stabilizer in zirconia in electrolyte, anode, and often cathode) and lanthanum (as the key component of the cathode) and in some cases cerium, scandium, gadolinium or samarium[6]. Cobalt is also used in the ceramic cells of some SOFC designs.

In light of the new RFI, DOE's NETL thought it relevant to update the investigation of the potential impact of SOFC commercialization on critical material markets and *vice versa*, which is the purpose of this paper.

For DOE's convenience, the discussion in this paper is aligned with the relevant categories in the DOE's RFI[7]:

Category 1: ***Critical Material Content:*** Which critical materials are used in SOFC, how much, and what is their function? What substitutes are available?

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[5] The rare earth elements are: yttrium, scandium, and the lanthanides (atomic numbers 57 – 71, including lanthanum, cerium, praseodymium, neodymium, promethium, samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, and lutetium). Note that strontium is not considered an REE. Often REEs are discussed by referring to their stable oxides, rare earth oxides (REOs)

[6] In SOFC REEs are typically found as oxides (rare earth oxides or REOs), but for consistency and transparency, we will refer to the elements throughout this paper.

[7] The remaining categories in the DOE RFI (3, 4, and 7) are not relevant for SOFC applications and hence are not discussed in this paper.

Category 2: ***Supply Chain and Market Projections:*** How will SOFC production and use fit into the value chains for critical materials? How will commercialization of SOFC increase demand in critical materials?

Category 5: ***Energy Technology Transitions and Emerging Technologies:*** How will emergence of SOFC impact critical material availability? To what extent might limited availability and price increases for critical materials affect the economic viability of SOFC and its commercialization?

Category 6: ***Impact of REE Cost & Availability on SOFC Commercialization:*** What opportunities are there for recycling critical materials from SOFC applications and how will that impact critical material demand?

Critical Material Content of SOFC (DOE RFI[8] Category 1)

Several critical materials, especially REEs, fulfill several crucial roles in the core electrochemically-active components of SOFC: the ceramic cells.

Overview of Critical Materials Used in SOFC

Table 2 provides an overview of relevant materials used in SOFC ceramic cells. As the table shows, yttrium is the only material used in SOFC that is listed as critical (both near term and medium-term). Lanthanum and cerium are both considered critical in the near term, but not critical in the medium term[9]. The other SOFC materials on the original list the DOE investigated, cobalt and samarium, were deemed not critical.

Table 2 Criticality Ratings and Uses of Materials Relevant for SOFC

Material	Criticality Rating in DOE CMS		Use in SOFC
	Near-Term	Medium Term	
Yttrium	x	x	+
Cerium	o	-	+
Lanthanum	o	-	+
Samarium	-	-	?
Cobalt	-	-	+
Scandium	?	?	?

x=critical; o = near-critical; - = not critical; + = used typically; ? = possible application

For completeness, we added scandium to the list, even though it wasn't on DOE's original critical materials list. Technically, scandium is the most suitable alternative to yttrium.

[8] Categories from DOE's RFI (Request for information), USDOE (2011). Critical Materials Strategy - Request for Information (RFI). U. D. o. Energy. Washington.

[9] DOE defines the medium term as 2015, so given SOFC's commercialization timeline only the medium term is truly relevant. For completeness we included the other materials in the analysis as well.

However, scandium is currently produced in small (essentially research) quantities[10]. Not surprisingly, scandium's current price is high compared with the other REEs.

In summary, the focus of this report is placed on the use of yttrium, lanthanum, and cerium in SOFC.

SOFC Working Principles and Function of Critical Materials

The heart of any SOFC is a multilayer ceramic cell, which allows the generation of power by electrochemically oxidizing the fuel. A simple overview of the ceramic cell's function and architecture is shown in Figure 1. As can be seen, rare earth elements are used throughout the layers of the cell and cobalt is commonly used in the cell's cathode.

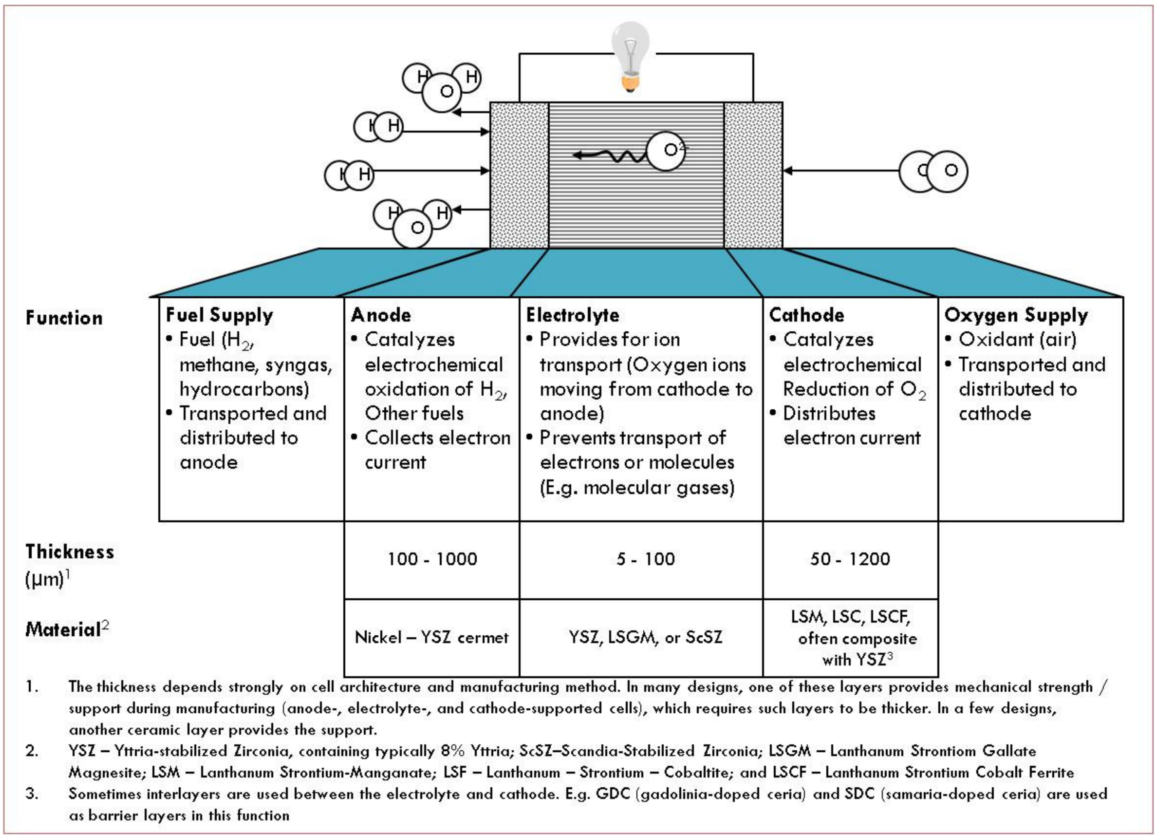

Figure 1 Overview of Architecture, Function, and Materials of SOFC

Yttrium

Yttrium, which was labeled critical by DOE, is used in oxide form (yttrria) as a dopant to stabilize the zirconia commonly used for the electrolyte, and sometimes in the electrodes as well. Yttria stabilizes the particular crystal structure that provides the ionic conductivity for the

[10] Likely the reason scandium wasn't on DOE's critical materials list.

electrolyte (and electrodes)[11]. The yttria doping level is most typically 8 mole % in those structures (or about 14% yttria or 11% yttrium by weight) but different doping levels are sometimes used, especially for structural components (e.g. the anode support in anode-supported cells). The most commonly considered alternatives to YSZ as an electrolyte are Scandia-Stabilized Zirconia (ScSZ) and Lanthanum Strontium Gallate Magnesite (LSGM), each of which contain significant fractions of scandium or lanthanum, which may be near-critical materials themselves[12]. Aside from its role as electrolyte, YSZ is often used in SOFC electrodes (anode, cathode) to provide some ionic conductivity to electrode materials that don't have enough, and, in some SOFC, as a structural cell support. For example, a Ni-YSZ cermet is commonly used as anode material in SOFC. Similarly LSM (see below) cathodes are often mixed with YSZ.

Lanthanum

Lanthanum, which was labeled near-term critical by DOE, is another common and key component of most SOFC: mixed oxides of lanthanum provide the electronic conductivity, high catalytic oxygen reduction activity, and ionic conductivity needed for high-performance cathodes[13]. Some common compositions are shown in Table 3. The table suggests that while a variety of cathode materials is being considered, many contain ~50% lanthanum. The literature reports experience with several REE-free cathode materials (Singhal and Kendall 2003) though not all alternatives necessarily lead to lower cost cathodes even at today's REE prices. For example, platinum was used as a cathode material in early SOFC experiments.

Cerium

Cerium oxide (ceria) is commonly used in interlayers used between various SOFC ceramic cell layers (especially in the cathode-electrolyte interface) to prevent or minimize unwanted reactions between electrochemically mismatched layers. For these applications ceria is usually doped with samarium (samarium doped ceria or SDC) or gadolinium (gadolinium doped ceria or GDC). Samarium and gadolinium are also REEs but were not labeled critical by DOE. It may be possible to substitute the REEs in the interlayer structures, but the amounts used currently are so small that this is likely not to be a priority from either a cost or strategic perspective.

Other REEs and Potentially Critical Materials used in SOFC

Cobalt and Samarium were also considered in the DOE's CMS, but they were found not to be critical by DOE's definition. Cobalt is commonly used now as a constituent of SOFC cathodes.

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[11] i.e. the yttria stabilizes the crystal structures that provide oxygen mobility (and hence ionic conductivity) combined with low electrical conductivity.

[12] Lanthanum was

[13] LSM has been commonly used as a SOFC cathode. It is commonly mixed with YSZ to provide the cathode with mixed ionic electronic conductivity (MIEC). More recently, LSC, LSF, and LSCF, which are MIEC cathode materials, have gained in popularity (Borglum (2005), Shaffer (2004)).

Depending on the formulation the cathode materials contain 5 – 12% Co. Samarium is used as a dopant for ceria in the interlayers between electrodes and electrolyte (see discussion on cerium). SDC is doped with up to ~17% samarium.

Scandium was not considered in the DOE study, probably because so far most of its uses are academic. But scandium oxide (scandia) has long been considered a viable, and perhaps desirable, alternative to yttria for the stabilization of the zirconia electrolyte (Scandia stabilized zirconia or ScSZ) for some SOFC designs[14]. Scandium was not considered in the DOE CSM, probably because scandia is used mainly for research purposes and produced commercially in minute quantities (global production ~2 tons per year). However, as a potential replacement for yttrium, the small production (and high price) motivated us to include a discussion of scandium in this paper.

Table 3 Overview of Critical Material Content of Various SOFC Materials

Common Name	Chemical Formula	Critical Material Content[15]	Comments
YSZ	Y_2O_3/ZrO_2	**Y: 3-8%**	Most common electrolyte
ScSZ	Sc /ZrO_2	**Sc: 6-10%**	Alternative for Yttrium
LSM	$La_xSr_yMnO_3$ (x= 0.8 – 0.85; y = 0.15 – 0.2)	**La: 56%**	Also contains Sr 9% (not critical). Most SOFC are switching to LSC, LSCF, or LSF (below)
LSCF	$La_{0.6}Sr_{0.4}Co_{0.2}Fe_{0.8}O_{3-\delta}$	**La: 44%** Co:5%	
LSC	$La_{0.6}Sr_{0.4}Co_{0.4}O_3$	**La: 51%** Co:12%	
LSF	$La_{0.6}Sr_{0.4}FeO_{3-\delta}$	**La: 44%**	
SDC	$Ce_{0.8}\ Sm_{0.2}O_{1.9}$	**Ce: 83%** Sm: 17%	
GDC	$Ce_{0.8}\ Gd_{0.2}O_{1.9}$	**Ce: 82%** Gd (18%)	

Critical Materials Content in Ceramic Cells

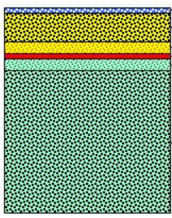
As shown above, all SOFC ceramic cells currently contain some critical materials. However, the amounts used (in this context most usefully expressed in terms of unit weight per unit power

[14] Though in principle ScSZ could be used in many types of SOFCs, so far it has mainly been considered in SOFC architectures that place special demands on the electrolyte, such as certain tubular and metal-supported SOFC. In planar anode-supported SOFC such as those used by most leading developers, SSZ has not been seriously considered because of the high cost of scandia.

[15] These figures are in terms of oxides, but for consistency, elsewhere in this paper REEs are expressed as their elements, rather than as their stable oxides, i.e. Y_2O_3, La_2O_3 etc.

output, e.g. g/kW) are heavily dependent on the cell materials used, cell architecture, and cell power density, as is shown in Figure 2 below.

Ceramic Layer Structures



	Planar Anode-Supported	Tubular Cathode Supported
Layer Thickness (µm)		
Cathode Contact Layer	LSC 10	NA
Cathode Current Collector/Support	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-Performance[2]	0.4 (0.3 – 0.6)	0.2 (0.15 – 0.3)
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	-
Cobalt	0.5 – 2.7	-

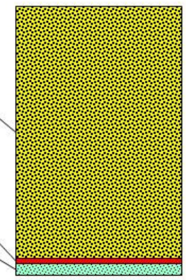


Figure 2 Materials and REO Content of Some Typical SOFC Structures Reflecting the Current State-of-the-Art (for detailed Assumptions, see (Thijssen 2007))

The overall critical material content of planar anode-supported SOFC is modest: around 30 g/kW or less, with most of it in REEs. Cathode-supported tubular cathode-supported SOFC contain ~1500 g/kW[16]. For perspective, the figure for planar anode-supported SOFC is about 50-100x the platinum loading targets DOE has for polymer electrolyte membrane(aka proton exchange membrane, PEM) fuel cells for vehicle applications (which are 0.2 g/kW for 2015). Platinum (and other Platinum Group Metals or PGMs) are about 10,000 times less abundant than REEs. Even at today's REE prices (April 2010) PGMs are ~500 times more expensive than REEs.

16 The tubular cells discussed here are flattened, high-surface area tubes, not the older type cylindrical tubes. Other SOFC architectures, including those based on planar electrolyte-supported and tubular anode-supported cells, will contain different amounts of each of the REEs, falling between the two cases discussed here. SOFC that are supported on a REE-free substrate (e.g. strip design cells) may have significantly lower REE content than planar anode-supported cells.

As can be seen in Figure 3, the critical material content of SOFC is strongly influenced by the cell structure. Although anode-supported SOFC have dramatically lower overall use of certain REEs (e.g. lanthanum), the amounts of critical materials are comparable to that of tubular cathode-supported cells. The reasons cathode-supported cells contain so much more lanthanum include:

- The supporting anode of planar anode-supported cells has a 10x lower REE content (~5% Yttria, compared with ~50% lanthanum in tubular cells) ,
- The supporting layer (the thickest layer) is less thick (~600 μm for planar anode-supported cells vs 1200 μm for tubular cells),
- Tubular cells tend to have more inactive area than now common large-format planar cells.

In addition, there is a significant difference in the types of critical materials used in each type of SOFC (see Figure 3):

- REO content in tubular cathode-supported SOFC is dominated by lanthanum use. This is the consequence of the thick structural cathode made of LSM (Which is ~50% lanthanum). Lanthanum is considered a critical material in the near term, but not in the long term.
- Lanthanum and yttrium dominate REO content of planar anode-supported SOFC, together responsible for about 75% of REO content. Cerium and gadolinium or samarium represent the balance.
- Most state-of-the-art planar SOFC use cathodes that contain cobalt, but quantities are less than 3 g/kW.

The production processes currently envisioned for most planar SOFC mainly involve tape casting, calendaring, and screen printing[17](Thijssen 2007). At maturity, the process yields associated with such processes are typically around 90- 95%. Several studies, as well as discussions with ceramics producers, confirm that such figures are plausible for SOFC. Indeed, the figures are consistent with pilot production experience.

[17] Other production processes considered, such as extrusion and plasma spray methods may have lower yields, but the losses can be relatively easily recycled either inside the process, or back to the raw material suppliers. As a consequence, the net REO demand from these processes is dominated by the REO content of the product, with process losses a relatively modest factor.

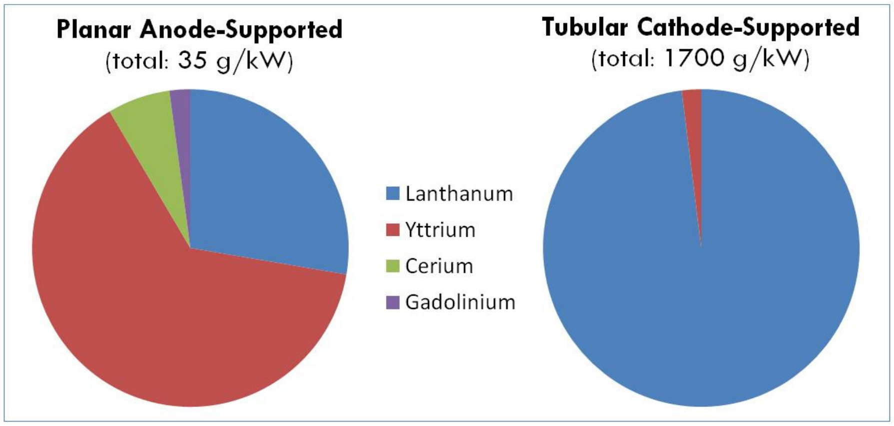


Figure 3 REO Content of Typical State-of-the-Art Planar Anode-Supported and Tubular Cathode-Supported SOFC[18]

When considering all of the uncertainties in cell material use, architecture, and production methods the REE use in the production of SOFC ceramic cells based on current state-of-the-art technology already shows a fairly broad range (Figure 4):

- Layer thicknesses between designs vary by a factor two. The supporting layers for planar anode-supported designs vary between about 600 – 800 μm.
- Material choices for at least some of the components could affect uses, especially of the minor constituents (such as cerium, gadolinium, and samarium), which may or may not be used depending on the cell architecture.
- The manufacturing process overall may be expected to reach around 90-95% yield, which has been demonstrated by some developers using pilot production equipment(Borglum 2005). However, yield on individual layers may be lower (e.g. because of overspray in plasma spray processes).
- Variations in power density further broaden the range. In this analysis, power densities for planar anode-supported cells between 0.4 – 0.5 W/cm^2 have been taken into account, consistent with recent performance

In the future, considerable reductions in REE content of SOFC can be expected, especially if REE prices remain high (see Figure 4 again). This trend is likely because of three principal factors:

- *Increases in power density* will reduce REE content per kW, even if the REE use per unit active area stays the same
- *Reduction of layer thicknesses* especially of the support layers can drastically reduce REEs content

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[18] Cell structures and material uses are consistent with the current state-of-the-art. Details on cell structure are discussed in detail in Thijssen (2007) ,current performance was based on Vora (2010), Ghezel-Ayagh (2010), and Pierre (2010). Figures are on mass basis, accounting for REEs as elements

- *Changes in layer composition* can reduce REE content (e.g. via substitution by other materials).

As the figure shows, these improvements can be expected to cut in half the REE intensity of SOFC (in g/kW). The use of cobalt is roughly proportional with that of lanthanum with current technologies under development.

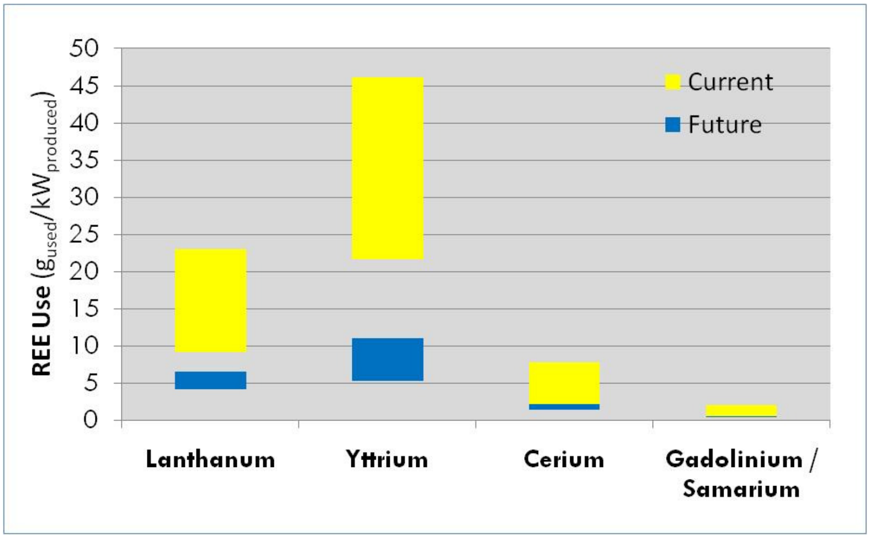

Figure 4 REO Use for the Production of Planar Anode-Supported SOFC Including Production Losses. Ranges Reflect both Typical Current State-of-the-Art and Potential for Future Improvements by 2015[19]

Critical Materials Use in Other SOFC Components

While use in ceramic cells is clearly the highest-impact use of REEs and other critical materials in SOFC, we want to mention other potential uses for completeness. Other applications of REEs and other critical materials in SOFC systems could include:

- Reformer / fuel processing catalysts may contain certain REEs as catalytic agents or support. Some developers have considered the use of ceria-based catalysts for reforming hydrocarbon fuels.
- Cobalt is commonly used as a component for coatings or as alloying element in high-temperature steel SOFC system components such as interconnects, manifolds, and high-temperature heat exchangers.
- Some SOFC systems call for an exhaust gas catalytic oxidation device, which may use a ceria-based catalyst.

[19] Range for current state-of-the-art reflects a range of power densities, layer thicknesses, and compositions. Future projections consider improvements in power density, layer thickness, and some material substitution.

Nevertheless, use of REEs in these applications is far from universal, and in most applications competitive alternative materials are available. Most of these contemplated applications of critical materials are for small-scale SOFC systems (vehicle auxiliary power units, smaller generators) which, though commercially exciting, are likely to present a small fraction of total SOFC MW produced. In stationary power SOFC systems the above uses do not apply; the same functions are carried out with catalysts that do not contain critical materials. Even where REEs are used outside the stack, the amount of REEs used in is less than 10% of that used in the ceramic cells. Therefore, we will not delve any more deeply into these other uses of REEs for SOFC systems at this point.

Quality Requirements

The REEs used in current processes and contemplated for production of SOFCs are high-purity fine powders of the respective REOs (i.e. oxides, they are used in tape casting, screen printing, and plasma spray processes primarily). Currently, purity requirements for these applications are typically in the 99.5% or better range. The purity requirements can, in some cases also be more prescriptive in terms of the specific impurities of interest (e.g. Si). The purity requirements vary somewhat according to the precise materials system and cell architecture used. In research projects, higher purities are sometimes used out of an abundance of caution to minimize experimental variations (the added cost of high purity is small compared to the overall cost of the tests).

In addition to the purity requirements, the particle size distribution and surface area of the powders are of importance and differ according to the use of the powder. For example, for the electrolyte typically a fine powder is needed to facilitate rapid densification while for electrodes surface area is typically important.

The price impact of specifications is considerable: ultra-fine pure powders typically sell for 3-10 times the bulk material (still 99.9% pure) market price. The large mark-up results from the additional processing cost, and the supply-demand dynamics in markets for these pure products. Ergo, when basic REE prices increase, the increase in high-quality REO powders may be expected to be less than proportional. In addition, while most REE production is concentrated in China, the purification and processing of REOs is (still) partly the domain of Japanese and Western specialty ceramics companies. Nevertheless, to be conservative, we assumed that the mark-up factor between bulk REE prices (FOB China) and fine powder prices remains constant.

Impact of Stack Replacement

Because current SOFC stacks require periodic replacement (because of gradual irreversible degradation in performance) we must consider the REE demand resulting from the demand for replacement stacks (in addition to stacks for new systems). Currently SOFC stacks degrade at a rate of around 1% per 1,000 hrs (Borglum 2009; Kerr 2009), which would result in a service life of 2 yrs or less. However, in order to be commercially viable stack life should be extended to about 5 yrs, and the DOE has set R&D targets commensurately. As technology improvements proceed, stack life is expected to continue to improve after the initial commercialization of SOFC. Although technically different, Phosphoric Acid Fuel Cell (PAFC) stack life was around 20,000 hrs for the initial commercial systems, while current stacks last for over 60,000 hrs (UTC-Power 2005). Similar improvements were made with the molten carbonate fuel cells (which are more like SOFC). So for our projection, we consider an initial stack life of around 5 yrs (in 2015) and an improvement to a 10 yr stack life by 2030.

Supply Chain and Market Demand (DOE RFI Category 2) + Recycling Opportunities (DOE RFI Category 6)

Supply Chain Considerations

Because SOFC developers use high-quality REE powders, they are largely positioned at the very end of the REE supply chain. Most SOFC developers of SOFC technology, including most US developers, have business plans based on purchasing high-purity powders from established suppliers, and incorporate realistic cost structures for these materials. Given the modest cost impact of critical materials on the overall SOFC systems (see …) vertical integration does not appear to be essential under normal market conditions.

Several developers (e.g. Kyocera) are somewhat vertically integrated in that they have capabilities for the production of powders in-house. Though given the considerable margin between raw materials and refined powders vertical integration could become valuable, rising raw material prices make that a weaker argument (unless the business is completely vertically-integrated).

Market Demand

DOE's projects a cumulative installed base of about 15 GW of Integrated Gasification Fuel Cell (IGFC) plant by 2030 (DiPietro and Krulla 2010). Considering typical ramp-up profiles and initial commercial market introduction of IGFC systems in the 2020-2025 timeframe this implies an annual new SOFC capacity addition of 3-5 GW. To assess the implications of this level of market penetration as well as the longer-term impacts of SOFC production on demand for REEs, we consider three scenarios[20]:

[20] While other applications may be commercially significant, their impact in terms of production volume, and hence REE use, is small compared with coal-based applications.

1. ***Baseline Projection Gross Demand in 2030*** – the gross demand for new and replacement stacks based on the DOE's SOFC market penetration projections,
2. ***Baseline Projection Net Demand in 2030*** – taking into account a plausible mature recycling rate,
3. ***Long-Term Demand Potential*** – the demand that would result from SOFC stack replacement rate if all coal-fueled capacity were replaced with SOFC.

Scenario 1: Baseline Gross Demand for 2030

The DOE's current projections envision commercial introduction of SOFC around 2015 for initial applications (distributed generation, APUs, industrial, and military applications) and around 2020 for utility –scale applications. Because of their modest cost and high efficiency, as well as the potential to provide CO2 capture at marginal additional cost and loss of efficiency, SOFC sales are thought to increase rapidly, reaching 15 -20 GW of installed capacity by 2030.

Based on this, 2030 demand for new capacity, as stated above, is implied to be around 4 GW/yr. 2030 is an estimated 5-10 yrs into commercialization cycle of coal-based SOFC applications (which represent the majority of projected demand). Hence the projected annual demand is sensitive to the assumptions surrounding the commercialization (e.g. initial commercial availability, rate of market penetration).

By 2030 only stacks installed in the initial years of IGFC commercialization will have reached the first stack replacement cycle, so stack replacement would add only about 1 GW/yr or less. Because this figure would rise dramatically in 2031 – 2035, we assume instead that the replacement rate is equal to new capacity additions for this analysis, resulting in a gross demand for SOFC stacks of 8 GW/yr.

Figure 5 shows the projected gross baseline REE demand for SOFC applications obtained by combining the projected REE use (in g/kW from Figure 4) with the projected gross SOFC demand (in GW/yr).

The combined demand for all REEs in this scenario would be 300 – 700 tons / yr. The range shown in the figure reflects only variations in REO use per unit output (compare Figure 4). Uncertainties in demand for both new and replacement SOFC capacity would further broaden that range. The reader is encouraged to consider all three scenarios to appreciate the impact of these uncertainties in demand.

The REE demand will of course depend on the choice and performance of SOFC technology. For example, if tubular cathode-supported SOFC technology were used, lanthanum demand would be about 16,000 – 20,000 t/yr, about 40-75x higher than for planar anode-supported technology (yttrium use would be comparable, no other REEs would be used).

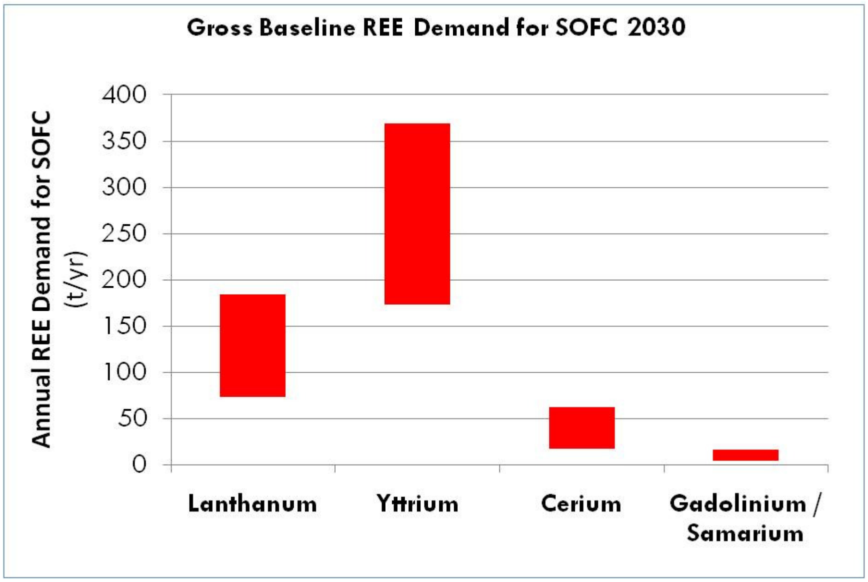

Figure 5 Projected Annual Gross REE Demand for New Systems and Replacement Stacks in 2030 (for Planar Anode-Supported SOFC, Demand in Metric Ton per Year Measured as Metals, based on current Technology)

Noteworthy is that the highest demand is for yttrium, also the only material that was classified as critical in the medium term by DOE's CMS.

Scenario 2: Baseline Net Demand for 2030 – The Impact of Recycling

Recycling of production waste as well as spent stacks will likely significantly reduce REE use for SOFC, especially in the long run. Given the concentration of rare earths and metals in used stacks, it is not unlikely that used stacks will be recycled. The processes used to process REE ores appear suitable for recycling of used stack materials.

Assuming the ceramics from the stacks are separated from the metals first, e.g. using conventional smelting technology, our analysis shows that the REO content of stack ceramics[21] would range from around 20% - 60%, depending on stack architecture, compared with 7-10% for typical ores(Haxel, Hedrick et al. 2002). Concentrations of REOs in production waste (e.g. overspray, rejected parts) can be even higher. These high concentrations will make recycling REEs from spent stacks attractive to REE producers.

Given the use patterns of SOFC, and the anticipated business structures for replacement stacks, a high rate of recycling would appear to be feasible. Especially if stack life remains relatively short (i.e. close to 5 yrs), it is likely that such a market for recycling REOs from the stack will arise even by 2030.

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[21] We exclude the nickel from the cermet anodes as we assume that in a recovery process that would be relatively straightforward and profitable to recover as nickel metal.

Given the attractiveness of recycling it would not likely impact the cost of SOFC strongly but it would be economically self-sufficient (i.e. REO producers would pay to recover portions of SOFC stacks).

Given the situation, a recycling rate of about 85% - 95% for production waste and spent stacks combined appears reasonable. With a 85% recycling rate the demand for REEs in 2030 would drop by around 50%, as shown in Figure 6. The resulting overall REE demand would be in the 160 – 360 t/yr range[22].

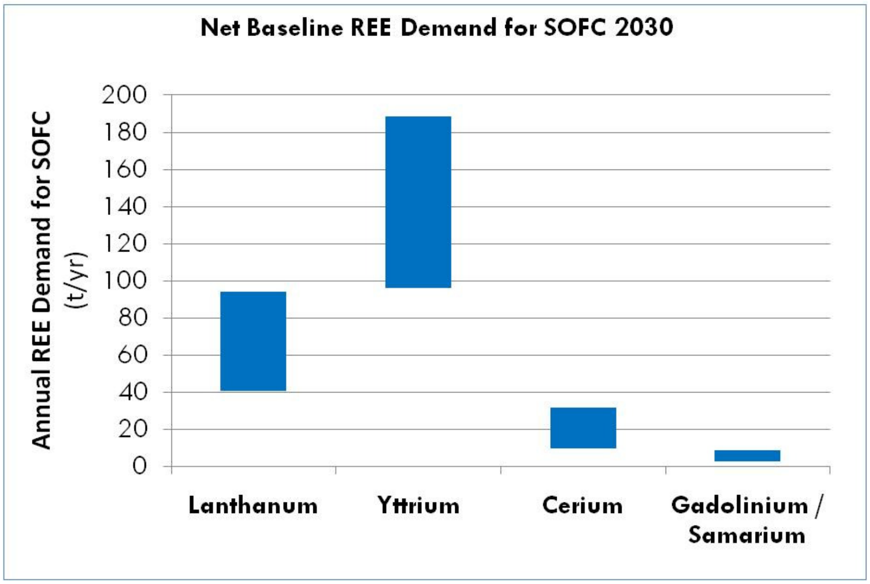

Figure 6 Projected Net REE Demand for SOFC in 2030 (for Planar Anode-Supported SOFC, Demand in Metric Ton per Year Measured as Metals)

Scenario 3: Long-Term REE Demand

Because 2030 is still early in the commercialization of SOFC technology, we thought it useful to assess the potential long-term contribution of SOFC to REE demand. To that end we considered a future scenario in which:

- Installed capacity of SOFC equals 100% of today's coal-fueled electric generating capacity. No growth in capacity is assumed, consistent with negligible net growth in coal-fired capacity over the past 10 yrs.
- SOFC stack life is 10 yrs, requiring stack replacement every 10 yrs.
- Recycling rates vary between 85 – 95%.
- REE use per kW is taken from the future range presented in Figure 4.

[22] Even by 2030 85% recycling will not lead to a 85% reduction in demand because a substantial portion of the market will still be a new market. With recycling, demand will stabilize sooner.

As can be seen in Figure 7, REE consumption under such a scenario is reduced by 30 – 80% compared with net baseline consumption. This indicates that REE use for SOFC is likely to be sustainable in the long-term.

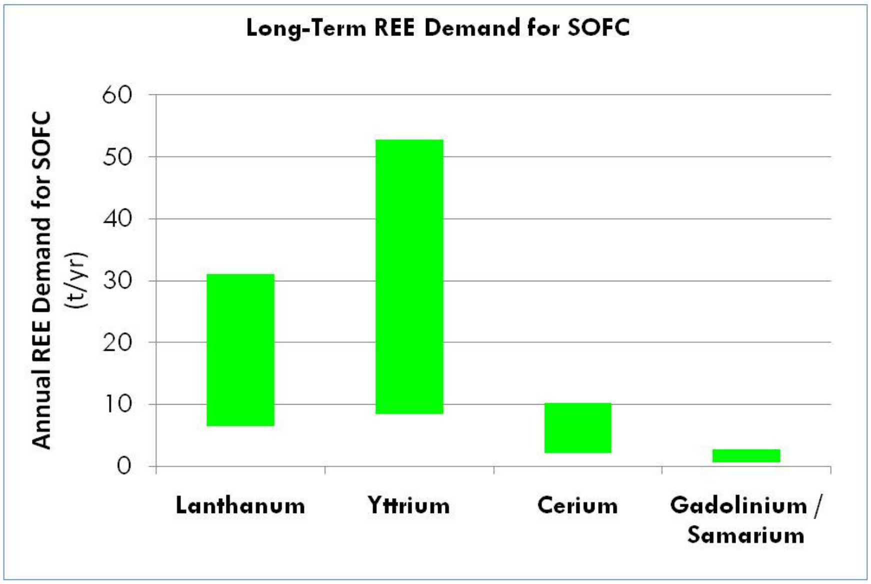

Figure 7 Projected Net Long-Term REE Demand for SOFC (for Planar Anode-Supported SOFC, Demand in Metric Ton per Year Measured as Metals)

Availability and Prices of Critical Materials

The availability and prices for REEs and other critical materials have been the subject of much media attention recently. Even after the release of the DOE CMS in late 2010 REE prices have more than tripled. Yttrium metal prices have risen around $5/kg until mid-2007 to around $40/kg in late 2010 to about $200/kg in recent months (Metal-Pages 2011). Recent dramatic increases in REE prices have been driven primarily by export restrictions being imposed by China. In recent years, China supplied around 90% of all REEs worldwide. Thus it is not surprising that China's announced 40% reduction of REE availability for export has led to REE shortages and dramatic price increases.

In addition to China, other countries, including the US, Australia, and Canada also hold considerable REE deposits. However, production from these countries has dwindled in recent years because Chinese suppliers were low-cost producers. Not surprisingly, in response to China's tightening of supplies, US, Australian, and Canadian companies are considering a resumption or increase in production of REEs in their respective countries.

Considering these factors and market forces, some analysts are suggesting (Fickling 2011) that rare earth prices will continue to rise for the coming year (to a peak around 50% higher than May 2011 prices). Starting in 2012, they predict, prices will start to decline back to levels similar to those seen over the past year. This view is broadly consistent with that of the DOE CMS. Thus, it appears that current (May 2011) prices are a reasonable (perhaps conservative) proxy for prices around 2015 and beyond, which is when commercial introduction of SOFCs is projected.

Compared with the quantities used today, the additional potential REE demand from SOFC applications appears modest (Table 4). Considering that SOFC demand will grow to projected levels over a period of 5-10 years, SOFC-driven demand for REE products appears unlikely to significantly challenge the supply chain or world reserves. In the following, production and reserve data for REEs are taken from a variety of USGS sources as well as from the US DOE CMS (Haxel, Hedrick et al. 2002; Salazar and McNutt 2010; USDOE 2010; USGS 2010; USDOE 2011). Following the table, we discuss each of the key materials in some detail.

Table 4 Summary of SOFC REE content and demand, REE Production, and REE Reserves (USDOE 2010)

	Content of SOFC	SOFC-Driven Net Demand[23]	Production (2010)	Estimated Reserves	Projected Production (2015)
	g/kW	t/yr (2030)	t/yr	T	t/yr
Yttria	21	40	9,000	540,000	10,000
Lanthanum Oxide	9.2	95	34,000	>10 million	50,000
Ceria	<3	<12	50,000	~50 million	79,000

Yttrium (Critical near and medium term):

- The projected 2030 net baseline SOFC demand (see scenario 2 above) for yttrium is 100 - 190 ton/yr. A rationalization of yttrium use for the anode (by moving from 8YSZ to 3YSZ, reducing film thicknesses, e.g.) could reduce that figure to ~8 ton/yr, as represented in the future scenario.
- Compared with a 2009 US consumption rate fluctuating between 400 – 742 t/yr net baseline use for SOFC is significant. However, the figure for the future scenario is not likely to materially impact overall yttrium markets. USGS estimates world mine production to be at least 9,000 t/yr. In that context, the impact of the net baseline demand would be modest (1-2%) and that of the future scenario essentially negligible (~0.1%).

[23] Assuming annual SOFC production of 4 GW/yr of new capacity plus 4 GW/yr of stack replacements assuming 90% REE recycling.

Consequently, the impact of potential future SOFC demand on overall demand and prices of yttrium is likely to be small.

- The abundance of yttrium in the earth's crust is 31 ppm similar to that of nickel and chromium. However, as other REEs, it is relatively disperse, with relatively few discovered more concentrated deposits (even in these deposits yttrium is not very concentrated: 200 – 500 ppm typically). USGS estimates reserves of yttrium at 540,000 tons, about 220,000 of these in China, and about 100,000 tons in the US (mainly in the Mountain Pass deposit in California).
- Virtually all Y used in the US is currently imported. More than 90% of world production is currently in China. The Chinese government has recently (in July 2010) announced cuts in REE exports by about 40%.
- Prices for bulk yttria (Y_2O_3, 99.9% pure or more, FOB China) have risen from around $5/kg in 2002 to around $40/kg in September 2010 and to around $200/kg in May 2011. High-volume prices for ultra-pure fine powders of yttria however can be significantly higher ($25-100/kg higher than bulk prices), depending more on purity level, physical form, and purchase volume. In fact, as there are currently no high-volume markets for ultra-pure fine yttrium powders it can be expected that if SOFC demand for such products increases the margin between medium and ultra-high purity powders will shrink.
- Nevertheless, DOE considers, due to other demands for yttrium (E.g. ofr use as phosphors in advanced lighting technologies), yttrium to be a critical material both for the near and medium term.

Lanthanum (near-critical near term, not critical medium term):

- The projected 2030 net baseline SOFC demand for lanthanum oxide is 40-90t/yr. Reduction in layer thicknesses in SOFC, and other improvements, could further reduce this amount. However, the potential for reduction is likely more limited than for yttrium, to 10 -30 t/yr. The demand that would be generated by alternative SOFC technologies, especially tubular cathode-supported SOFC, if commercialized at similar levels would be 50x higher, or around 4,000 t/yr. That level of demand would likely be sufficient to significantly affect lanthanum oxide markets and prices.
- Compared with annual global production of 34,000 t/yr (USDOE 2011), the potential demand for SOFC is modest (less than 0.5%) and appears unlikely to materially alter lanthanum markets.
- Lanthanum's abundance in the earth's crust is about 30 ppm, between that of tin and nickel, although, like other REEs, it is relatively disperse in the earth's crust. But compared with yttrium, REE deposits have high concentrations of lanthanum, with concentrations of ~25% in large deposits such as the Mountain Pass deposit in California

and about 15% in many Chinese deposits. Given this, lanthanum reserves in producible deposits are thought to be over ten million tons. Because of these large reserves of producible deposits lanthanum is categorized as not-critical for the medium term by DOE in its CMS.

- Notwithstanding considerable US deposits, nearly 100% of lanthanum is currently imported in the US, mostly from China.
- Along with other REEs, the prices for bulk lanthanum oxide (La_2O_3, 99.9% pure or more, FOB China) have increased dramatically from around $3/kg in 2002 to nearly $50/kg in September 2010, and on to about $150/kg in May 2011. This dramatic price increase is driven largely by to short-term supply-demand imbalances caused by drastic increases in lanthanum use in NiMH batteries (primarily for hybrid vehicles) but strongly exacerbated by China's export restrictions.

Cerium:

- Net demand for ceria for SOFC applications appears likely to remain around 10-30 t/yr or less.
- Compared with global production of cerium compounds of around 50,000 t/yr this projected demand from SOFC is small (<1%), and appears unlikely to materially affect overall Cerium markets and prices.
- The abundance of cerium in the earth's crust, at about 60 ppm, is the most abundant of the lanthanides on earth. Its abundance is similar to that of chromium, though it is less concentrated. Found mostly in conjunction with the lanthanides, cerium-rich deposits are found predominantly in China, with smaller deposits in the US and Australia. Ceria are thought to represent almost half of REE reserves; i.e. about 50 million tons. Clearly, demand for SOFC will in not likely strain world reserves. These large reserves are also the reason why, while classified as near-critical in the near term (driven by use in catalysts, metallurgical uses, batteries, and lighting applications), cerium is considered not-critical in the medium term by DOE.
- Prices for cerium too have risen sharply from about $2/kg in 2002 to around $37/kg in September 2010, and have risen to around $170/kg in May 2011.

Gadolinium and Samarium (not-critical near and medium term):

- Projected 2030 baseline SOFC demand for gadolinium or samarium is 2-8 t/yr. Future demands could be reduced to below 1 t/yr.
- Compared with report current global gadolinium production of around 400 t/yr this demand is modest. Samarium production is estimated at around 700 t/yr.
- Gadolinium is about 5 times less abundant than yttria, at about 6 ppm, while samarium has a similar abundance as yttrium. Gadolinium and samarium reserves worldwide,

found in China, the US, Australia, Brazil and India, are estimated to be around 1 million tons and 2 million tons respectively.

- Gadolinium and samarium oxide prices were historically several times higher than those of yttria, lanthanum oxide, and ceria (about $10-$12/kg in 2002). Current (September 2010) prices are similar to the other rare earths of interest however at near $40-$50/kg.

*Scandium (not considered in DOE CMS, (**Hocquard** 2003)):*

- Scandium is not used in state-of-the-art SOFC. However, if it were substituted for yttrium, demand would likely be similar to that for yttrium (depending on the doping level used , it could be twice as high) or 40-90 t/yr.
- Scandium is currently only used in small quantities, primarily as a dopant in aluminum (provides similar properties as titanium for sports equipment and niche aerospace applications). Other applications include lighting applications (as a phosphor for high-intensity lighting and lasers) and for research purposes. Global production of Sc_2O_3 is estimated to be less than 2 t/yr, while less than 10 kg Sc metal is estimated to be produced annually. Most scandium is produced in the former soviet union (FSU) from stockpiles produced during the cold war. BRGM estimates only 400 kg/yr is produced by virgin mines. Most production is currently in the FSU, followed by China.
- Scandium is estimated to have an abundance of around 20 ppm in the Earth's crust, though it can be concentrated considerably more in rare minerals. Because few concentrated resources can be found, there is not a good estimate of total global reserves today.
- According to USGS, prices of Scandium are significantly higher than those of other REEs, with prices ranging from $2,000 - $3,500/kg in 2003. However, other organizations question these prices (**Hocquard** 2003) suggesting actual market prices are 3-10x lower. Short of a structural change in scandium markets, these prices make scandium uncompetitive with yttrium for SOFC applications.
- Clearly even a small fraction of potential SOFC scandium demand would completely overwhelm current production capacity. In addition, it is far from clear whether adequate global, economically producible reserves exist (Even at current prices) to support SOFC demand in a sustainable manner.

The expectation is that if Chinese cuts in REE persist for some time, prices will likely stabilize at a higher level, as additional production capacity in other countries will supplant the reduced Chinese supply. However, because of the market risk the Chinese policy poses (China's marginal cost of production is still lowest, and hence could undercut other suppliers at any time if it wanted), such investments are likely to be made with caution.

Energy Technology Transitions and Emerging Technologies (DOE RFI Category 5)

As an emerging energy technology, we must also consider how prices and availability of critical materials (in particular yttrium) might influence the commercialization of SOFC. The previous chapter showed that availability is not likely to be a problem given the small amounts of REEs that will be required for SOFC production. Because of partial overlap in the categorization used in the DOE's RFI, we refer to the previous chapter.

Price Impact

The impact of yttrium prices on SOFC cost and economic viability in the context of IGFC systems(Kearns 2010) or natural gas fueled systems (Thijssen 2009) is limited, as REEs contribute around $10/kW to the first cost of SOFC stacks:

- The total capital cost[24] + stack replacement cost together represent about 4.5 ¢/kWh
- Of the ~$1750/kW installed CAPEX of IGFC systems about $700/kW is related to the SOFC power unit;
- Of the $700/kW power unit, about $100/kW is the manufactured cost of the stack;
- Of the $175/kW stack, less than $10/kW are represented by the cost of the ceramic powders;.
- Of the ceramic powders, REEs represent about $10/kW based on September 2010 prices (based on pre-2008 prices, REOs would cost about $1/kW). The combined impact of $10/kW stack cost (including both capital cost effects and stack replacement cost) on LCOE would amount to around 0.05 ¢/kWh, which is in the margin of error of such LCOE estimates at this time.

Figure 8 shows the impact of REE prices on SOFC stack cost. Clearly, given recent volatility in prices, further significant increases appear plausible. However, several organizations expect that price will drop again long-term, as the supply chains responds to the trade barriers and increased demand. For example, sustained high prices will stimulate production in other countries (than China). The price impact of REE prices on SOFC should be monitored in the coming years however. An additional price escalation of the same relative magnitude as the one over the past two years (i.e. a ~10x increase) would fundamentally alter the economics and viability of SOFC in central power applications.

[24] Total capital cost of the plant, not just the SOFC

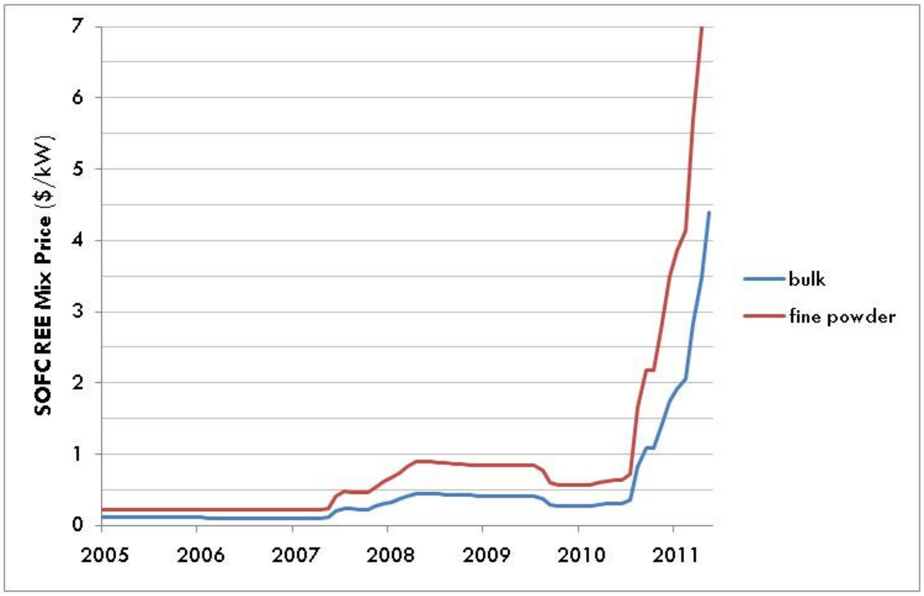

Figure 8 Historical Impact of REE Prices on SOFC Stack Cost (bulk figures represent just REE bulk prices FOB China, fine powder figures assume a 1.5x +$25/kg mark-up over bulk prices)[25]

It is worth noting that the price impact of other REEs (though not identified as critical in DOE's CMS) can be comparable to that of yttrium, or even significantly higher for some cell architectures. For example, at today's prices bulk REE cost for tubular cathode-supported SOFC cells would amount to more than $300/kW (most of the cost is in lanthanum), which would be prohibitive. Where REE use was hardly a factor in determining the relative cost competitiveness of various SOFC technologies based on 2002 prices, it appears that current prices lead to material differences in cost between various technologies.

Conclusion and Recommendations

A few REEs (notably yttrium, lanthanum, and cerium) are crucial to the functionality of SOFC. Of these, yttrium is the only one identified by DOE as a critical material in the medium term (timeframe relevant for SOFC). Economically viable alternatives for yttrium have not been identified for applications in SOFC ceramic cells so far, but opportunities for substantial reductions in SOFC yttrium content appear available. Although yttrium is critical for SOFC, the quantities used in SOFC are so small that incremental SOFC-related demand for SOFC (less than 2%) is unlikely to have a material impact on yttrium markets. Conversely, at current prices yttrium content represents less than $10/kW of SOFC production cost, which is not likely alter the economics and viability of SOFC in central power applications decisively.

[25] The mix price is determined by the sum of the products of REE use per kW (Figure 2) and REE prices for each of the REEs (all for state-of-the-art planar anode-supported SOFC). The fine powder mark-up presumably presents the supply-demand dynamics as well as processing cost. We show the 1.5x +$25/kg mark-up as a worst-case scenario.

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