Supplementary Information

1. Material Selection

For the material selection of this study (and the overriding research project, respectively) a criticality assessment has been carried out assessing two categories (economic importance and supply risk) with 12 indicators (see [1,2]). Besides indicators used in most criticality assessments such as concentration of supply and demand, current consumption, etc., the environmental burdens of the material production as well as the use for products with potential for environmental relief has been assessed. Those two indicators were chosen since the research project aims at especially assessing materials which are of interest from an environmental perspective.

Applying these indicators (described in detail in [1]) resulted in the selection of the following metals: gallium, germanium, indium, rhodium, palladium, platinum, gold, yttrium, lanthanum, cerium, neodymium, samarium, europium, gadolinium, terbium, dysprosium, and erbium.

Based on this list of materials, applications for further analysis have been selected considering the relevance in terms of quantity as well as the list of products analyzed in the parallel project RePro (see e.g., [3] for further details) that focuses on electric and electronic equipment. Further details on the selection of products are given in [4]. Besides the products analyzed in the main paper (different types of industrial catalysts, thermal barrier coatings, and photovoltaic cells) the following products are analyzed in the ongoing project: automobile catalysts, automobiles, metallurgical applications of mischmetall, NiMH batteries, polishing agents, special lenses, medical laser applications, (gearless) wind energy converters, different medical devices, fuel cells, optical fiber applications, LEDs, electric bikes, air conditioners, ceramics, selected equipment in nuclear reactors, high temperature super conductors, and data centers. Details on the analysis of these products will be published in late 2014.

2. Thermal Barrier Coatings

2.1. Aircraft Engines

2.1.1. Specifics of TBC in Aircraft Engines

Regarding the specifics of thermal barrier coatings (TBC) used in aircraft engines, data has been gathered from a variety of sources including literature as well as industry and expert information. The data refer to the technical specifics of the coating (metal concentration, thickness, estimation of total coated surface, *etc.*) as well as information on the coatings lifespan.

The main technical parameters of the coating are given in the following Table S1.

Table S1. Main parameters of TBC in aircraft engines.

Parameter	Value	Reference
Y_2O_3 content in the coating	7–8 mol-%, 13.7 wt.%	[5–8]
layer thickness	50–250 µm; Ø 150 µm	[9–12]
ρ (density)	6 g/cm³	Assumption, based on stationary gas turbines
Coated surface per engine	3.3–7.8 m^2	Calculated based on expert information

Based on this, the specific YSZ concentration per engine can be calculated to 411 to 959 g of Y_2O_3 per engine. As stated in the main article, an average value of 685 g is used in the baseline scenario.

The coated parts in an aircraft engine are vanes, blades, and the combustor. From various sources, data referring to the amount of coating (yttria stabilized zirconia, YSZ) on the different components has been available, too, as shown in the following Table S2.

Table S2. Coating per component.

Component	Min. (g)	Max. (g)	References	# per engine	References
Blades	2	5	[9]	–	–
Blades	2	7.5	[13]	64–80	[5,13]
Vanes	10	10	[14]	–	–
Vanes	10	50	[5,13,15]	–	–
Vanes, Stg. 1	10	32.5	[13]	38	[5,13]
Vanes, Stg. 2	11	35	[13]	40–42	[5,13]
Combustor	1200	4000	[13]	1	–

Calculating the amount of YSZ and Y_2O_3, respectively, results in a slightly larger spread of about 300 to 1200 g per engine, while the average content of 750 g is rather close to the value of 685 g described above.

The lifespans of the coatings in the engines have been determined based on the flight hours between the service intervals in which the coatings are replaced and the total flight hours per year. The respective data are given in the following Tables S3 and S4.

Table S3. Flight hours between service intervals.

Aircraft type	Min (h)	Max (h)	Average (h)	References
Short distance	8,000	10,000	9,000	[5,9,15]
Mid-/Long-Distance	20,000	23,000	21,500	[5,9,15]

Table S4. Flight hours per year.

Aircraft type	Min (h)	Max (h)	Average (h)	References
Short distance	3,000	5,000	4,000	[16–25]
Mid-/Long-Distance	3,000	5,000	4,000	

Based on this, the lifespan of TBC in engines of short distance aircrafts can be calculated to 2.25 years, and of TBC in mid-/long-distance aircraft to 5 years.

2.1.2. Results/Sensitivity Analysis

Secondary Y_2O_3 flows from aircraft engines in different years resulting from different k (shape parameter) and c (metal concentration) values are given in Table S5.

Table S5. Secondary Y_2O_3 flows in EOL-TBC (kg) (aircraft engines)-Sensitivity analysis.

Year	k	c (g/eng.)				
		300	**411**	**685**	**959**	**1200**
2014	1.5	103	142	236	330	413
	2.0	102	139	232	325	406
	2.5	100	137	229	321	401
2016	1.5	130	178	297	416	520
	2.0	129	176	294	412	515
	2.5	129	176	294	412	515
2018	1.5	141	193	321	449	562
	2.0	143	196	326	456	571
	2.5	145	198	330	462	578
2020	1.5	145	198	330	462	578
	2.0	147	201	335	469	587
	2.5	148	203	339	475	594

2.2. Stationary Gas Turbines

2.2.1. Specifics of TBC in Stationary Gas Turbines

As well as for TBC used in aircraft engines, for TBC used in stationary gas turbines data has been gathered from various sources.

Data referring to the technical specifics of the coating (metal concentration, thickness, coated surface, *etc*.) as well as lifespans of both fields of application is given in the following Table S6.

Table S6. Main parameters of TBC in stationary gas turbines.

Parameter	Description	References
Y_2O_3 content in the coating	7–8 wt%	[9,15,26–35]
layer thickness	400 µm–1.5 mm; Ø850 µm	
ρ(density)	6 g/cm³	
Coated surface per engine	0.16 m^2/MW to 0.53 m^2/MW	Calculated based on expert information [32]
Lifespan	4 years for centralized gas turbines 5 years for decentralized gas turbines	[9,15,27,29–31,36–41]

Based on these parameters, a range of 70.8 to 165.3 g yttrium per megawatt is used in the analysis presented in the main paper.

2.2.2. Results/Sensitivity Analysis

Secondary Y2O3 flows from stationary gas turbines in different years resulting from different k (shape parameter) and c (metal concentration) values are given in Table S7.

Table S7. Secondary Y_2O_3 flows in EOL-TBC (kg) (stationary gas turbines).

Year	c (g/MW) k	71	118	165
2014	1.5	530	852	1174
	2.0	537	867	1198
	2.5	534	872	1211
2016	1.5	571	938	1305
	2.0	572	947	1323
	2.5	571	951	1331
2018	1.5	608	1009	1410
	2.0	601	1000	1401
	2.5	597	994	1393
2020	1.5	635	1056	1479
	2.0	637	1062	1487
	2.5	636	1061	1486

3. CIGS-Photovoltaics

3.1. Collected and Compiled Data

Concerning the material intensity of CIGS photovoltaic cells (embodied In and Ga per MW) a broad literature research has been carried out. Several of the identified potentially relevant studies had to be excluded from the further analysis since they did not provide the required information, referred not to a specific technology but an average of different PV technologies, or referred to the material input to production, *i.e.*, it included material losses in production [42–50].

The remaining data is shown in the following Table S8.

Table S8. Material intensity of CIGS photovoltaic cells.

Reference	[51]	[52]	[53]
Unit	kg/kW	kg/MW	g/W
Gallium	0.0124–0.0185	2.34	0.0053
Indium	0.0154–0.0231	63.28	0.0231

This data has been complemented by data provided by experts and manufacturers and has been normalized to kg/kW. The resulting data is shown in the following Table S9.

Table S9. Collected and compiled data for CIGS material intensity.

Unit	[51]	[52]	[53]	Expert/ manufacturer information A	Expert/ manufacturer information B	Expert/ manufacturer information C	Expert/ manufacturer information D
	kg/MW						
Gallium	12.4–18.5	2.34	5.3	12.8	19.7	14.7	3.8
Indium	15.4–23.1	18.99	23.1	15.9	24.4	18.3	9.8

4. Polymerization Catalysts

4.1. Data on Average Beverage Consumption

Additional data used to calculate the germanium flows resulting from polymerization catalysts are given in the following tables. Table S10 provides information on the beverage consumption in Germany. Table S11 show the shares of PET bottles for different beverage types. Table S12 shows additional parameters used in the calculation such as the GeO_2 concentration in the PET, the specific concentration of GeO_2 per 1-liter bottle and the number of cycles of returnable bottles.

Table S10. Beverage consumption in Germany (in Mio. liters) [54].

Beverage type	2004	2005	2006	2007	2008	2009	Average
Bear and shandy	7.429, 4	7.354,0	7.510, 4	7.547, 0	7.425, 6	7.343, 5	7.434, 98
Water	12.247, 8	12.369, 7	12.995, 6	13.253, 0	13.131, 6	13.204, 5	12.867, 0
Soft drinks	10.557, 3	10.740, 6	11.131, 7	11.301, 1	11.432, 2	11.288, 3	11.075, 2

Table S11. Share of PET bottles for different beverage types.

Beverage types	Share	Comment	References
Water	15%/20%	returnable bottles	[54–56]
Soft drinks	15%/25%	returnable bottles	
Beer and shandy	6%/7%/8%	One-way bottles	
Water	50%/56.1%/70%	One-way bottles	
Soft drinks	50%/60.5%/70%	One-way bottles	

Table S12. Additional parameters used for calculations.

Parameter	Value	Comment	Reference
GeO_2 concentration in product (PET)	1:100,000 to 7:100,000	1:25,000 used in model	[57]
Specific concentration	0.88 to 1.22 mg/1l-bottle	one-ways bottles	calculated based on [55,58]
	2.83 to 2.48 mg/1l-bottle	returnable bottles	calculated based on [55,58]
Share of Ge-bearing catalysts in production of PET bottles	10%	–	based on [59,60]
Cycles of returnable bottles	15	Data referring to situation in Germany and Austria	[55,61]

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