# Sustainability in Materials Science and Engineering Education and Research

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March 28, 2016

All technologies require resources (materials, energy) to fabricate.

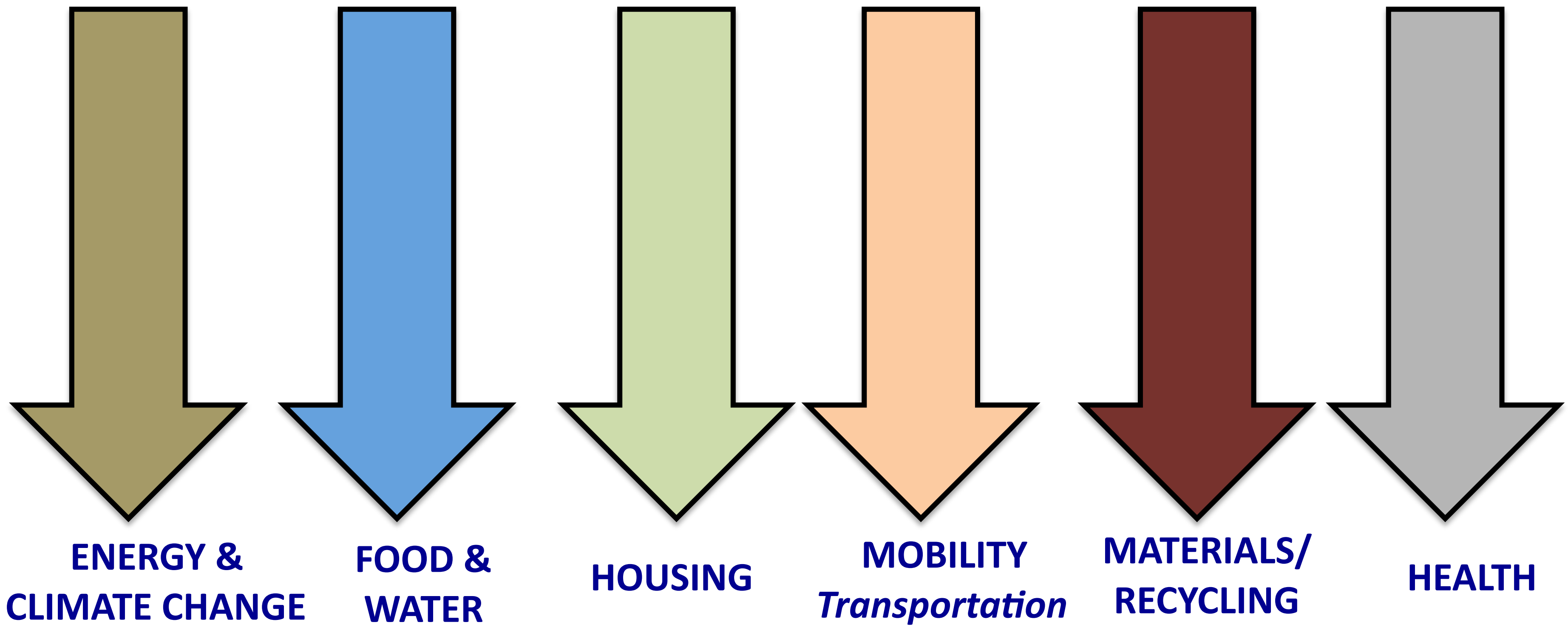
Many products require hazardous/toxic substances in the product itself and/or in the production process. Others utilize materials that are in limited supply or are difficult to recycle.

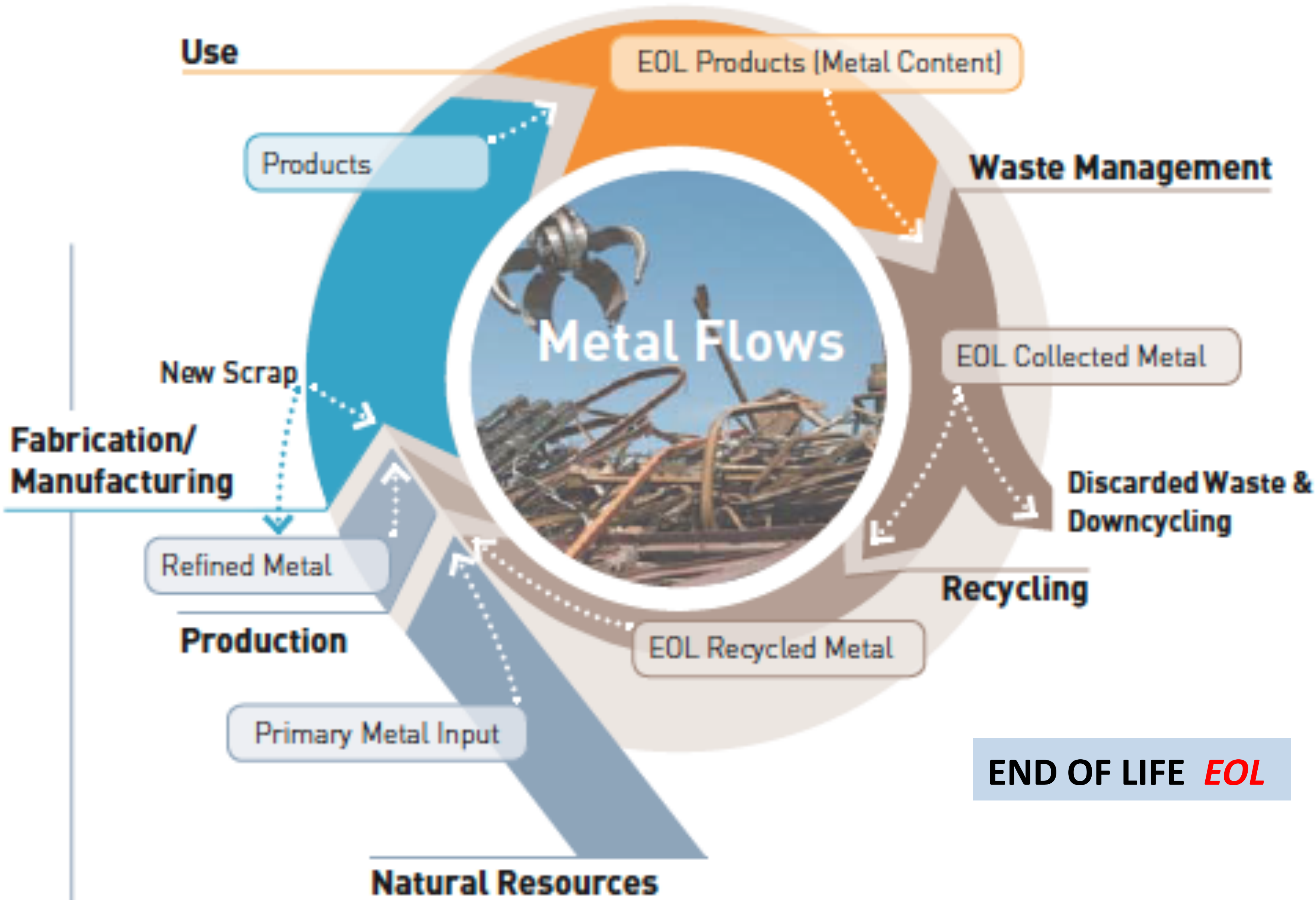
MSE students and researchers play an important role in defining product composition and processing details. They need to play a role in selecting materials and process chemicals that are not harmful to humans and the environment.

They can also become part of the community expanding sustainability assessment methodologies.

# SUSTAINABLE DEVELOPMENT

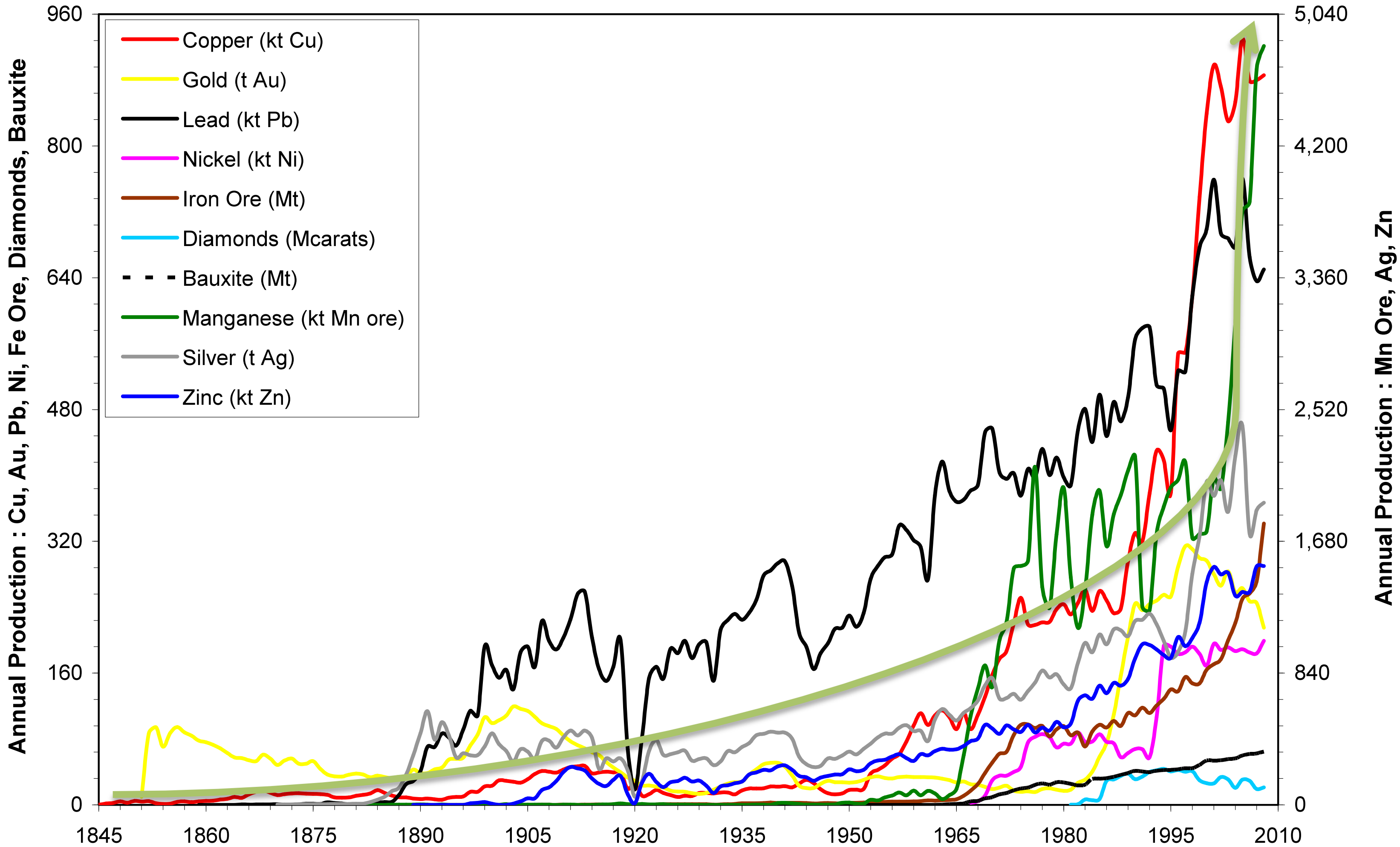
*SOCIETAL NEEDS - CHALLENGES*




Use
EOL Products (Metal Content)
Products
Waste Management
Metal Flows
EOL Collected Metal
New Scrap
Fabrication/
Manufacturing
Discarded Waste &
Downcycling
Refined Metal
Recycling
Production
EOL Recycled Metal
Primary Metal Input
END OF LIFE *EOL*
Natural Resources

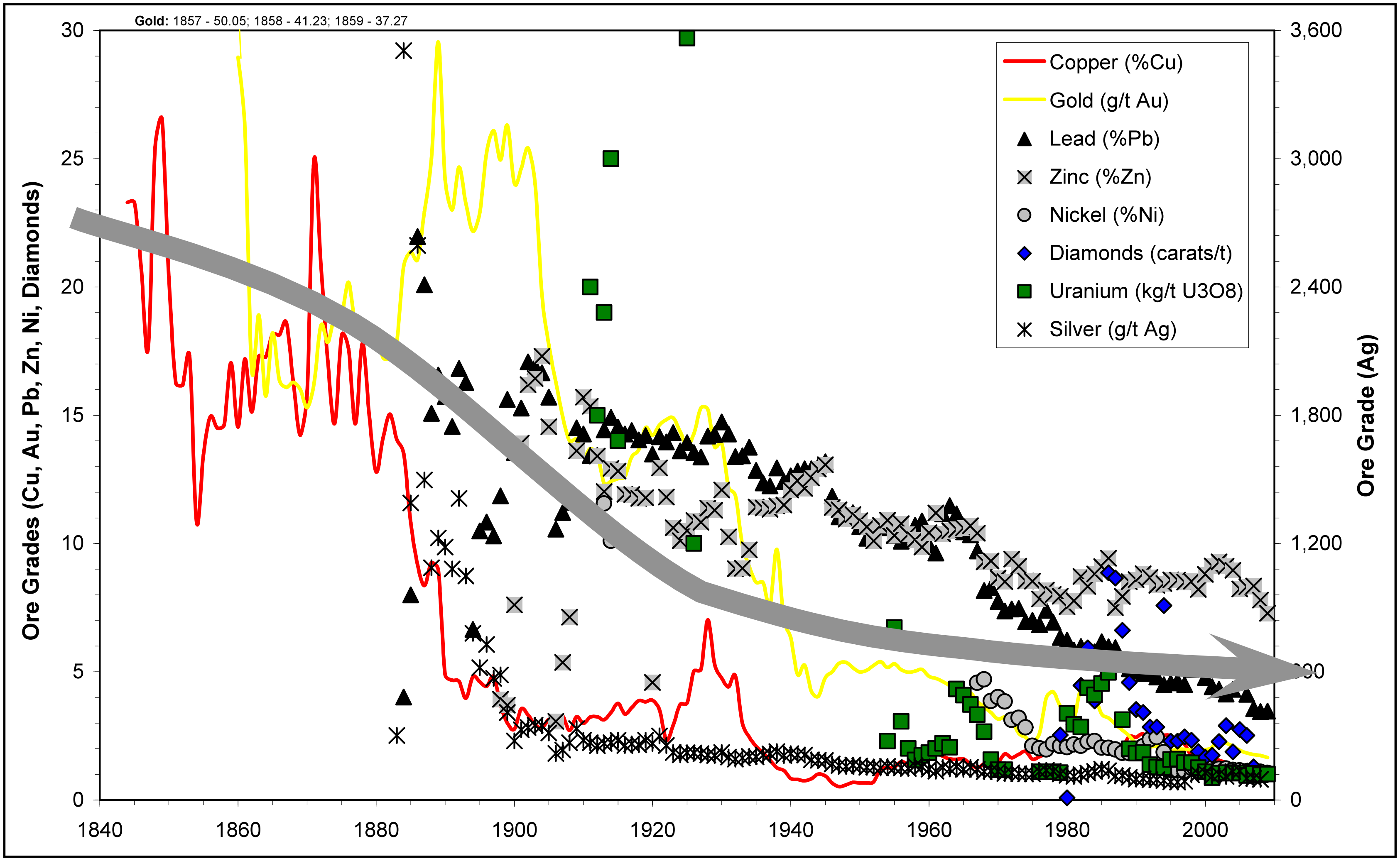
*UNEP 2011*

# Metal Production Trends




*G. Mudd, 2009, Sustainability of Mining*

# Trends in Ore Grade




*G. Mudd, 2009, Sustainability of Mining*

# *Consumer products are increasingly complex*


© Umicore

- Ag, Au, Pd… (precious metals)
- Cu, Al, Ni, Sn, Zn, Fe, Bi, Sb, In… (base & special metals)
- Hg, Be, Pb, Cd, As… (metals of concern!)
- halogens (Br, F, Cl...)
- plastics & other organics
- Glass, ceramics

These devices represent a considerable metal stock in society

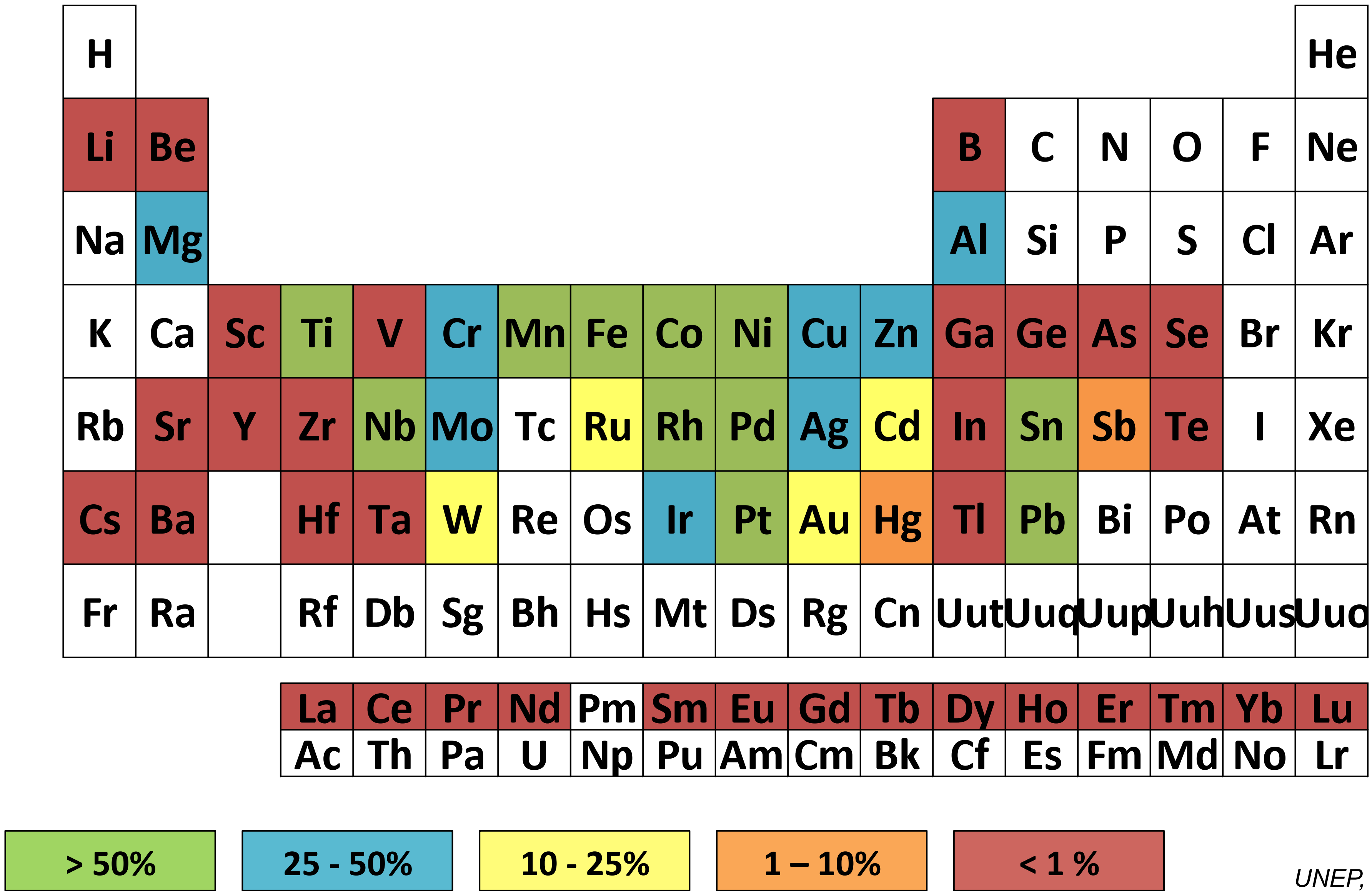
**Cell phones*:**
**1300 Million units x 250 mg Ag ≈ 325 t Ag**
**x 24 mg Au ≈ 31 t Au**
**x 9 mg Pd ≈ 12 t Pd**
**x 9 g Cu ≈ 12,000 t Cu**
**x 3.8 g Co[1] ≈ 4900 t Co**

**PC & laptops*:**
**300 Million units x 1000 mg Ag ≈ 300 t Ag**
**x 220 mg Au ≈ 66 t Au**
**x 80 mg Pd ≈ 24 t Pd**
**x ≈ 500 g Cu ≈ 150,000 t Cu**
**≈140 M batteries[2] x 65 g Co ≈ 9100 t Co**

* based on 2008 sales, Gartner 2.3.2009 [1] 20 g Li-ion battery [2] Li-ion batteries is used in >90% of laptops

*Credit: C. Meskers - Umicore*

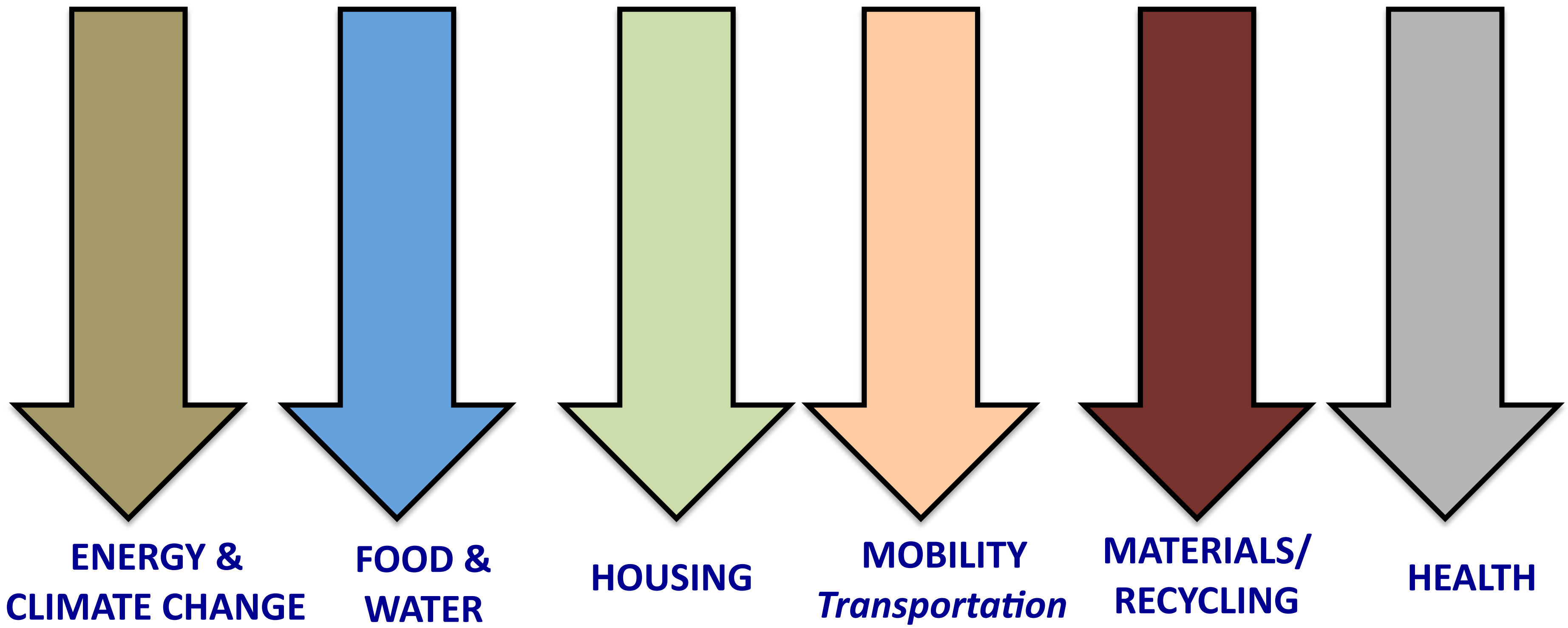
# End-of-life Recycling Rates




*UNEP, 2010*

# SUSTAINABLE DEVELOPMENT

## *SOCIETAL NEEDS - CHALLENGES*



# Toxicity Characteristic Leaching Procedure (TCLP) Regulatory Levels

| METALS | TCLP Regulatory Level, mg/L | EPA Hazardous Waste Number | Recommended Test Method |
|---|---|---|---|
| Arsenic | 5.0 | D004 | 7061 |
| Barium | 100.0 | D005 | 7080 |
| Cadmium | 1.0 | D006 | 7130 |
| Chromium | 5.0 | D007 | 7190 |
| Lead | 5.0 | D008 | 7420 |
| Mercury | 0.2 | D009 | 7471 |
| Selenium | 1.0 | D010 | 7741 |
| Silver | 5.0 | D011 | 7760 |

*High values are preferred.*

Reference: 40 CFR 261, Appendix II, 1993 ed., as amended by 58 FR 46040, August 31, 1993.

S-R. Lim, D. Kang, O.A. Ogunseitan, J.M. Schoenung, "Potential Environmental Impacts of Light-Emitting Diodes (LEDs): Metallic Resources, Toxicity, and Hazardous Waste Classification," *Environmental Science & Technology, 45: 320-327 (2011).*

# Leachability Test: LED Diodes ♪

○ TTLC results for State of California hazardous waste classification (units mg/kg)

"N/A" : Not Applicable, "-" : Not Detected; Low Values are Preferred; High Thresholds are Less Hazardous

| Substance | TTLC Threshold | LED (color/intensity) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Red /Low | Red /High | Yellow /Low | Yellow /High | Green /Low | Green /High | Blue /Low | Blue /High | White |
| Aluminum | N/A | 97.0 | 158.0 | 104.0 | 156.0 | 79.6 | 156.0 | 153.0 | 73.4 | 84.5 |
| Antimony | 500 | 15.4 | 2.0 | 2.8 | 1.9 | 3.6 | 2.5 | 1.3 | 1.5 | 25.9 |
| Arsenic | 500 | 11.8 | 111.0 | 8.0 | 84.6 | 7.8 | 15.2 | 5.7 | 5.4 | - |
| Barium | 10000 | - | - | - | - | - | - | - | - | - |
| Cerium | N/A | - | - | - | - | - | - | - | - | - |
| Chromium | 500(VI);2500(III) | 138.0 | 28.6 | 32.7 | 27.9 | 84.1 | 49.3 | 50.9 | 30.3 | 65.9 |
| Copper | 2500 | 87.0 | **3818.0** | 956.0 | **2948.0** | 1697.0 | **3702.0** | **3892.0** | 2153.0 | 31.8 |
| Gadolinium | N/A | - | - | - | - | - | - | - | - | - |
| Gallium | N/A | 135.6 | 95.0 | 63.8 | 79.1 | 75.6 | 3.1 | 2.1 | 1.5 | 3.8 |
| Gold | N/A | 39.8 | 45.8 | 30.5 | 30.1 | 40.2 | 176.3 | 32.5 | 118.6 | 115.9 |
| Indium | N/A | 3.4 | 1.7 | - | - | 2.5 | - | - | - | - |
| Iron | N/A | 285558.2 | 363890.8 | 300905.6 | 398630.4 | 310720.6 | 395652.2 | 339234.5 | 256499.3 | 311303.6 |
| Lead | 1000 | **8103.0** | 8.9 | 7.7 | - | 5.0 | - | - | - | - |
| Mercury | 20 | - | - | - | - | - | - | - | - | - |
| Nickel | 2000 | **4797.0** | **2054.0** | 1541.0 | **2192.0** | **2442.0** | **2930.0** | 1564.0 | 1741.0 | **4083.0** |
| Phosphorus | N/A | 114.2 | - | 58.4 | - | 78.5 | 91.8 | 79.1 | 84.3 | 110.8 |
| Silver | 500 | 430.0 | 409.0 | 248.0 | 336.0 | 270.0 | 306.0 | 418.0 | **721.0** | **520.0** |
| Tungsten | N/A | - | - | - | - | - | - | - | - | - |
| Yttrium | N/A | - | - | - | - | - | - | - | - | - |
| Zinc | 5000 | 48.2 | 66.2 | 36.5 | 63.6 | 41.8 | 62.5 | 42.6 | 36.7 | 49.2 |

**Table I. Environmental releases (2009) and human health toxicity indices for selected chemicals.[a,b]**

| | Total TRI[10] releases in 2009 (kg) | Human exposure limits[c,11,12] | | | IARC classification[d,13] | NTP classification |
|---|---|---|---|---|---|---|
| | | PEL (mg/m³) | TLV (mg/m³) | REL (mg/m³) | | |
| **Metals** | | | | | | |
| Aluminum | 11,400,000 | 5 | 1 | 10 | – | – |
| Antimony | 444,000 | 0.5 | 0.5 | 0.5 | – | – |
| Arsenic | 339,000 | 0.01 | 0.01 | – | Group 1 | Known carcinogen |
| Barium | 2,310,000 | 0.5 | 0.5 | 0.5 | – | – |
| Beryllium | 4730 | 0.002 | 0.00005 | – | Group 1 | Known carcinogen |
| Cadmium | 183,000 | 0.005 | 0.002 | 0.1 | Group 1 | Known carcinogen |
| Chromium | 3,610,000 | 0.5 | 0.5 | 0.5 | Group 3 | – |
| Cobalt | 135,000 | 0.1 | 0.02 | 0.05 | Group 2B | – |
| Copper | 4,440,000 | 0.1 | 0.2 | 0.1 | – | – |
| Lead | 6,480,000 | 0.05 | 0.05 | 0.05 | Group 2B | Anticipated carcinogen |
| Manganese | 6,420,000 | – | 0.2 | 1 | – | – |
| Mercury | 56,000 | – | 0.025 | 0.05 | Group 3 | – |
| Nickel | 2,330,000 | 1 | 1.5 | 0.015 | Group 2B | Anticipated carcinogen |
| Selenium | 65,000 | 0.2 | 0.2 | 0.2 | Group 3 | – |
| Silver | 62,000 | 0.01 | 0.1 | 0.01 | – | – |
| Thallium | 171 | 0.1 | 0.1 | 0.1 | – | – |
| Vanadium | 945,000 | – | – | – | – | – |
| Zinc | 5,400,000 | – | – | – | – | – |

[a]Acronyms: IARC, International Agency for Research on Cancer; NTP, National Toxicology Program; PEL, permissible exposure limit; REL, reference exposure level; TLV, threshold limit value; TRI, Toxics Release Inventory.

[b]Cells highlighted in rose contain quantitative or qualitative information sufficient to trigger caution in using the corresponding chemicals in manufacturing.

[c]High values are preferred for PEL, TLV, and REL.

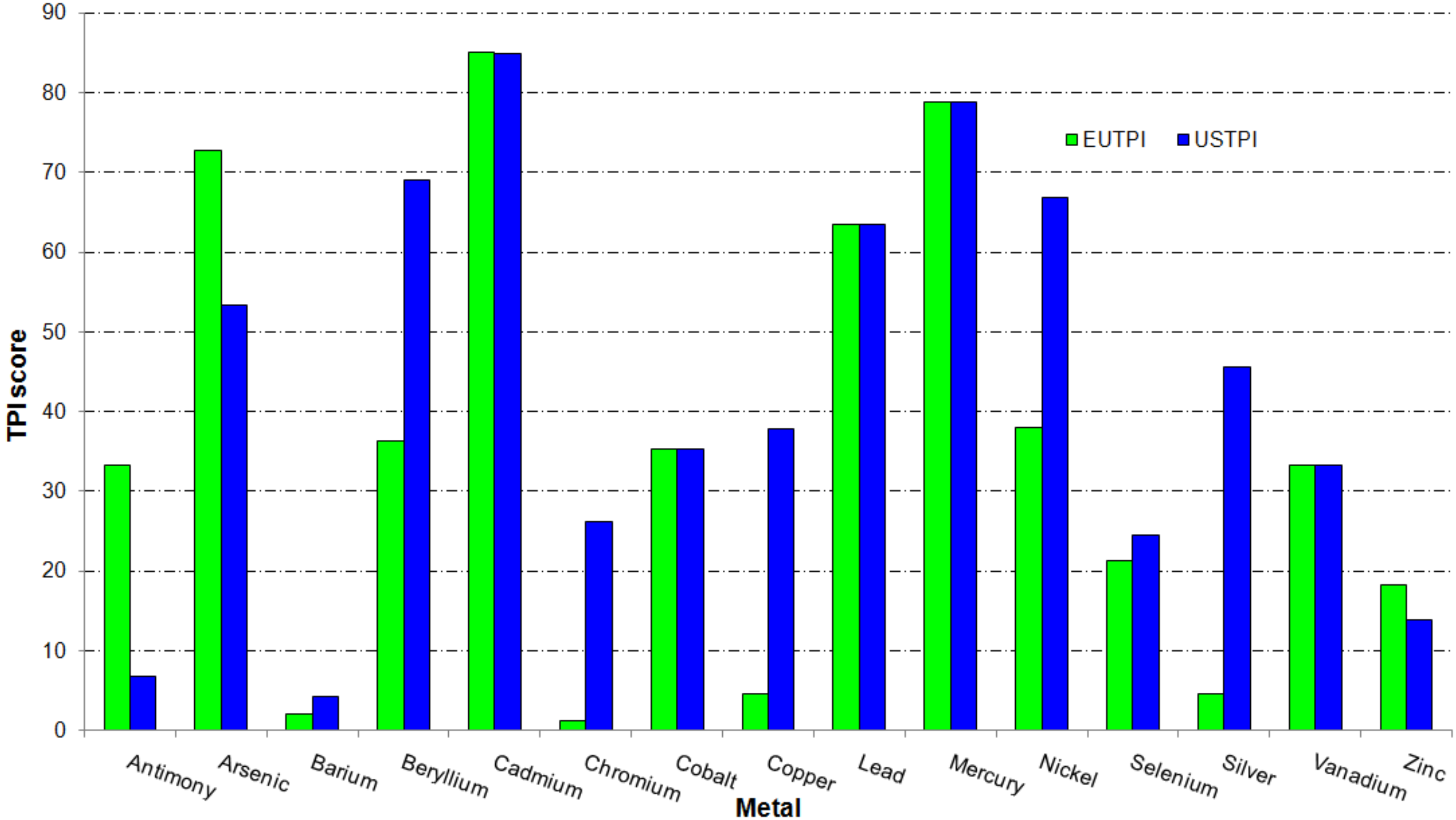
[d]The specific IARC group classifications are as follows: Group 1, carcinogenic to humans; Group 2A, probably carcinogenic to humans; Group 2B, possibly carcinogenic to humans; Group 3, not classifiable as to carcinogenicity to humans; and Group 4, probably not carcinogenic to humans.

(O.A. Ogunseitan, J.M. Schoenung, *MRS Bulletin, Volume 37, April 2012, pp. 356-363)*

# Toxic Potential Indicator (TPI) Scores for Metals

## Derived from: human health, environmental health and physical hazards

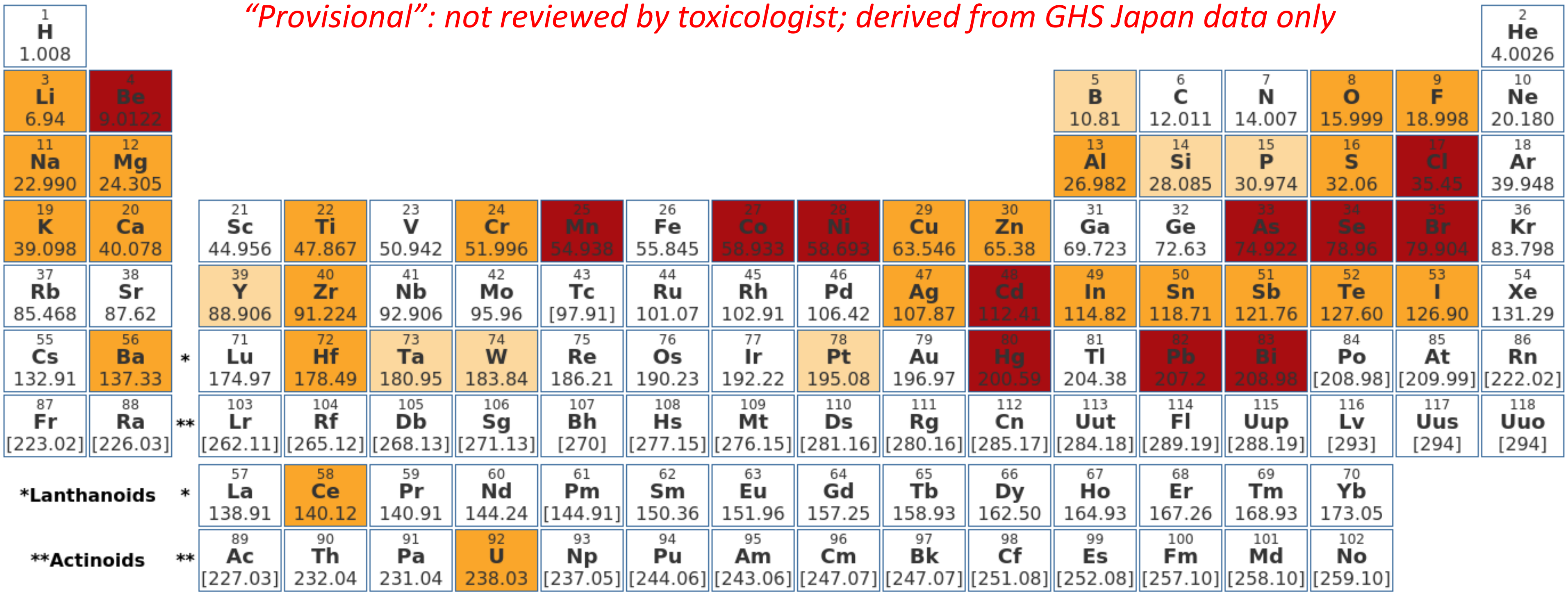
*Low scores are preferred; possible range is 0-100*




C.W. Lam, M.P. Aguirre, K. Schischke, N. Nissen, O.A. Ogunseitan, J.M. Schoenung, "International Harmonization of Models for Selecting Less Toxic Chemical Alternatives: Effect of Regulatory Disparities in the US and Europe," *Integrated Environmental Assessment and Management, Volume 8, Number 4, pp. 723-730*

# GreenScreen® Provisional Benchmark Scores

*"Provisional": not reviewed by toxicologist; derived from GHS Japan data only*




Benchmark 3: Use but Still Opportunity for Improvement

Benchmark 2: Use but Search for Safer Substitutes

Benchmark 4: Safer Chemical

Benchmark 1: Chemical of High Concern

Benchmark U: Unspecified due to Data Gaps

(Derived from data in: K. Wehage, P. Chenhansa, J.M. Schoenung, "An Open Framework for Automated Chemical Hazard Assessment based on GreenScreen for Safer Chemicals," *Integrated Environmental Assessment and Management, in press 2016; GreenScreen for Safer Chemicals®* methodology developed by Clean Production Action)

# GreenScreen for Safer Chemicals®: Hazard Traits

| Priority Human Health Effects (PE) | Human Health Effects (HH) | Ecotoxicity (Eco) | Environmental Fate (EF) | Physical Hazards (Phy) |
|---|---|---|---|---|
| Carcinogenicity (C) | Acute Toxicity (AT) | Acute Aquatic Toxicity (AA) | Persistence (P) | Explosivity (E) |
| Mutagenicity (M) | Irritation and Corrosion (IC) | Chronic Aquatic Toxicity (CA) | Bioaccumulation (B) | Flammability (F) |
| Reproductive (R) | Skin/Eye Sensitization (S) | | | |
| Developmental (D) | Immune System effects (IS) | | | |
| Endocrine Disruption (ED) | Systemic Organ Toxicity (SOT) | | | |
| Neurological (N) | | | | |

Utilizes 17 hazard traits from UN's GHS for hazard assessment

# Thin Film Solar Cells

## CIGS Deposition: Assessment Results

Hazard: Low → High Low → High

| CIGS Deposition Process | | GS-Based Benchmark frequency | | | | TPI score frequency | | | |
|---|---|---|---|---|---|---|---|---|---|
| Type of Processing | Specific Deposition Method | 4 | 3 | 2 | 1 | low | mid | high | very high |
| Industrial Process | Coevaporation | 0 | 1 | 4 | 0 | 1 | 1 | 2 | 1 |
| Ink Printing | Spray Pyrolysis of $CuInS_2$ | 0 | 0 | 2 | 1 | 0 | 0 | 3 | 0 |
| Electrodeposition | Kapmann Method | 1 | 1 | 4 | 2 | 2 | 0 | 5 | 1 |
| Industrial Process | Sulfurization/ Selenization | 1 | 1 | 4 | 1 | 1 | 1 | 3 | 1 |
| Chemical Vapor Deposition | AP-MOCVD | 0 | 0 | 6 | 1 | 3 | 0 | 2 | 1 |
| Electrodeposition | Kapmann Method with Ammonia | 1 | 1 | 4 | 3 | 2 | 1 | 5 | 1 |

D.A. Eisenberg, MYu, C.W. Lam, O.A. Ogunseitan, J.M. Schoenung, "Comparative Alternative Materials Assessment to Minimize Toxicity Hazards in the Life Cycle of Thin Film Photovoltaics," *Journal of Hazardous Materials 260 (2013) 534-542.*

## Toxicity Potential Summary: Bulbs ♪

- Comparison of the incandescent, CFL, and LED bulbs taking into account design lifetimes (1000, 10,000, 50,000 hr, respectively).

*Low values are preferred.*

| Environmental Impact Assessment Category and Method | | | Incandescent Bulb | CFL Bulb | LED Bulb |
|---|---|---|---|---|---|
| Resource Depletion Potential | CML 2001 | | 1 | 3 | 3 |
| | EPS 2000 | | 1 | 5 | 2 |
| Hazard-based Toxicity Potential | TLV-TWA | | 1 | 4 | 3 |
| | PEL-TWA | | 1 | 13 | 3 |
| | REL-TWA | | 1 | 8 | 2 |
| | TPI | | 1 | 16 | 2 |
| Life Cycle Impact (USEtox™)-based Toxicity Potential | Human-Toxicity Potential | Urban Air | 1 | 22 | 2 |
| | | Rural Air | 1 | 22 | 2 |
| | | Freshwater | 1 | 25 | 2 |
| | | Sea Water | 1 | 22 | 2 |
| | | Natural Soil | 1 | 26 | 2 |
| | | Agricultural Soil | 1 | 22 | 2 |
| | Eco-toxicity Potential | Urban Air | 1 | 22 | 3 |
| | | Rural Air | 1 | 22 | 3 |
| | | Freshwater | 1 | 22 | 3 |
| | | Sea Water | 1 | 23 | 2 |
| | | Natural Soil | 1 | 22 | 3 |
| | | Agricultural Soil | 1 | 22 | 3 |

S-R. Lim, D. Kang, O.A. Ogunseitan, J.M. Schoenung, "Potential Environmental Impacts from the Metals in Incandescent, Compact Fluorescent Lamp (CFL) and Light-Emitting Diode (LED) Bulbs," *Environmental Science & Technology, 47: 1040-1047* (2013).

UNIVERSITY OF CALIFORNIA, IRVINE
Department of Chemical Engineering & Materials Science

**CBEMS 195 & 249: Green Engineering: Theory and Practice**

**COURSE OUTLINE**

**Fall 2015**

| | |
|---|---|
| Objectives: | Study of the methods and impacts of selecting alternative technologies, processes, materials, chemicals, and/or products so as to reduce the pollution, waste and the use of toxic substances, thereby creating "green," environmentally responsible, and sustainable solutions. Topics include environmental regulations, recycling, life-cycle assessment, economic analysis, design for the environment, green chemistry and toxicology. |

| | | |
|---|---|---|
| Grading: | Attendance and Participation | 20% |
| | Current Event Journal | 20% |
| | Assignments | 20% |
| | Quizzes | 20% |
| | Project | 20% |

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**CBEMS 195 & 249: Green Engineering: Theory and Practice**

**TENTATIVE LIST OF TOPICS/SPEAKERS**

**Fall 2015**

Topics:

Introduction to Green Engineering/Green Chemistry/Pollution Prevention
Human Health Risk Assessment
Occupational Exposure
Hazard Traits: EPA DfE, GHS, OEHHA
Screening Tools and Checklists
Life Cycle Assessment (LCA)
Life Cycle Impact Assessment (LCIA)
Data Sources and Decision-Making Tools
Recycling, Recovery, Reuse
Environmental Law; State, Federal and International Initiatives

Possible Case Studies:

- Electronics
- Buildings
- Foods/Beverages
- Soaps/Shampoos/Cleaning Products/Cosmetics
- Critical Materials

All technologies require resources (materials, energy) to fabricate.

Many products require hazardous/toxic substances in the product itself and/or in the production process. Others utilize materials that are in limited supply or are difficult to recycle.

MSE students and researchers play an important role in defining product composition and processing details. They need to play a role in selecting materials and process chemicals that are not harmful to humans and the environment.

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