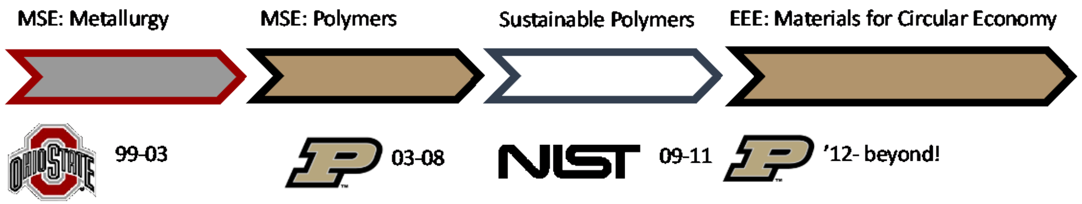
Semiconductors and Sustainability

John Howarter
Purdue University
Nov 29, 2023
SCALE K-12

John Howarter – Sustainable Materials and Manufacturing



Associate Professor, Materials Engineering

Associate Professor, Environmental and Ecological Engineering

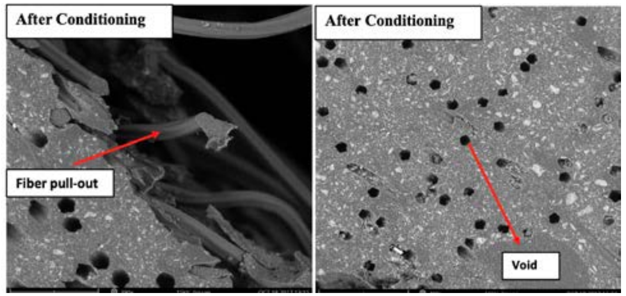
Postdoc, National Institute of Standards and Technology (NIST)

PhD, Materials Engineering, Purdue University

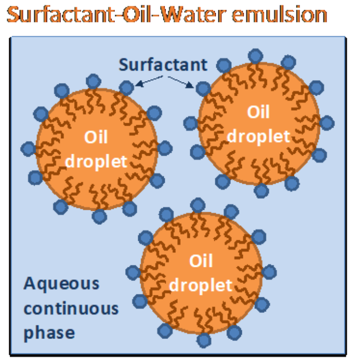
BS, Materials Engineering, Ohio State University

Core research areas

Manufacturing of bio-plastics, sustainable nanocomposites, performance life and end-of-life characterization.

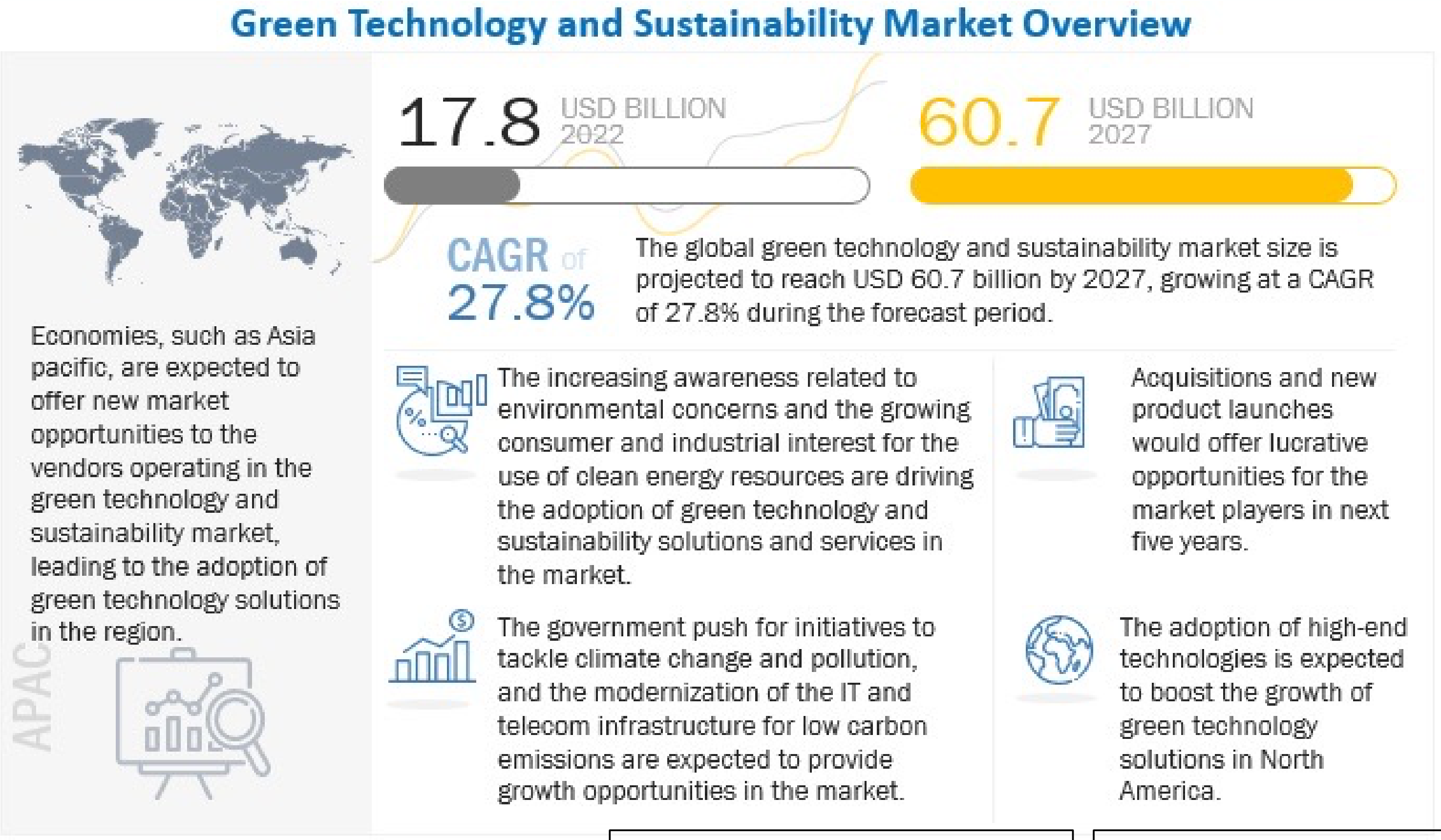


Desalination & oil-water separations, polymer thin films, coatings.



Materials in circular economy, green materials, recycling and reprocessing of complex materials.

Research Needs: Sustainability Engineering



Mobility/transportation

Materials Processing

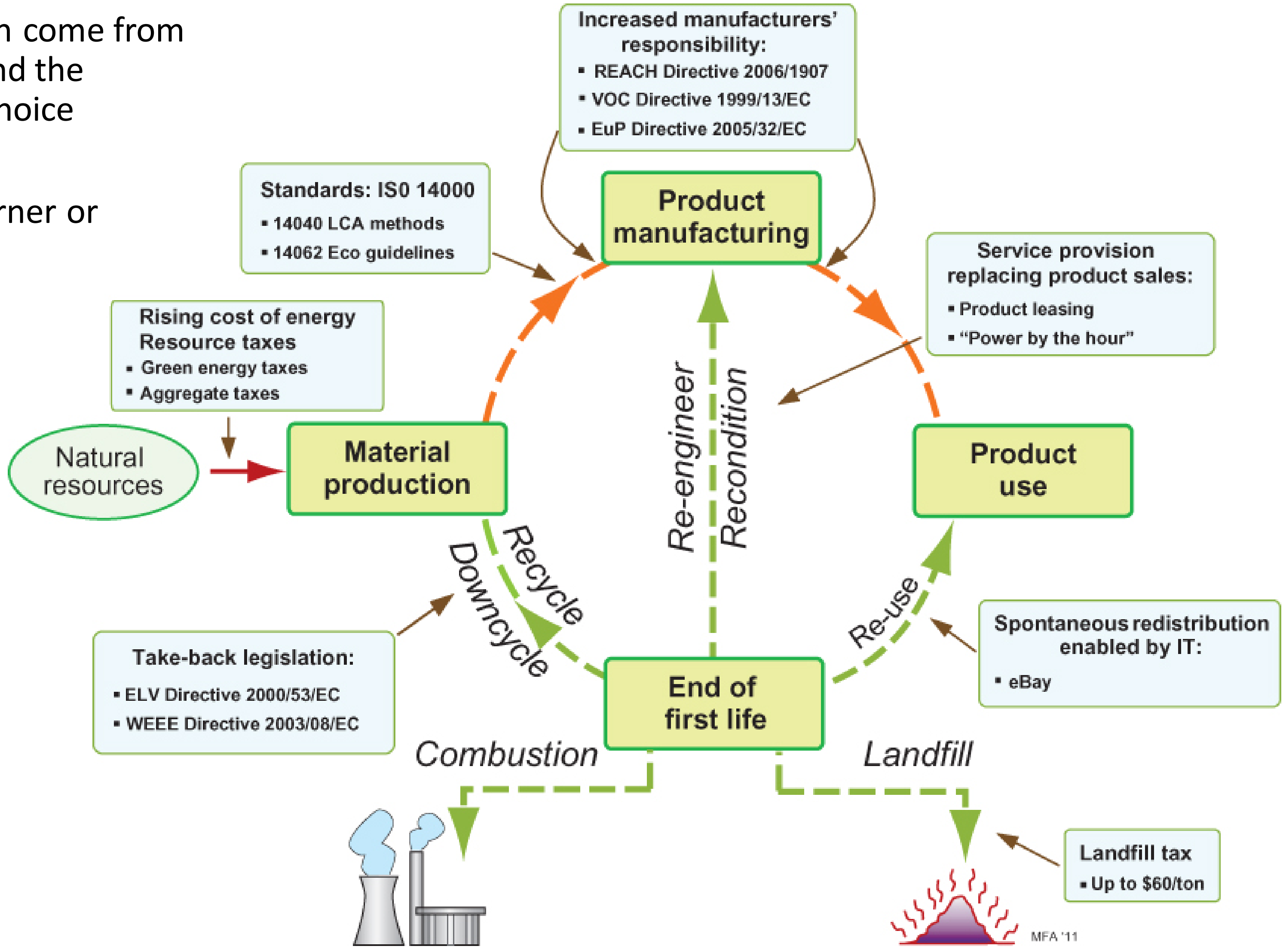
Application Areas

ration & distribution systems

Pharmaceuticals

Interventions and other mechanisms that influence the flows in the material life cycle.

- A number of figures in this presentation come from this book: Michael Ashby - Materials and the Environment: Eco-informed Material Choice
    - ISBN-13 : 978-0128215210
    - Those figures have MFA in the corner or Elsevier 2013 copyright



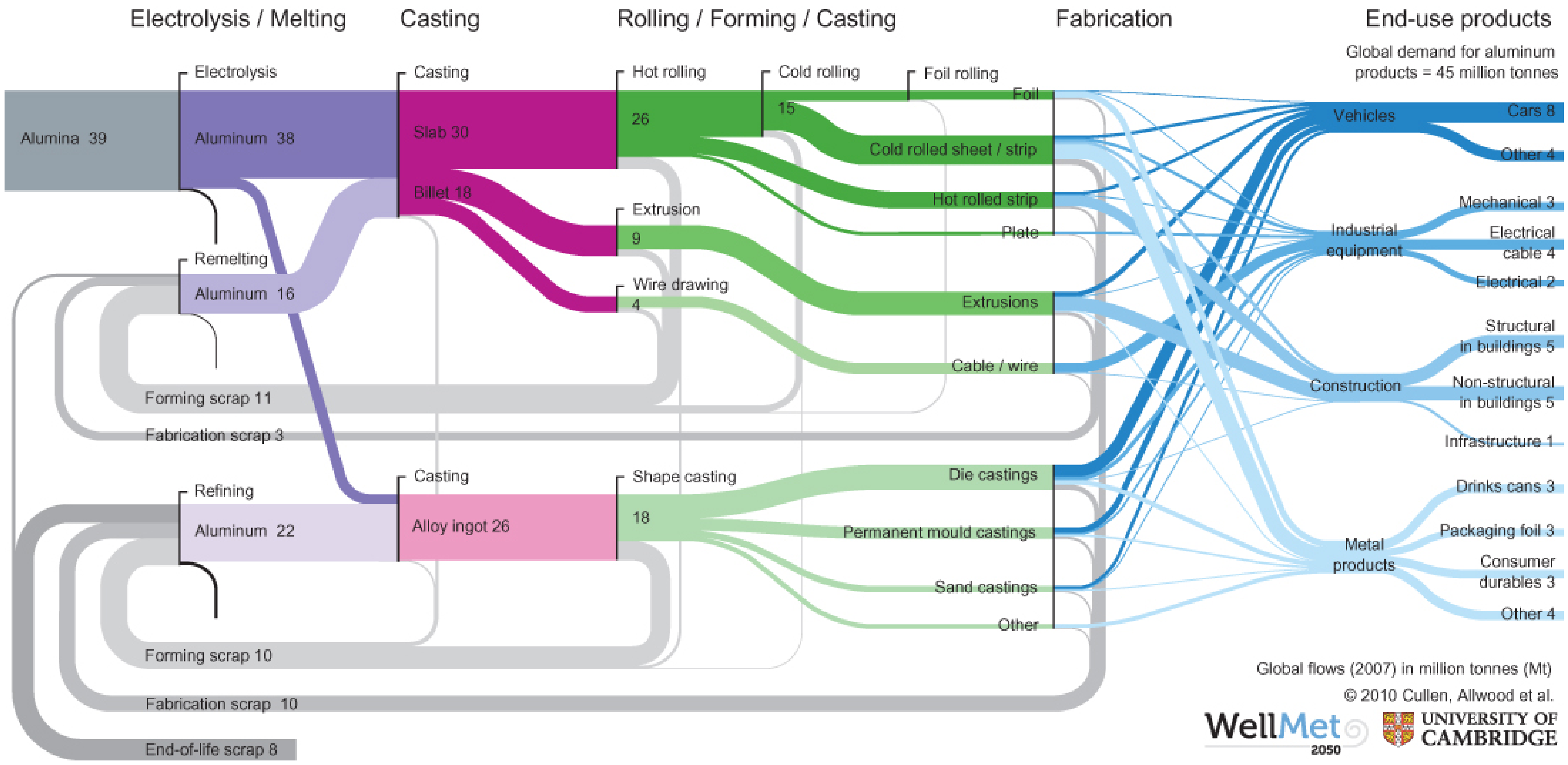
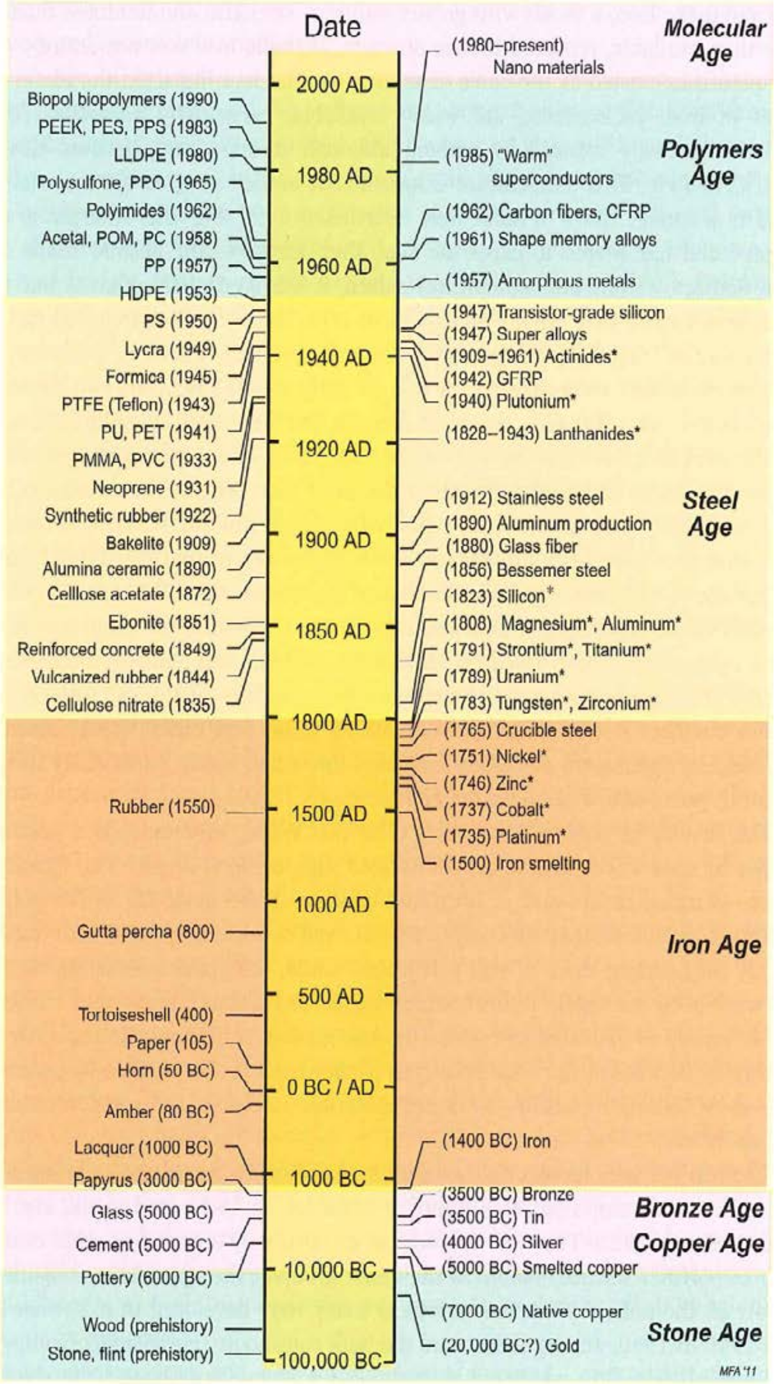
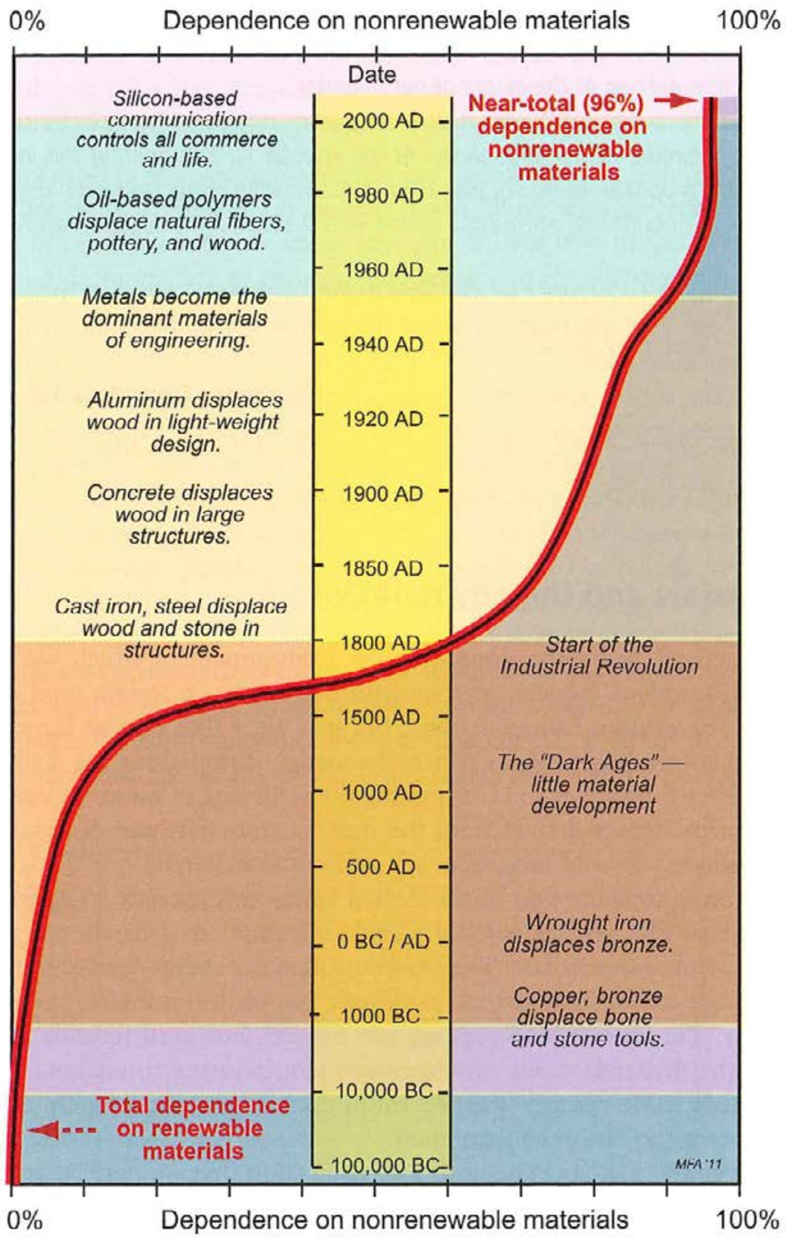


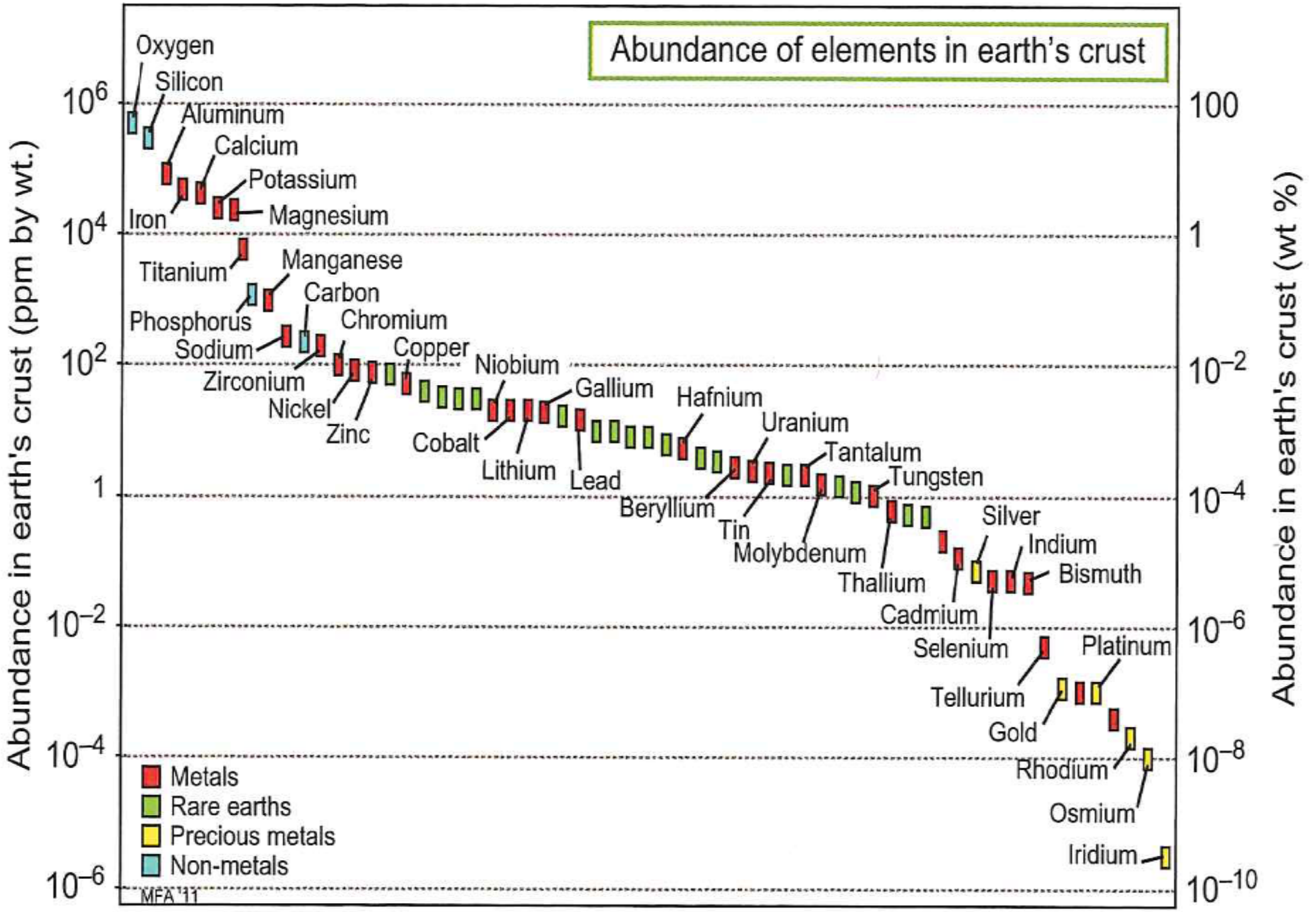
Figure 13.3 Sankey diagram for the flow of aluminum through the economy (Cullen, Allwood et al. 2010).



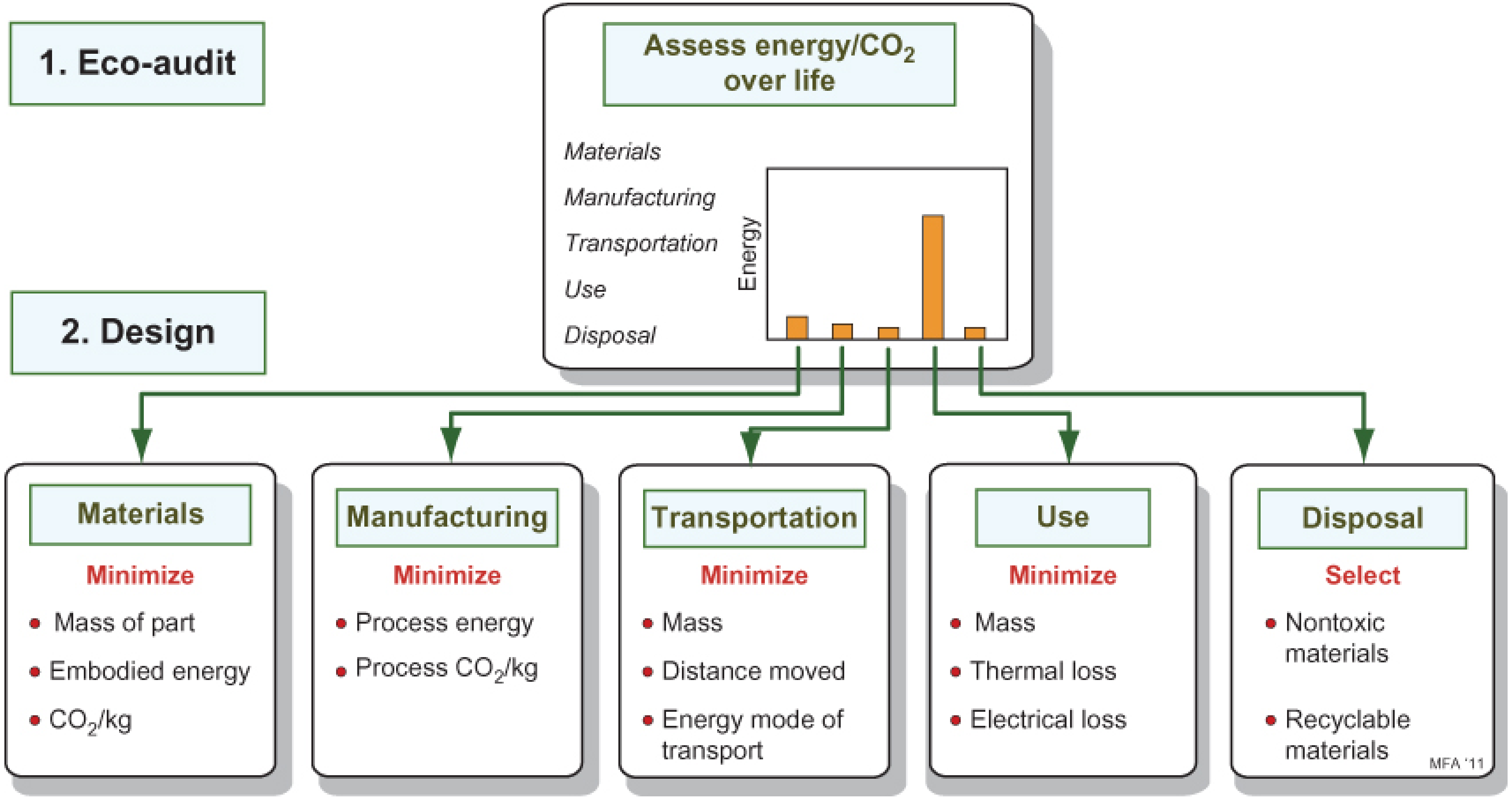
Date
Molecular Age
(1980–present) Nano materials
2000 AD
Biopol biopolymers (1990)
PEEK, PES, PPS (1983)
LLDPE (1980)
(1985) "Warm" superconductors
Polymers Age
1980 AD
Polysulfone, PPO (1965)
Polyimides (1962)
(1962) Carbon fibers, CFRP
Acetal, POM, PC (1958)
(1961) Shape memory alloys
PP (1957)
1960 AD
HDPE (1953)
(1957) Amorphous metals
PS (1950)
(1947) Transistor-grade silicon
Lycra (1949)
(1947) Super alloys
(1909–1961) Actinides*
Formica (1945)
1940 AD
(1942) GFRP
PTFE (Teflon) (1943)
(1940) Plutonium*
PU, PET (1941)
(1828–1943) Lanthanides*
PMMA, PVC (1933)
1920 AD
Neoprene (1931)
(1912) Stainless steel
Steel Age
Synthetic rubber (1922)
(1890) Aluminum production
Bakelite (1909)
(1880) Glass fiber
1900 AD
Alumina ceramic (1890)
(1856) Bessemer steel
Celllose acetate (1872)
(1823) Silicon*
Ebonite (1851)
(1808) Magnesium*, Aluminum*
1850 AD
Reinforced concrete (1849)
(1791) Strontium*, Titanium*
Vulcanized rubber (1844)
(1789) Uranium*
Cellulose nitrate (1835)
(1783) Tungsten*, Zirconium*
1800 AD
(1765) Crucible steel
(1751) Nickel*
(1746) Zinc*
Rubber (1550)
1500 AD
(1737) Cobalt*
(1735) Platinum*
(1500) Iron smelting
1000 AD
Gutta percha (800)
Iron Age
500 AD
Tortoiseshell (400)
Paper (105)
Horn (50 BC)
0 BC / AD
Amber (80 BC)
(1400 BC) Iron
Lacquer (1000 BC)
Papyrus (3000 BC)
1000 BC
(3500 BC) Bronze
Bronze Age
Glass (5000 BC)
(3500 BC) Tin
Cement (5000 BC)
(4000 BC) Silver
Copper Age
Pottery (6000 BC)
10,000 BC
(5000 BC) Smelted copper
(7000 BC) Native copper
Wood (prehistory)
(20,000 BC?) Gold
Stone Age
Stone, flint (prehistory)
100,000 BC
MFA '11



0%
Dependence on nonrenewable materials
100%
Date
Silicon-based communication controls all commerce and life.
2000 AD
Near-total (96%) dependence on nonrenewable materials
Oil-based polymers displace natural fibers, pottery, and wood.
1980 AD
1960 AD
Metals become the dominant materials of engineering.
1940 AD
Aluminum displaces wood in light-weight design.
1920 AD
Concrete displaces wood in large structures.
1900 AD
1850 AD
Cast iron, steel displace wood and stone in structures.
1800 AD
Start of the Industrial Revolution
1500 AD
The "Dark Ages"— little material development
1000 AD
500 AD
Wrought iron displaces bronze.
0 BC / AD
Copper, bronze displace bone and stone tools.
1000 BC
10,000 BC
Total dependence on renewable materials
100,000 BC
MFA '11
0%
Dependence on nonrenewable materials
100%


Abundance of elements in earth's crust
Abundance in earth's crust (ppm by wt.)
Abundance in earth's crust (wt %)
10^6
10^4
10^2
1
10^-2
10^-4
10^-6
100
1
10^-2
10^-4
10^-6
10^-8
10^-10
Oxygen
Silicon
Aluminum
Calcium
Potassium
Iron
Magnesium
Titanium
Manganese
Carbon
Phosphorus
Chromium
Sodium
Copper
Zirconium
Niobium
Nickel
Gallium
Zinc
Hafnium
Cobalt
Uranium
Lithium
Lead
Tantalum
Tungsten
Beryllium
Tin
Molybdenum
Silver
Indium
Thallium
Bismuth
Cadmium
Selenium
Platinum
Tellurium
Gold
Rhodium
Osmium
Iridium
Metals
Rare earths
Precious metals
Non-metals
MFA '11

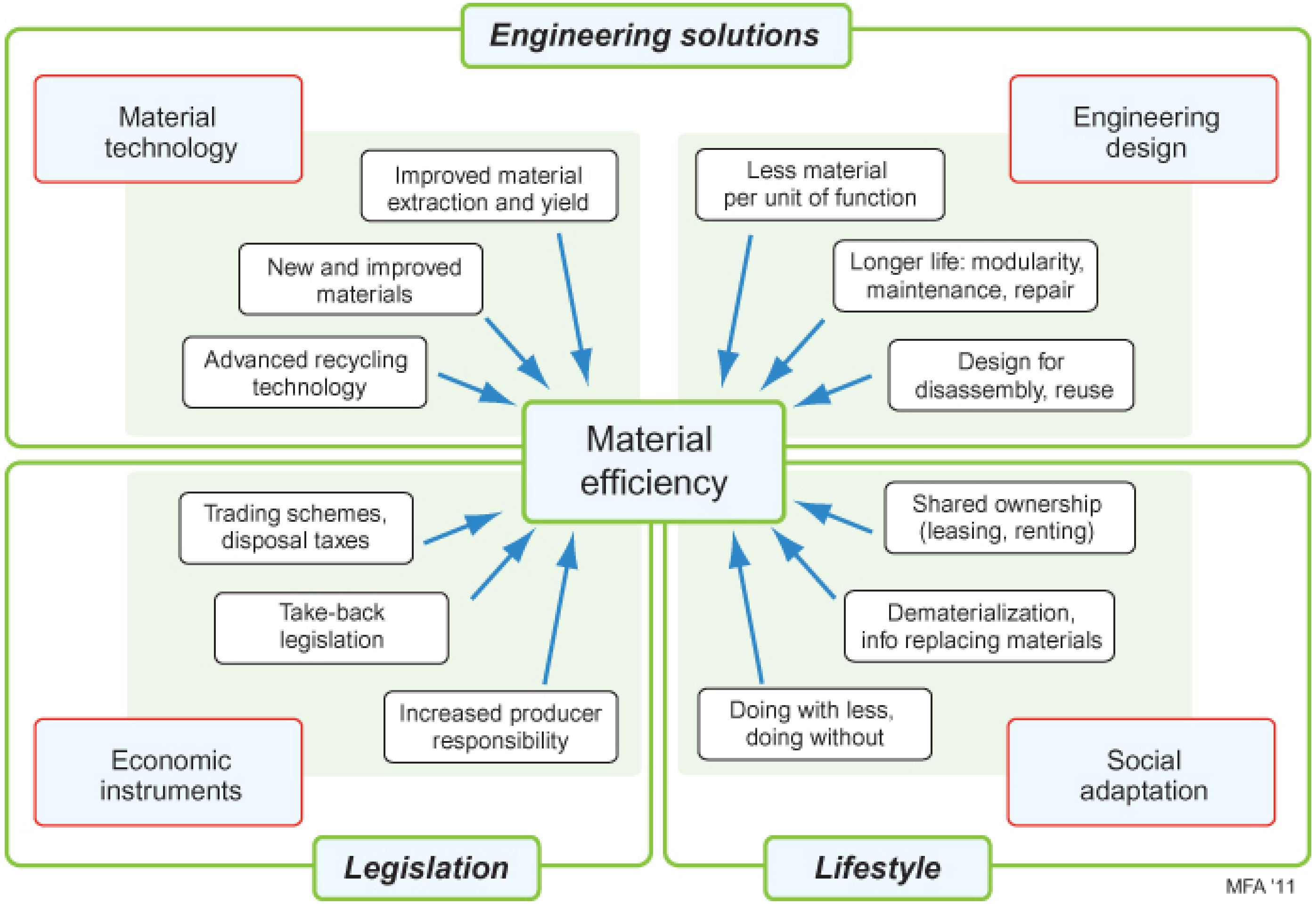
Sustainability in Complex Products



Material selection that only looks at materials & manufacturing is potentially leaving sustainability gains unrealized especially if current or future design requires a specific material (i.e. stainless steel)

Measures contributing to material efficiency.

- As engineers and designers we have strongest influence in upper right corner
- other quads are some of the pressures that impact how we approach material selection
  - Suppliers
  - Customers
  - Government



The 1.7 kilogram microchip: energy and material use in the production of semiconductor devices.

- **E. Williams, R. Ayres, M. Heller**

- **Published in Environmental Science and Technology 25 October 2002**
- **Engineering, Environmental Science**

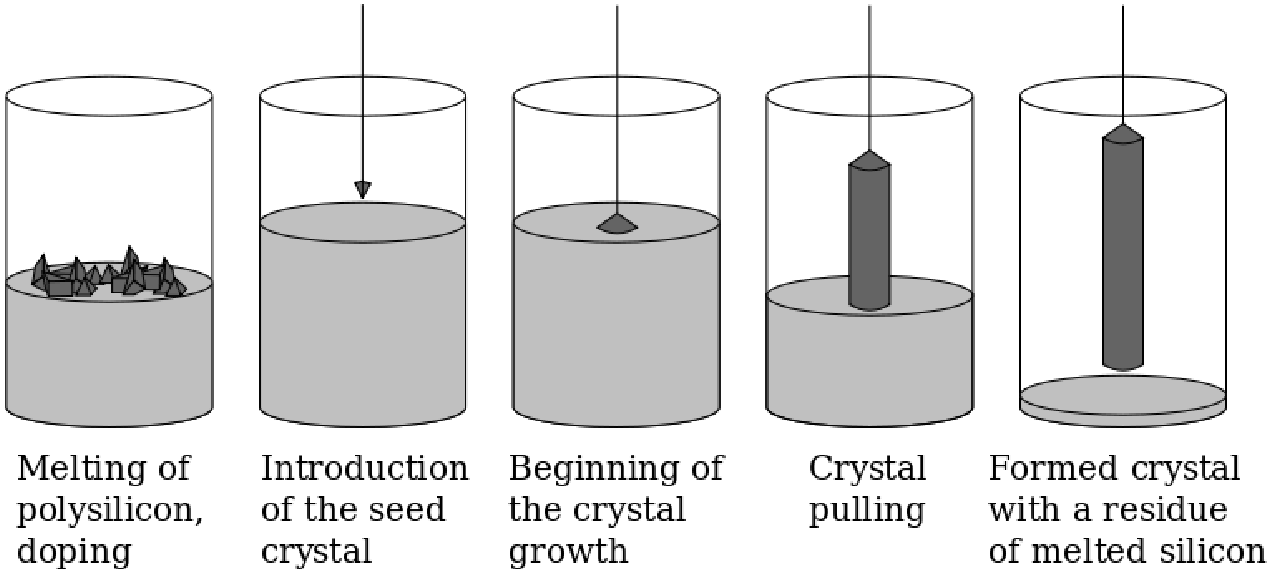
Electronics use a massive amount of material to make a very small but powerful device.

Compare to pharmaceuticals – small, precise, expensive! (and lots of waste!)

TABLE 3. Energy Use in Stages of Production of Silicon Wafers

stage	electrical energy input/kg silicon out	silicon yield (%)	data sources
quartz + carbon → silicon	13 kWh	90	(*29–31*)
silicon → trichlorosilane	50 kWh	90	(*32, 33*)
trichlorosilane → polysilicon	250 kWh	42	(*32–34*)
polysilicon → single crystal ingot	250 kWh	50	(*32*)
single-crystal ingot → silicon wafer	240 kWh	56	(*32, 35*)
process chain to produce wafer	2130 kWh	9.5	

Using a seed crystal and with very close temperature control, it is possible to pull from the melt.



a large cylindrical single crystal of silicon, of diameter in excess of 12.5 cm and

1-2m in length are routinely grown in this manner.

- Then the large single crystal is sliced up into wafers which are as thin as possible

(Silicon solar cells need only be 300μm or so thick to absorb most of the appropriate wavelength in sunlight)

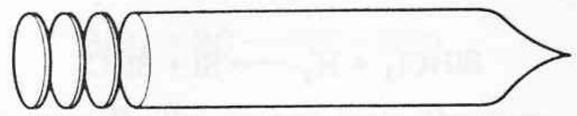
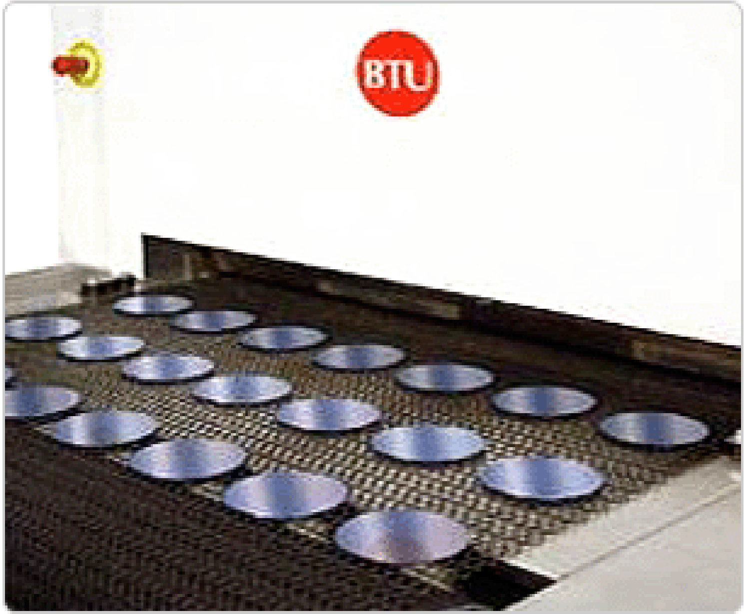
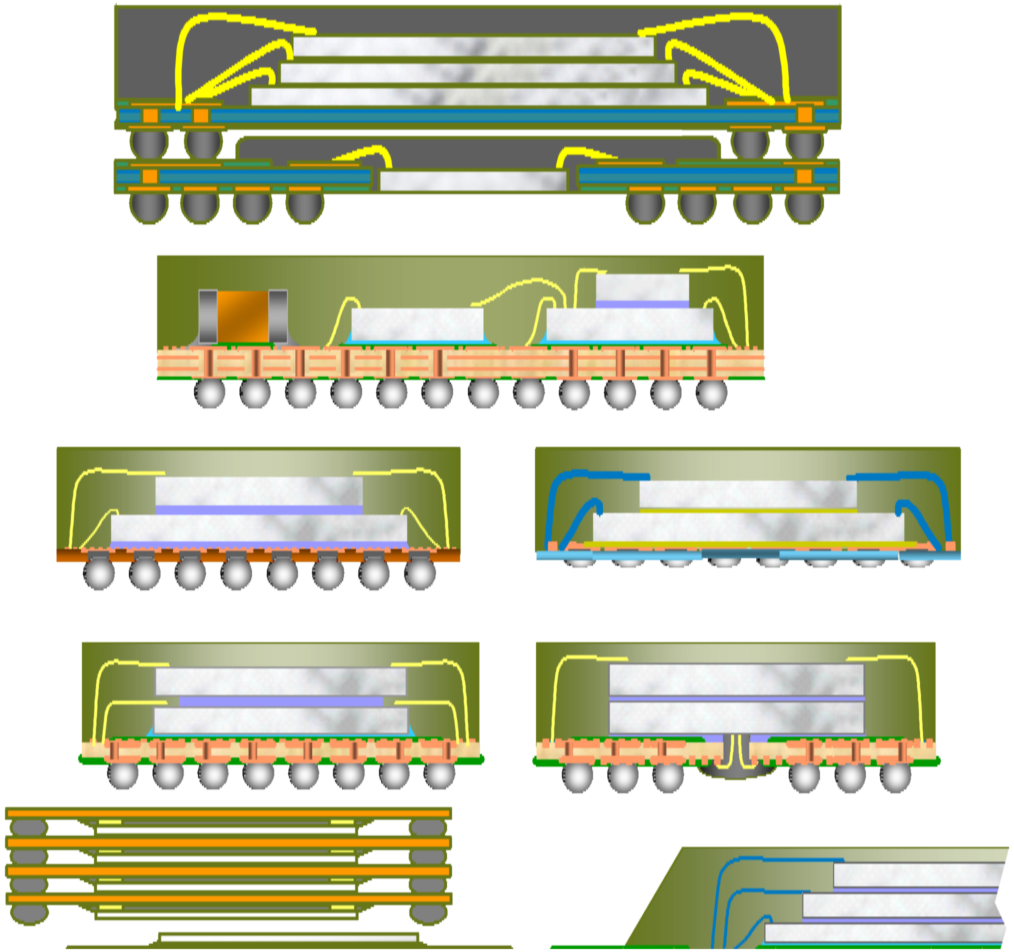


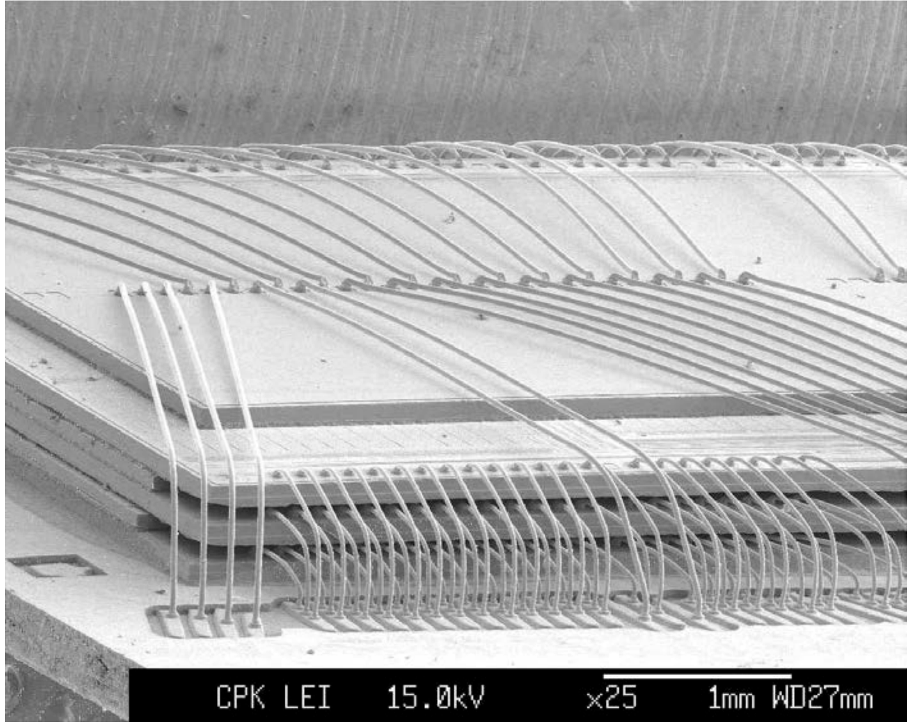
Figure 6.3. Slicing of thin wafers from a cylindrical ingot. The techniques used for this slicing process are described and compared in Ref. 6.3. About half the ingot is wasted as kerf or cutting loss in this process.

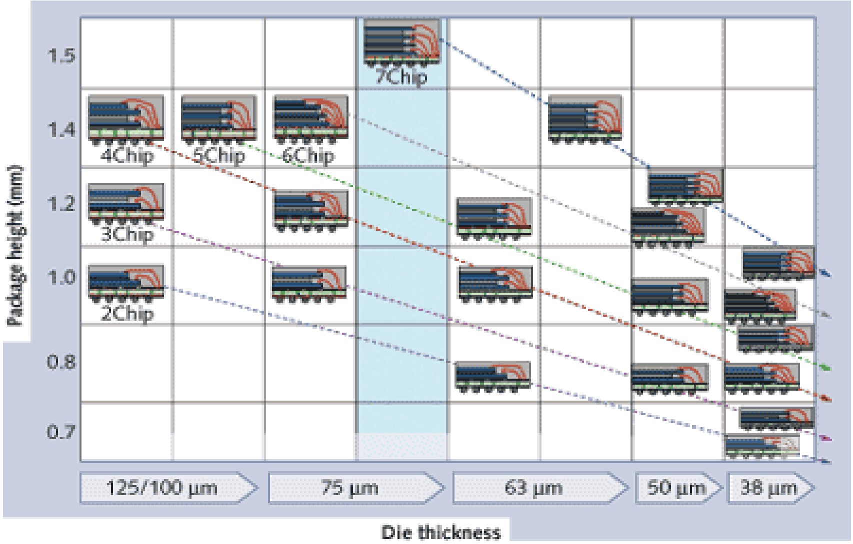


Stacked Chips

Smaller & thinner with greater functionality



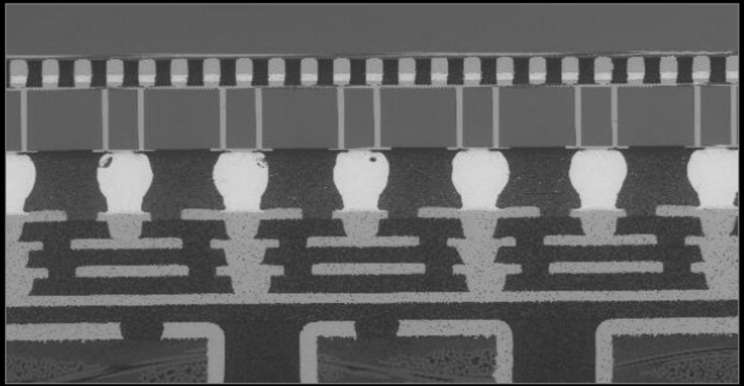


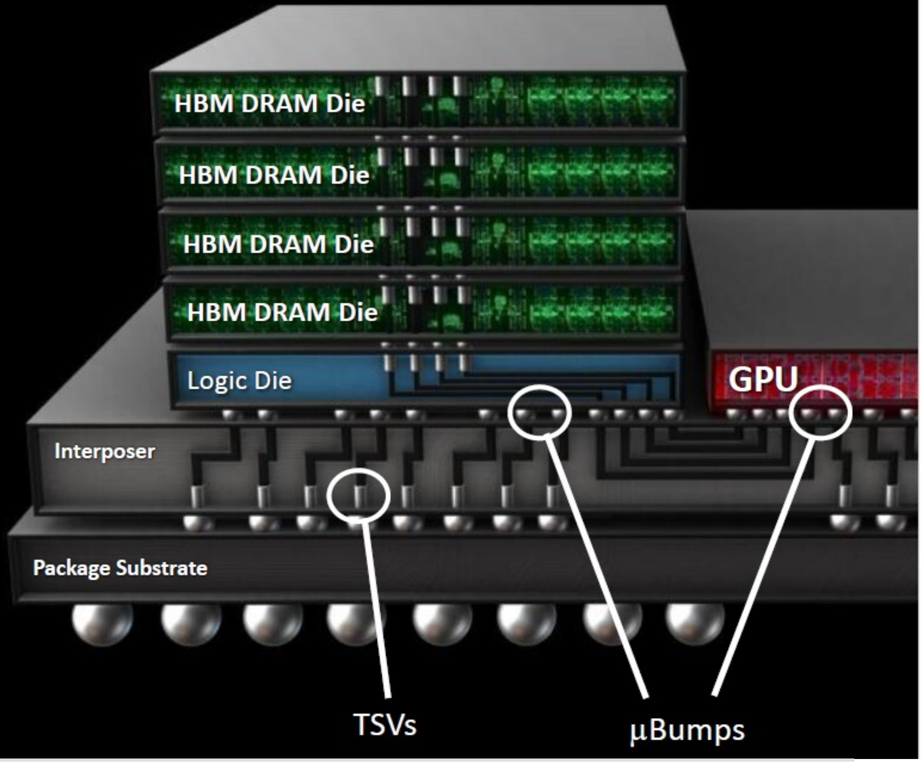


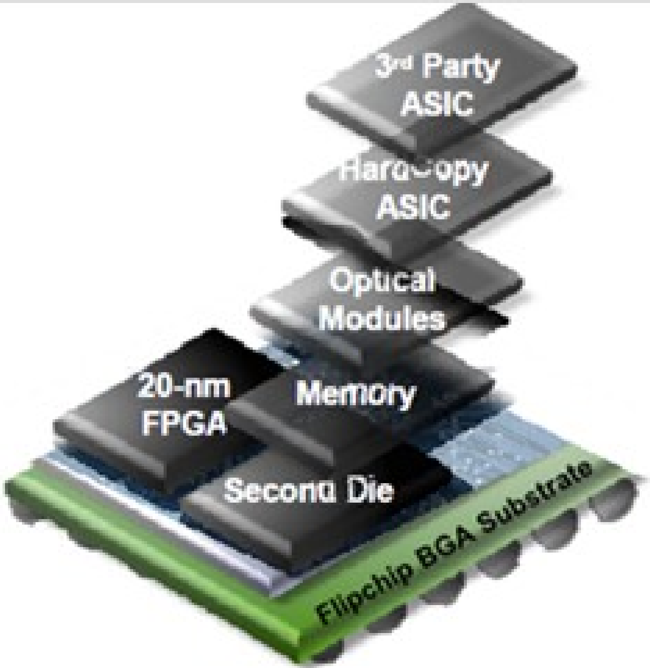
http://ap.pennnet.com/Articles/Article_Display.cfm?Section=Archives&Subsection=Display&ARTICLE_ID=209839

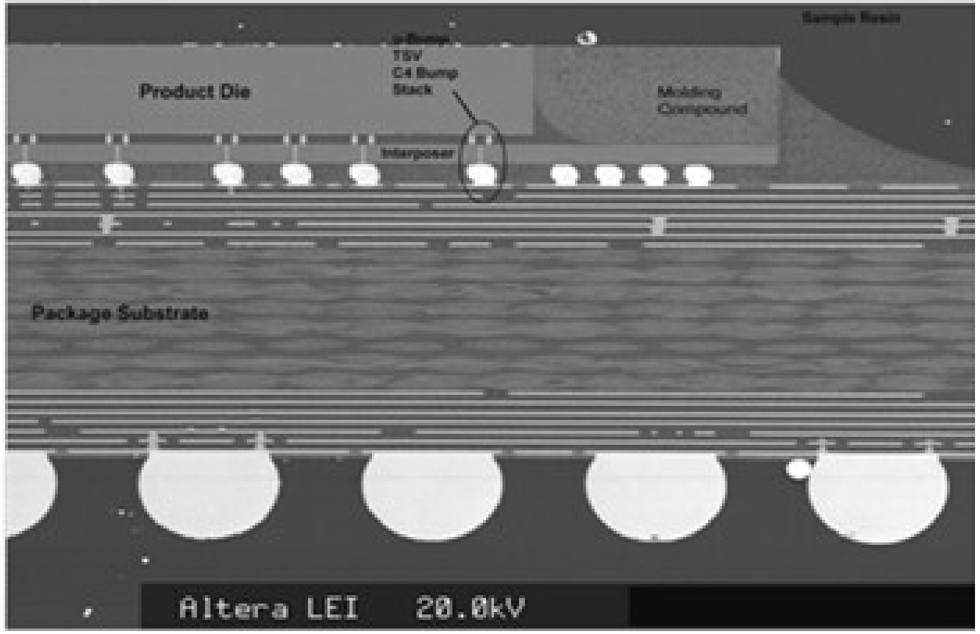
DIE STACKING TECHNOLOGY

- Die stacking facilitates the integration of discrete dies
- 8.5 years of development by AMD and its technology partners

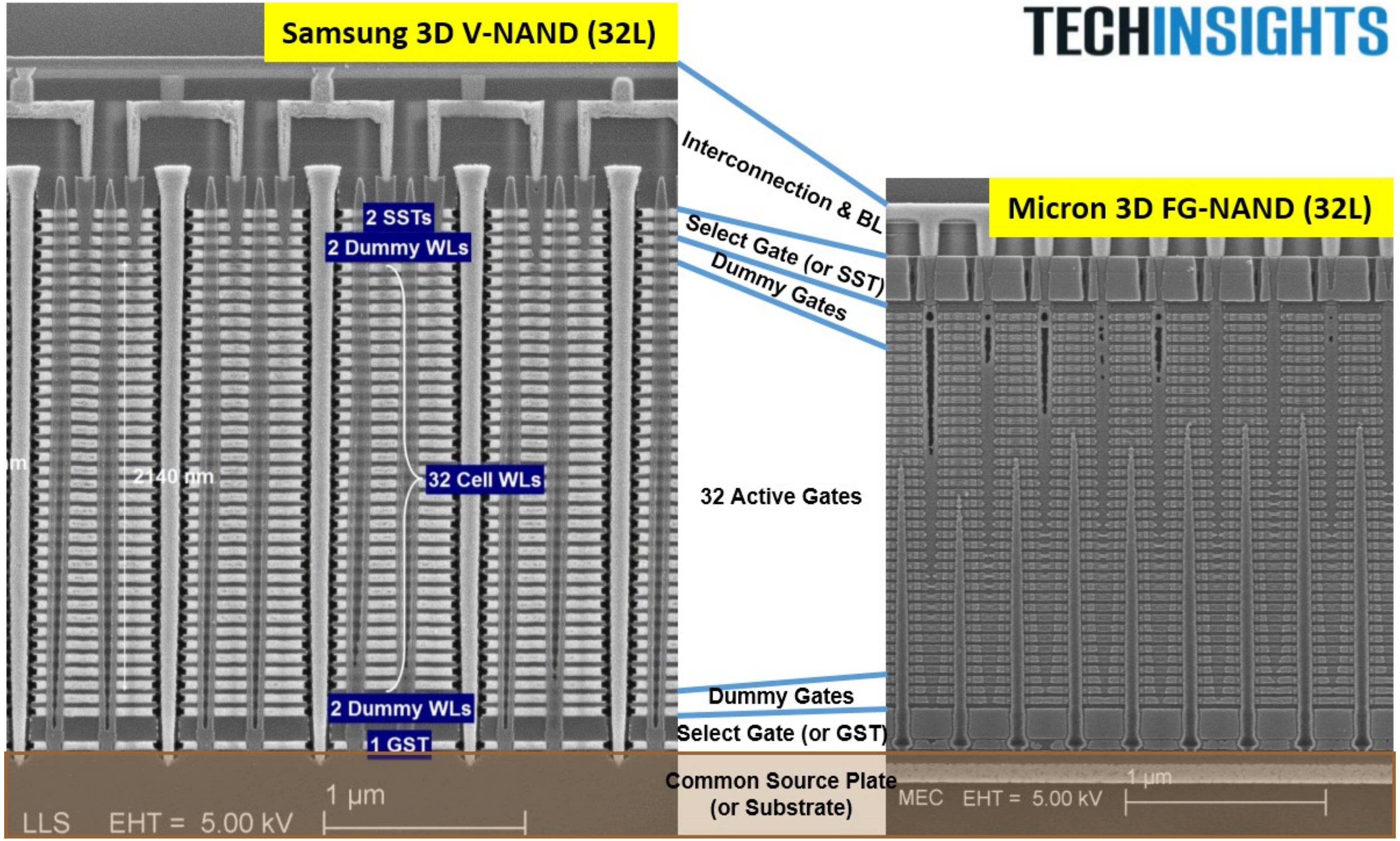








NAND gate (**negative-AND**) is a logic gate which produces an output which is false only if all its inputs are true; thus its output is complement to that of the AND gate



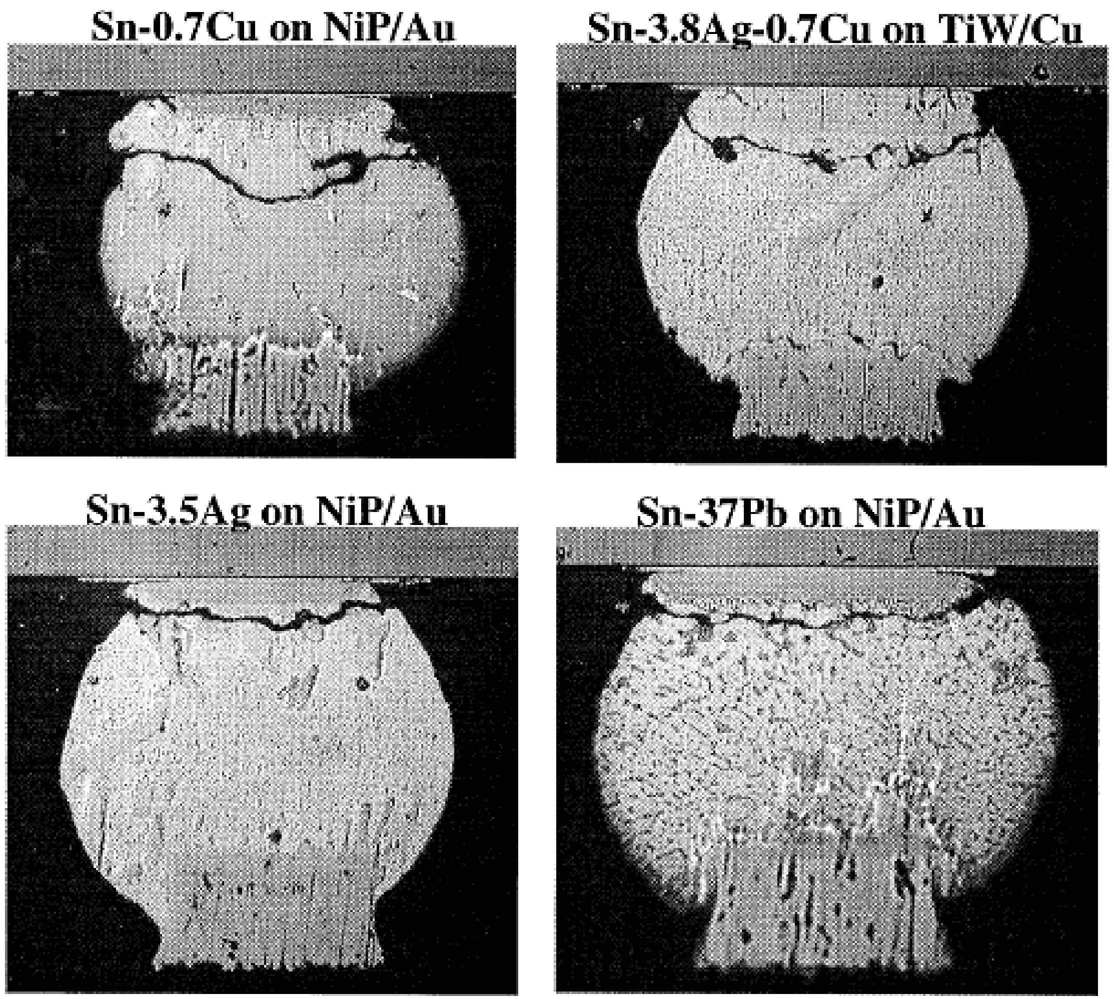


Fig. 15. Thermal fatigue failure modes of four solder/UBM systems.

Characterization of Lead-Free Solders and Under Bump Metallurgies for Flip-Chip Package

Jong-Kai Lin, *Member, IEEE*, Ananda De Silva, Darrel Frear, Yifan Guo, Scott Hayes, Jin-Wook Jang, Li Li, *Member, IEEE*, Dianne Mitchell, Betty Yeung, *Member, IEEE*, and Charles Zhang

Composition of E-waste

Table 1
Representative material compositions of printed circuit boards (wt%).

Materials	%[a]	%[f]	%[g]
Metals (Max. 40%)[a]			
Cu	20	17.85	23.47
Al	2	4.78	1.33
Pb	2	4.19	0.99
Zn	1	2.17	1.51
Ni	2	1.63	2.35
Fe	8	2.0	1.22
Sn	4	5.28	1.54
Sb	0.4	–	–
Au/ppm	1000	350	570
Pt/ppm	–	4.6	30
Ag/ppm	2000	1300	3301
Pd/ppm	50	250	294
Ceramic (Max 30%)[a]			
SiO_2	15		
Al_2O_3	6		
Alkaline and Alkaline earth oxides	6		
Titanates, Mica, etc.	3		
Plastics (Max 30%)[a]			
Polyethylene	9.9		
Polypropylene	4.8		
Polyesters	4.8		
Epoxies	4.8		
Polyvinyl-chloride	2.4		
Polytetra-flouroethane	2.4		
Nylon	0.9		

[a] Shuey et al. (2006) from Sum (1991).
[f] Kogan (2006).
[g] ICP–OES Analyses of cellphone printed circuit boards with hot aqua regia digestion.
* Incinerated printed circuit boards Product.

Be careful on weight based comparison!

I.O. Ogunniyi , M.K.G. Vermaak, D.R. Groot; "Chemical composition and liberation characterization of printed circuit board comminution fines for beneficiation investigations." Waste Management 2009

Urban mining “deposits”
can be much richer than primary mining ores

- **Primary mining**
  - ~5 g/t Au in ore
  - Similar for PGMs

- **Urban mining**
  - 200-250 g/t Au in PC circuit boards
  - 300-350 g/t Au in cell phones
  - 2000 g/t PGM in automotive catalysts

Example gold – principle is valid for many technology metals

Christian Hagelüken, Mark Caffarey, “Opportunities and Limits to Recycle Critical Metals for Clean Energies”- Umicore; Trans-Atlantic Workshop on Rare Earth Elements and Other Critical Materials for a Clean Energy Future, MIT Boston, (2010)

Brominated and Chlorinated Flame Retardants in Tree Bark from Around the Globe

Amina Salamova and Ronald A. Hites*

School of Public and Environmental Affairs, Indiana University, Bloomington, Indiana 47405, United States

Supporting Information

ABSTRACT: Brominated and chlorinated flame retardants were measured in about 40 samples of tree bark from 12 locations around the globe. The analytes were polybrominated diphenyl ethers (PBDE), Dechlorane Plus (DP), decabromodiphenylethane (DBDPE), hexabromocyclododecane (HBCD), hexabromobenzene (HBB), pentabromoethylbenzene (PBEB), pentabromobenzene (PBBz), and tetrabromo-*p*-xylene (pTBX). The highest concentrations of these compounds were detected at an urban site in Downsview, Ontario, Canada. Total PBDE and DP concentrations ranged from 2.1 to 190 ng/g lipid weight and from 0.89 to 48 ng/g lipid weight, respectively. Relatively high levels of DP (46 ± 4 ng/g lipid weight) were found at a remote site at Bukit Kototabang in Indonesia. The concentrations of total PBDE, DP, PBEB, and HBCD in the tree bark samples were significantly associated with human population in the nearby areas ($r^2 = 0.21-0.56$; $P < 0.05$). In addition, the concentrations of total PBDE and DP were significantly associated ($r^2 = 0.40-0.64$; $P < 0.05$). with the corresponding atmospheric concentrations of these compounds over a concentration range of 2–3 orders of magnitude.

Environmental Science and Technology, 2013

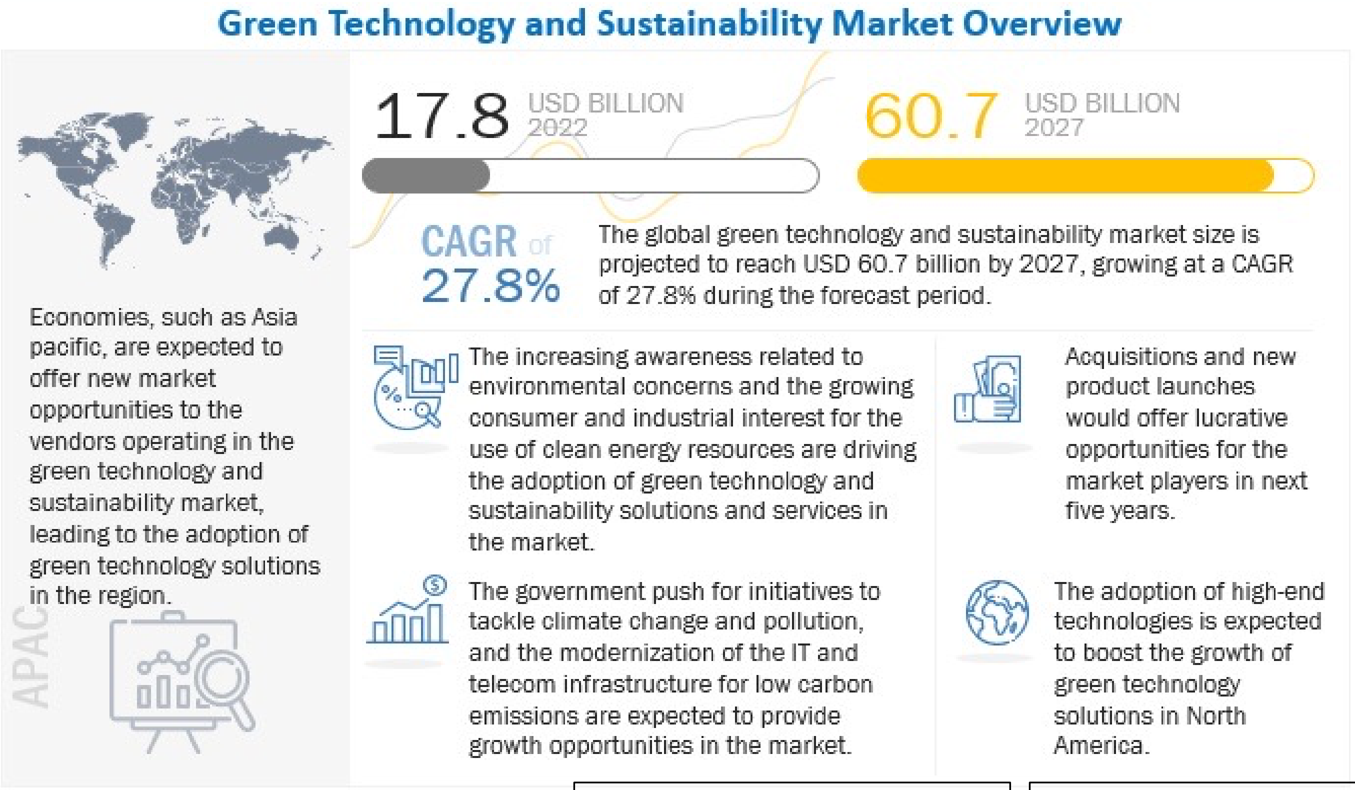
Currently ID’d Research Areas

- Short term Focus
  - 1) PFAS replacements in lithography materials and process metrology
  - 2) GHG replacements in etch, chamber cleans and deposition.
  - 3) impacts on legacy operations – both Facility level and unit process
  - 4) Indexing / benchmarking of sustainability metrics and gains
    - Partnership with SEMI (with their industry partners)

Core Questions for Big Sustainability Challenges

- Replacement and elimination of PFAS and similar halogenated compounds
- Transitions to low solvent or green solvent processes (photoresist, and wet process chemicals)
- Metrology of emissions both of wet chemicals and gas emissions
- Design improvements on emission control technology
- Recycling wet chemicals and developing closed loop processes (including water)
- Product stewardship, remanufacturing
- Reliability assessment across product life cycle
- Environmental Assessment of process improvements leading to sector based sustainability roadmap
- Quantifying Scope 1 & Scope 2 emissions
- Instrumented processes (metrology) for inline process control / diagnostics
    - Big opportunity for smart / connected data (cf. Strachan comments, chipsHUB_

Research Needs: Sustainability Engineering



Mobility/transportation

Materials Processing

Application Areas

ration & distribution systems

Pharmaceuticals

Extra Slides. EPA maps

- EPA Envronmental Justice Mapping and Screening tool
- https://www.epa.gov/ejscreen

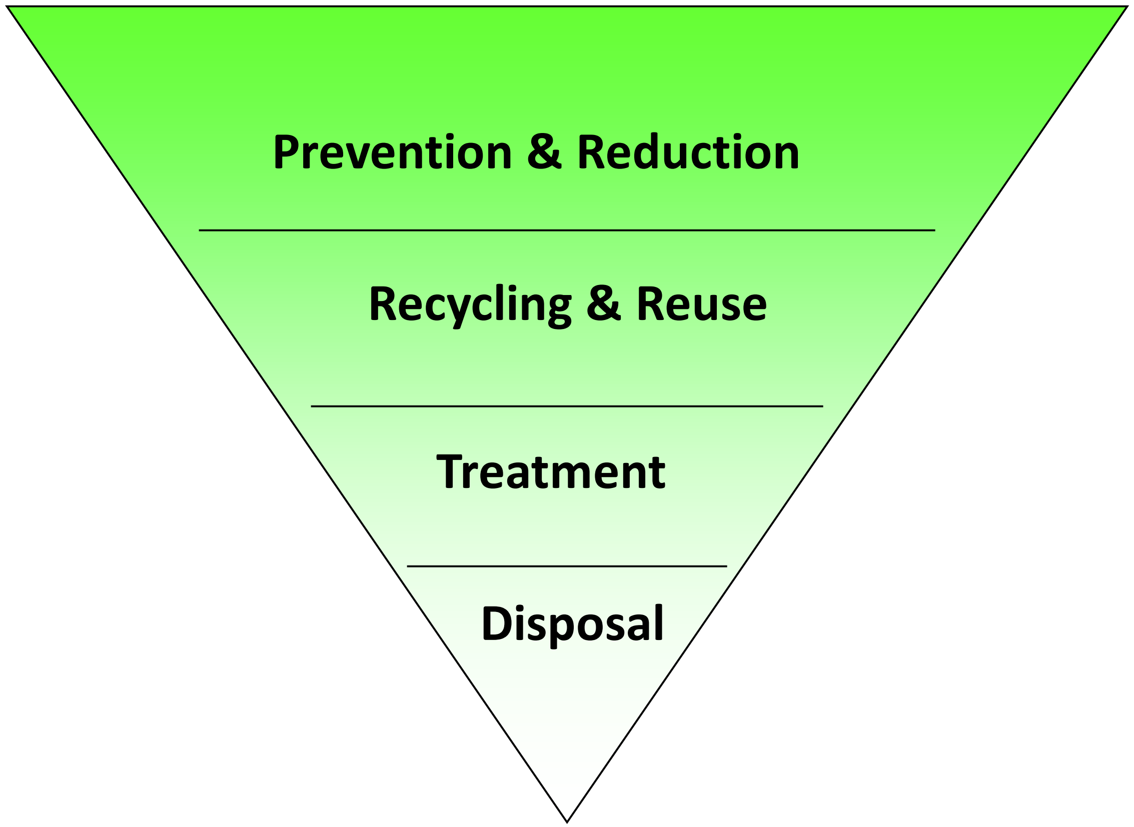
- EPA Superfund Map
- https://www.epa.gov/superfund/search-superfund-sites-where-you-live
- best to search this one by state or county not zip code.

The Old Attitude:

"By sensible definition any by-product of a chemical operation for which there is no profitable use is a waste. The most convenient, least expensive way of disposing of said waste—up the chimney or down the river—is best."

From *American Chemical Industry—A History*, W. Haynes Van Nostrand Publishers, 1954

Simple modern waste treatment hierarchy:



Economic Considerations For End of Life

- What is the value / cost of the waste?
  - Zero (worthless) --- news paper , copier paper
  - Negative – I have to pay for disposal (i.e. freon in old fridge)
  - Positive – aluminum cans

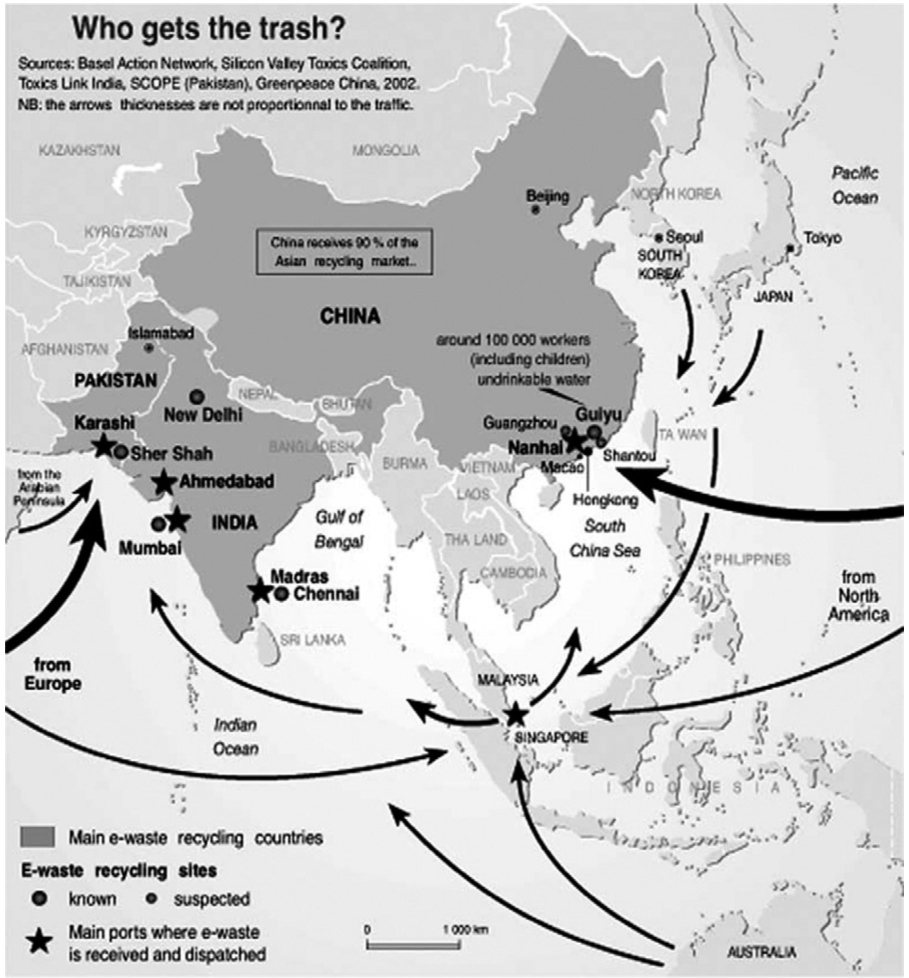
- What is the most valuable (unrecovered) waste that you generate?

- When / why do we pay a premium dispose of something ?

Industrial / Policy Interventions

Taxes, legislation other market interventions.

Can brainstorm with class here



Extended Producer Responsibility

- **"..environmental objective of a decreased total environmental impact of a product, by making the manufacturer of the product responsible for the entire life-cycle of the product and especially for the take-back, recycling and final disposal"**
- End of life strategies such as:
  - Implementing take back and recycling programs for products
  - Setting up collection points and recycling pickups for products
  - Designing new products that are easier to reuse, repair, and recycle
- Underpinning EPR is the idea that manufacturers are better placed to design less wasteful, harmful, and toxic products before they, in fact, become "waste". EPR attempts to move the burden of waste management away from consumers and government and back into the hands of manufacturers.

Benefits with EPR

- Stronger customer relationship
- Lower cost of goods sold due to secondary material supply
- Alternative supply of critical raw minerals
- Mitigated risks associated with hazardous materials handling
- Reduced environmental impacts

Indiana Electronics EPR

- Indiana became the first state to pass a major electronics recycling law in 2009 as Governor Mitch Daniels signed HB 1589 into law yesterday, making Indiana the nineteenth state to pass a law creating a statewide e-waste recycling program. Eighteen of these 19 states, including Indiana, have adopted “producer takeback” laws, requiring the manufacturers to pay for the collection and recycling of old products.

http://www.electronicstakeback.com/2009/05/14/indiana-passes-producer-takeback-e-waste-recycling-law/

Indiana Electronics EPR

- The Indiana law is similar to the law passed in 2007 by Minnesota, and requires manufacturers of video display devices (TVs, monitors, and laptops) to collect and recycle 60% by weight of the volume of products they sold in the previous year in Indiana. After the first two years, manufacturers who fail to meet those goals will pay an additional recycling fee for every pound they fall short of their goal. While the goals are based on sales of video display devices, the program allows consumers, public schools and small businesses to recycle a larger group of products for free, including TVs, computers, laptops, keyboards, printers, fax machines, DVD players, video cassette recorders. The program begins collection in April 2010.

Brief Case Studies

- Indiana Zinc Recycling

https://www.hecweb.org/issues/environmental-health-justice/toxic-ex
reduction/proposed-logansport-waelz-plant/

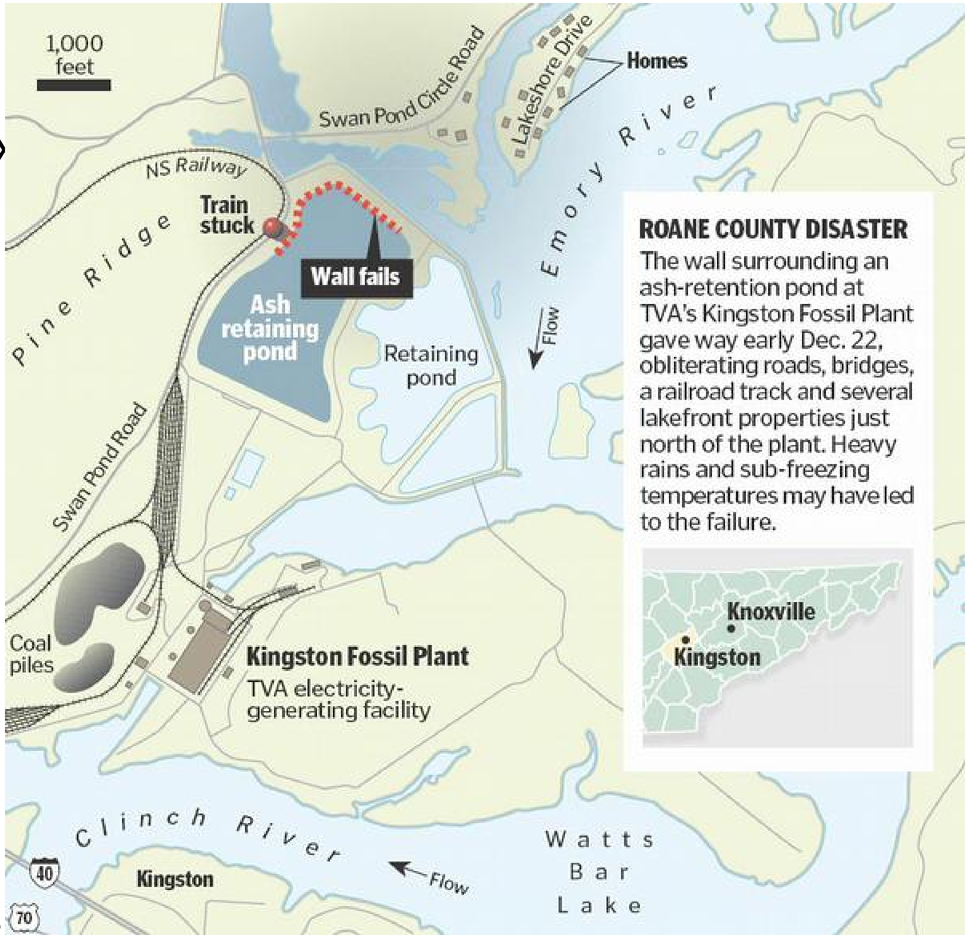
- Coal Ash storage & use.

On December 22, 2008, there was a catastrophic collapse of the dyke around an ash retention pond at the TVA coal-powered electricity generating facility at Kingston, Tennessee

See 60 minutes report on the outcomes:

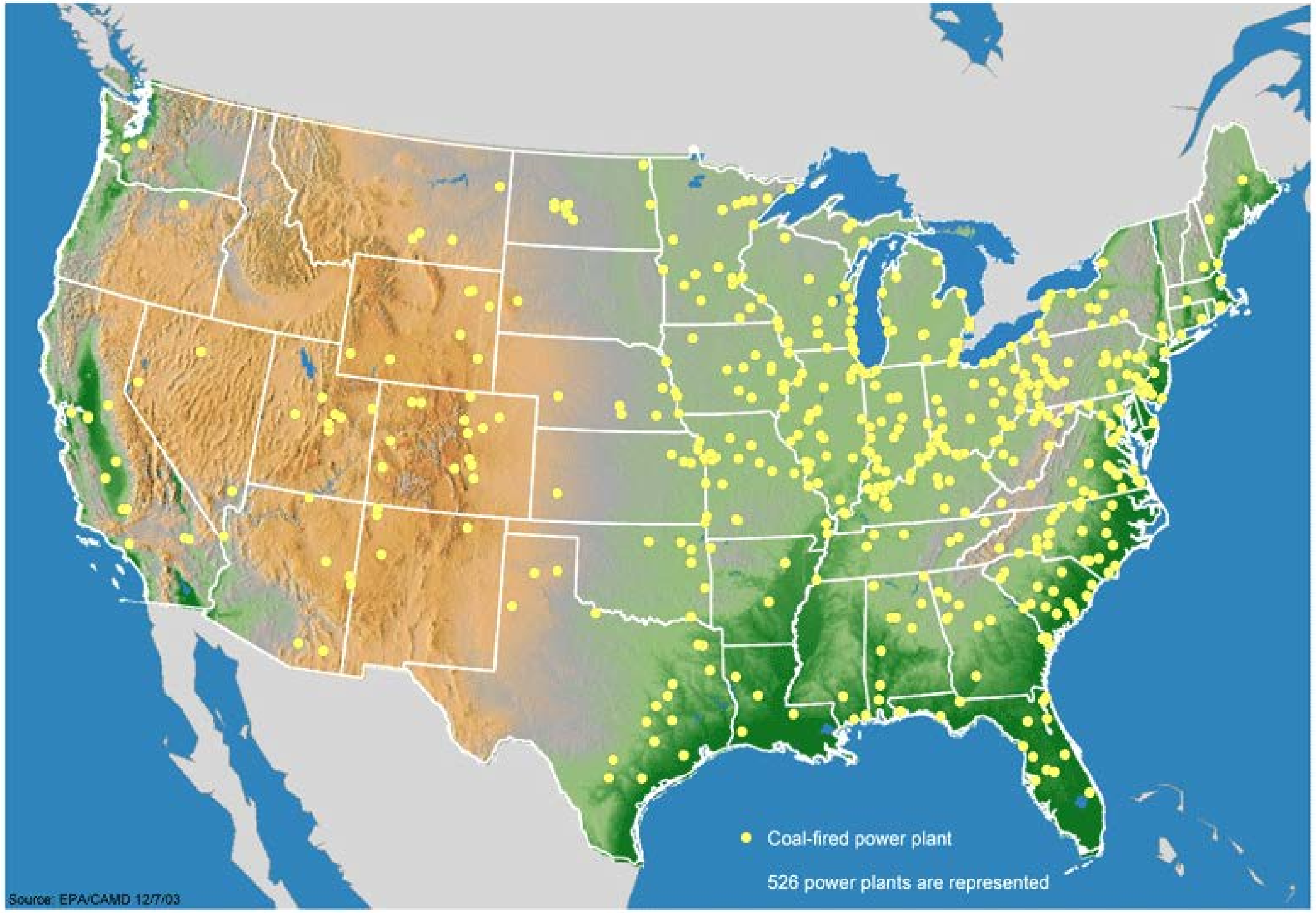
Coal Ash: 130 Million Tons of Waste

https://www.youtube.com/watch?v=1PYexB76KIQ



*** Note from John Howarter- coal ash is everywhere and this story is
Tennessee (and big catastrophe) but we burn a lot of coal in Indiana.

Coal-Fired Power Plants Are the Dominant Source of Air Emissions



U.S. Coal-Fired Power Plants

- There are about 530 power plants with 305 GW of capacity that consists of about 1,300 units.
- Coal plants generate the vast majority of power sector emissions:
  - 95% SO_2
  - 90% of NO_x
  - 83% of CO_2

Brian McLean, Experience with Acid Rain and NOx Cap and Trade Programs, 2007

Industrial Ecology – Indiana Zinc

WAELZ SUSTAINABLE PRODUCTS (WSP) HAS PROPOSED A NEW PLANT IN LOGANSPORT, INDIANA, THAT WILL PROCESS WASTE FROM STEEL MILLS TO MAKE ZINC AND IRON PRODUCTS.

Good News! Friday, August 21, 2020, the Cass County Council voted not to approve tax incentives for the WSP plant, but to send them back to the Redevelopment Commission for renegotiation. This is an opportunity for Cass County Citizens Coalition to negotiate for lower air emissions and better air monitoring.

The Waelz process, first invented in 1888, involves mixing electric arc furnace dust with a carbon source, like coal or petroleum coke, and heating it in kilns to between 1000° and 1500° Celsius. Zinc oxide is captured out of the fumes and referred to as Waelz zinc oxide or WZO. The residual solid material is high in iron and can be sold as Waelz iron product or WIP[1].

In Logansport, WSP is proposing to build a facility with two Waelz kilns on the property at 3440 W 300 S, Logansport, IN 46947, about 3 miles from downtown Logansport [2]. There is strong opposition in Cass County including from the Cass County Citizens Coalition.

https://www.hecweb.org/issues/environmental-health-justice/toxic-exposure-reduction/proposed-logansport-waelz-plant/

Industrial Ecology – Indiana Zinc – Emissions!

WSP's air permit application includes WSP's own estimates of its annual air emissions. They estimate that they will emit 161 tons per year of carbon monoxide, which is as much as 2,254 highway vehicles; and 171 tons per year of fine particulate matter, which is more than the Essroc Cement Corp plant that is already in Cass County. Fine particulate matter air emissions exacerbate respiratory and cardiac diseases.

The greenhouse gases that WSP estimated when it proposed building its plant in Muncie, Indiana, would have been the equivalent of adding more than 90,000 cars to the road.

https://www.hecweb.org/issues/environmental-health-justice/toxic-exposure-reduction/proposed-logansport-waelz-plant/

Industrial Ecology – Indiana Zinc – Emissions!

WSP's air permit application estimates 220 lbs of mercury air emissions per year, but their proposal for Muncie estimated 1500 lbs of mercury per year. The Logansport plant, according to WSP's own air permit application, would not add any pollution controls specific for capturing mercury, so how they got from 1500 lbs down to 220 is a mystery. The permit application asks for a limit of 1000 lbs of lead air emissions per year, and lead is well known to deposit out of air emissions in the first 2 miles. Logansport is directly downwind of the proposed WSP site, with many neighborhoods well within 2 miles. Lead accumulates in soil over time and is toxic to the nervous system, particularly for young children and babies.

https://www.hecweb.org/issues/environmental-health-justice/toxic-exposure-reduction/proposed-logansport-waelz-plant/