The Materials-Sustainability Nexus
(Linking Transformational Materials and Processing for an Energy Efficient and Low-Carbon Economy)

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Sustainability

• Sustainability is not scientifically defined. The basic principles of sustainability were originally proposed in the 1989 report of the UN's Brundtland Commission, and their definition is the most widely accepted: "...[to meet] the needs of the present without compromising the ability of future generations to meet their own needs".

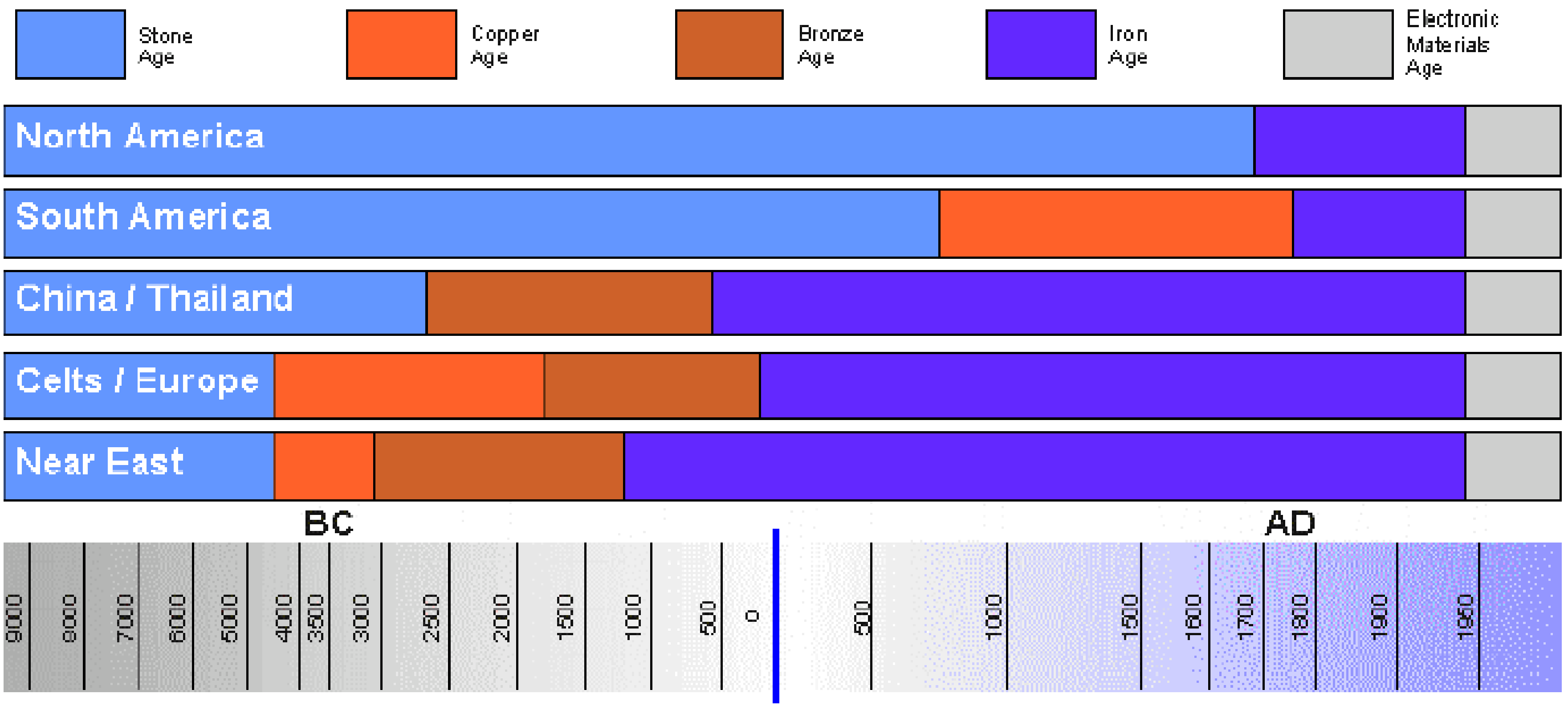
• Sustainability is a process, a new approach to development and environmental stewardship, where thorough scientific analysis would be used to guide decision making to insure continual improvement in three areas: (i) profitability, (ii) society, and (iii) the environment.

• The term "sustainability" is used as a buzzword for a very broad field encompassing such concepts as renewable energy, green manufacturing, environmental stewardship, water management, food availability, etc.

Sustainability

Materials are Technology Enablers

A Timeline of Materials Ages



Adapted with permission from R. E. Hummel, Understanding Materials Science, Springer (1998)

Sustainability and Materials

NEWS FROM MIT'S DEPARTMENT OF MATERIALS SCIENCE AND ENGINEERING

NANO · MICRO · MACRO · MOLECULAR · CRYSTAL · DENDRITE · INTERFACE

structure

SPRING 2009

LETTER FROM THE DEPARTMENT HEAD

Dear friends,

It is again with great pleasure and pride that I write to update you on Course III. First off, let me reassure you that while the financial situation is difficult everywhere, MIT is maintaining a prudent but steady forward course. We are taking a 5% cut in our departmental budget for 2010, with the expectation of an additional 5% reduction in 2011 and 2012. While serious, these cutbacks allow our core educational and research programs to continue. Indeed, the School of Engineering is currently conducting faculty searches. Our expected sophomore class is 46 students; this significant increase over 2008 and 2007 is due in large measure to the extraordinary efforts of our students, staff, and faculty in getting the word out to freshmen that MSE = Matter, Sustainability, and Energy—three aspects of a Course III education that are certainly helping attract students to our major. Other good news is that our graduate program maintained its first in the nation ranking from *US News and World Report*.

As the stimulus package kicks in and federal agencies deploy increased funding to help reverse the financial crisis, Course III faculty are playing large roles in helping MIT address the world's energy and environmental needs. On campus, events increasingly feature senior government leaders in energy and environmental policy. For example, at a recent MIT Energy Initiative colloquium on "Clean Power," Congressman Edward Markey, Chair of the Select Committee on Energy Independence and Global Warming, John Holdren, Assistant to the President for Science and Technology and Director of the Office of Science and Technology Policy, and Carol Browner, Assistant to the President for Energy and Climate Change, extensively cited MIT, in particular faculty and companies associated with Course III, as they outlined how science and technology and our great American research universities can

Promotions:	03
Events:	06
Honors:	12
Outreach:	15

Ned Thomas and bluefin tuna

MSE = Matter, Sustainability and Energy

Sustainability and Materials

- What does sustainability mean to the materials community? Terms that come to mind include, e.g., recycling/reuse/repurposing, materials substitution, renewable energy, clean energy technology, materials and product life cycle analyses (energy, carbon and water footprints)

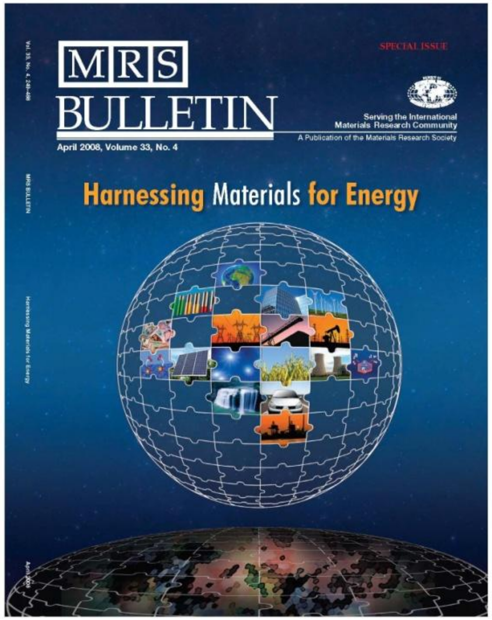
- Of the fourteen grand challenges recently articulated by The National Academy of Engineering, six can be identified where clearer scientific understanding of materials is needed to inform future decisions: 1) make solar energy economical; 2) provide energy from fusion; 3) manage the nitrogen cycle; 4) develop carbon sequestration methods; 5) provide access to clean water; 6) engineer the tools of scientific discovery.

- Policy makers and funders in government and industry are beginning to understand *that the participation of the global materials science and engineering community is absolutely essential to the realization of a sustainable future*.

- It is also clear that the scientific analyses proposed by the Brundtland Commission are *beyond the capabilities of the existing national and international infrastructure of measurements, standards, and data.*

Materials Research Bulletin (MRS)

- Special issue of the Materials Research Society (MRS) Bulletin entitled "Materials for Sustainable Development" (4/12)
- Modeled on "Materials for Energy" issue (4/08)



MRS Bulletin Special Issue

"Materials for Sustainable Development"

- ***Sub-Topic: Fostering More Efficient and Safe Use of Materials***

"Materials Science and Engineering's Pivotal Role for Sustainable Development for the 21st Century", D. Apelian, Worcester Polytechnic Institute, Worcester, MA

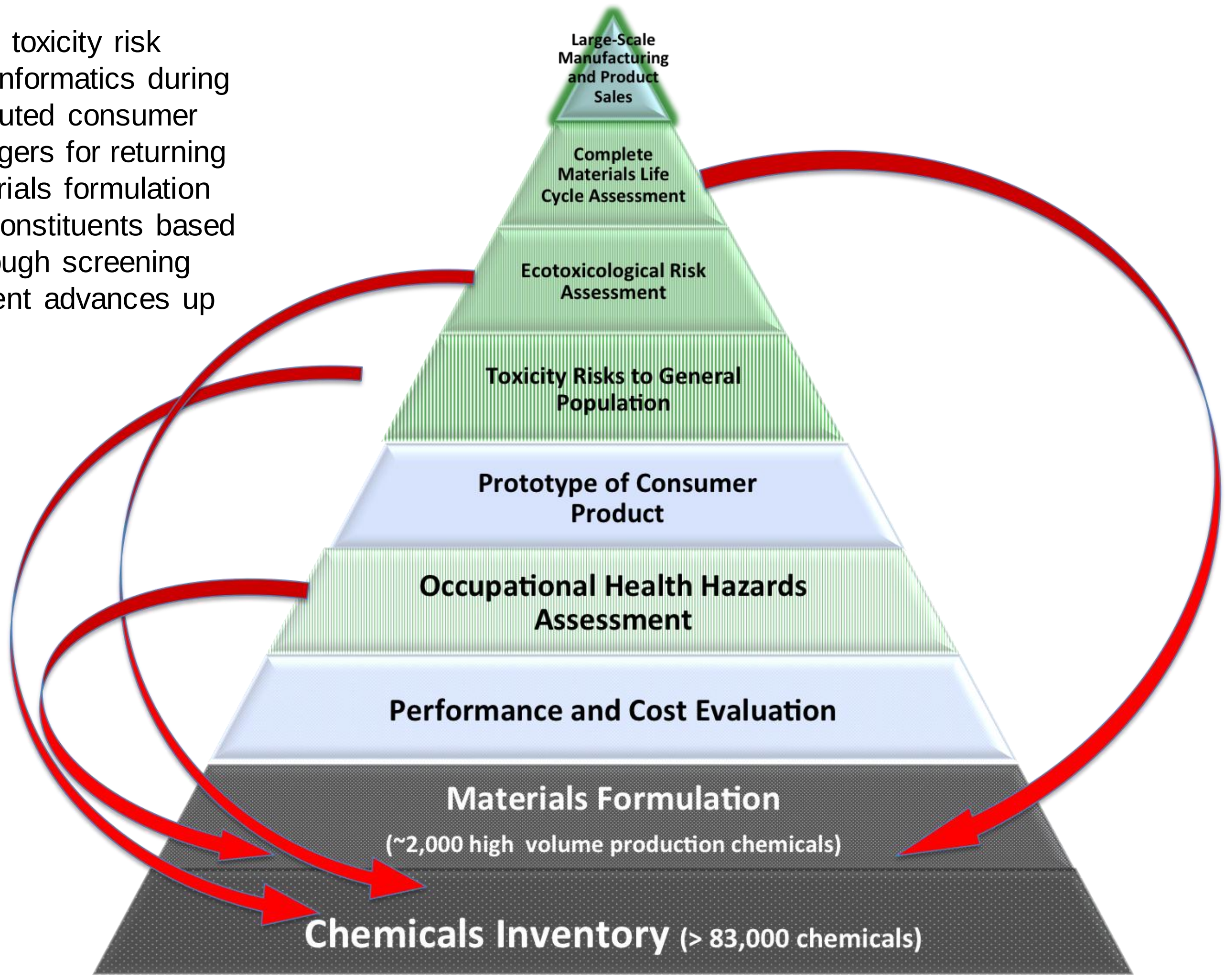
"Human Health and Ecotoxicological Considerations in Materials Selection for Sustainable Product Development", Oladele Ogunseitan (UC Irvine), and Julie Schoenung (UC Davis)

"Sustainable Development and Physical Infrastructure Materials", Chris Hendrickson and Francis C. McMichael, Department of Civil and Environmental Engineering, Carnegie Mellon University.

"The Energy-Water Nexus: Water Use Trends in Sustainable Energy and Opportunities for Materials R&D", Anthony Ku, GE Global Research, Michael Hightower, Sandia National Laboratory (potential co-author)

"Human Health and Ecotoxicological Considerations in Materials Selection for Sustainable Product Development", O. Ogunseitan (UC Irvine) et al

Proposed scheme for integrating toxicity risk assessment data into materials informatics during the manufacture of widely distributed consumer products. Red arrows signify triggers for returning to chemicals inventory and materials formulation to identify less toxic alternative constituents based on cautionary data gathered through screening processes as product development advances up the pyramid.



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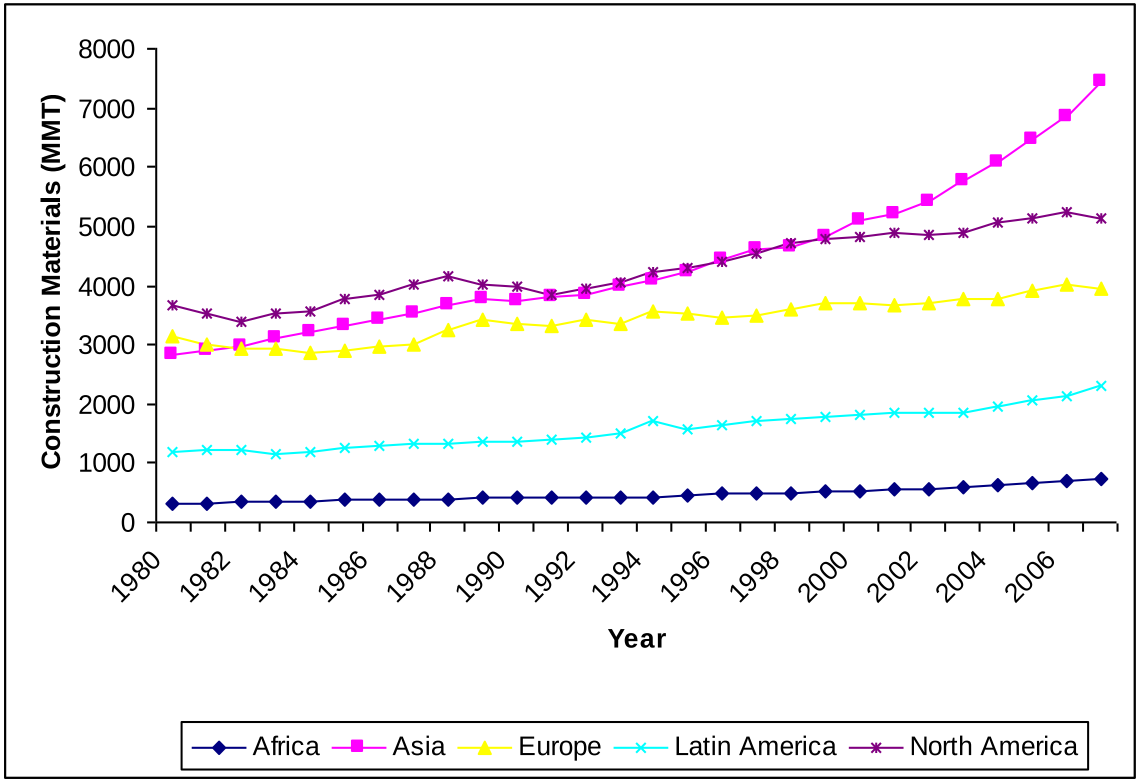
"Sustainable Development and Physical Infrastructure Materials"
C. Hendrickson et al (CMU)

Example: Total Extraction of Construction Minerals for Five Global Regions, Million Metric Tons (MMT), 1980-2007



The magnitudes of total extraction of construction minerals worldwide for the period 1980-2007 (SERI 2011). Construction minerals include asphalt, clay (for bricks), rock (for concrete and structures), limestone, sand, slate and gravel (SERI 2010). Extraction has been increasing over time as worldwide population grows and economies develop with additional infrastructure investments. By 2007, total extraction was 20 Billion tons per year. The increase in Asian extraction is particularly notable, with Asia becoming the largest extracting region of the five tracked in Figure 1 in the year 2000.

MRS Bulletin Special Issue

"Materials for Sustainable Development"

- ***Sub-Topic: Developing Materials for Energy Technology, and for Mitigation of Undesirable Environmental Impacts of Energy Generation and Manufacturing***

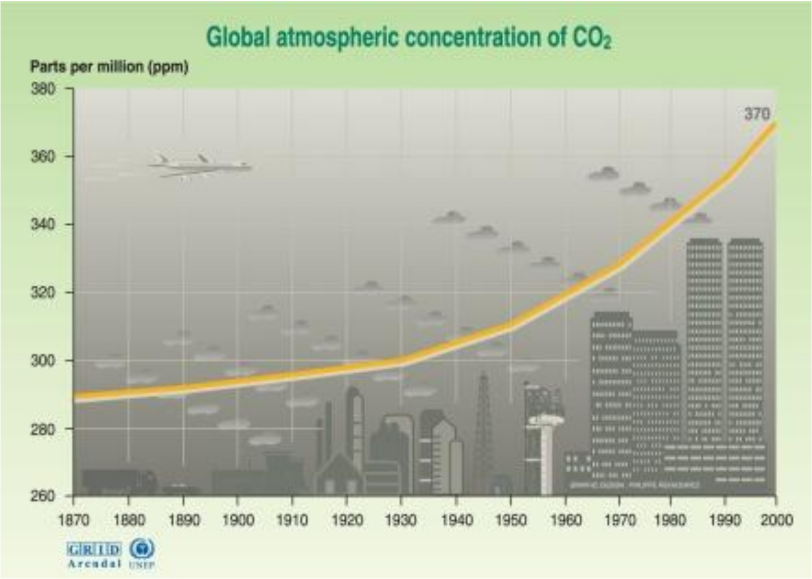
"Energy vs. Materials Sustainability", Igor Lubomirsky and David Cahen, Weizmann Institute (Israel)

"Sustainability Metrics for Photovoltaics Growth to Terawatt Levels", Vasilis Fthenakis, Columbia University

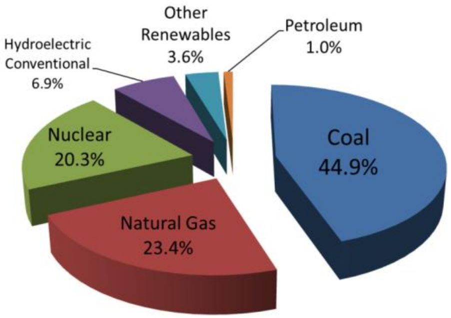
"Is Nuclear Fission a Sustainable Source of Energy?", Rodney Ewing (co-authors TBD), U. Michigan

"Material Challenges in Carbon Capture Technologies", Laura Espinal (NIST) and Cynthia A. Powell (NETL)

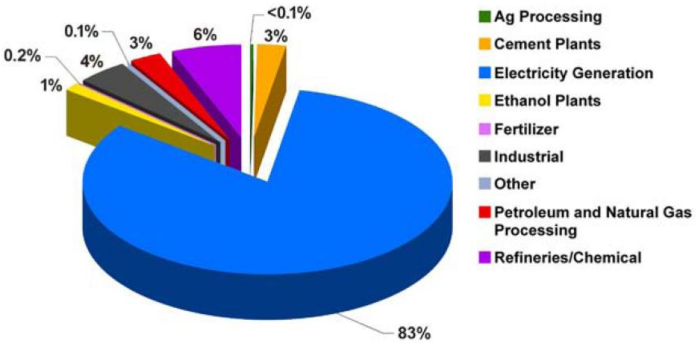
“Material Challenges in Carbon Capture Technologies”
L. Espinal (NIST) et al



US electricity generation:



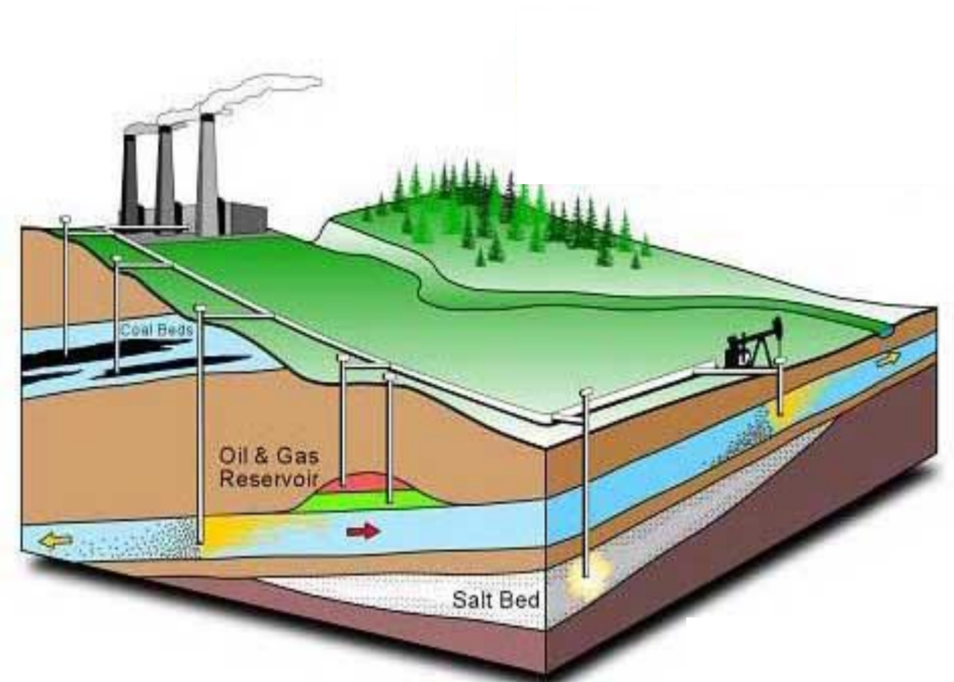
US stationary sources of CO_2 emissions:

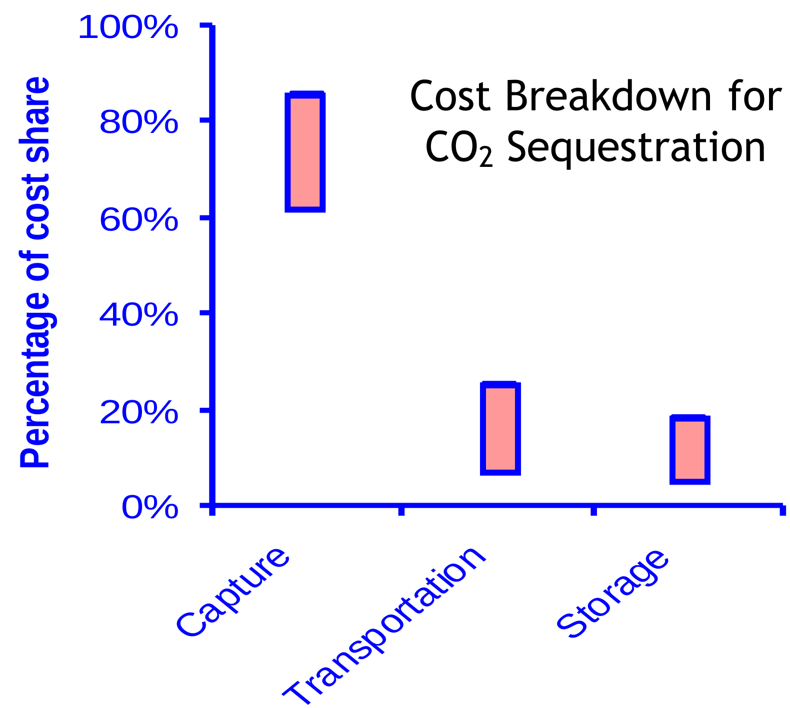


SOURCE: US Energy Information Administration

SOURCE: NETL Carbon Sequestration Atlas

"Material Challenges in Carbon Capture Technologies"
L. Espinal (NIST) et al





Cost assumptions:

- ✓ *Capture: \$40-60/t CO_2 avoided*
- ✓ *Pipeline: \$0.02-0.06/t .km*
- ✓ *Transportation mileage: 250 km*
- ✓ *Storage: \$5-10/t CO_2*

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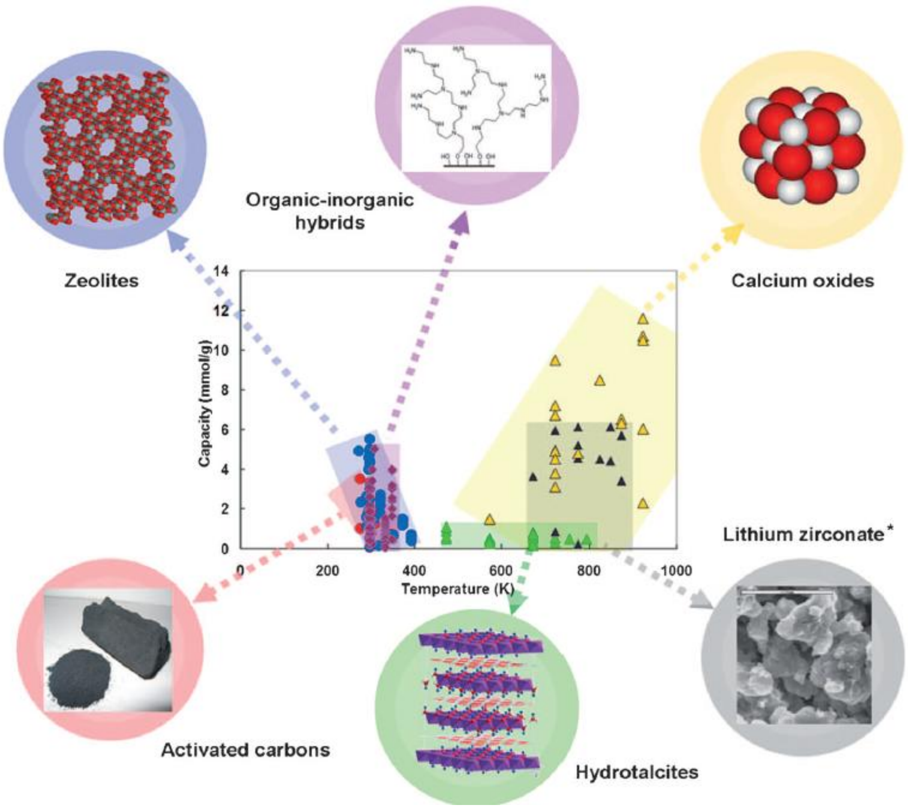
"Material Challenges in Carbon Capture Technologies"
L. Espinal (NIST) et al

Potential CO_2 Sorbents for Carbon Capture Applications

IMPORTANT PARAMETERS:
- CO_2 capacity
- Adsorption and desorption kinetics
- Operating window: adsorption and desorption temperatures or pressures
- Regenerability and multicycle stability
- Impact of common flue gas components or contaminants

"No single ideal adsorbent is likely to be invented. Rather, each adsorbent's strengths and weaknesses must be considered in the context of a practical adsorption process for effective CO_2 separation. Ultimately, winning adsorbents will be those that effectively work within a practical and efficient CO_2 separation process."

Jones *et al.*, ChemSusChem 2009



MRS Bulletin Special Issue
"Materials for Sustainable Development"

- ***Sub-Topic: Materials Life-Cycle and Supply Chain Analysis, and Quantification of the Carbon, Energy and Water Footprints of Materials and Products***

"Materials Availability: Analytical Challenges and Policy Responses", Lorenz Erdman (Institute for Future Studies, Berlin), and Tom Graedel, Yale University.

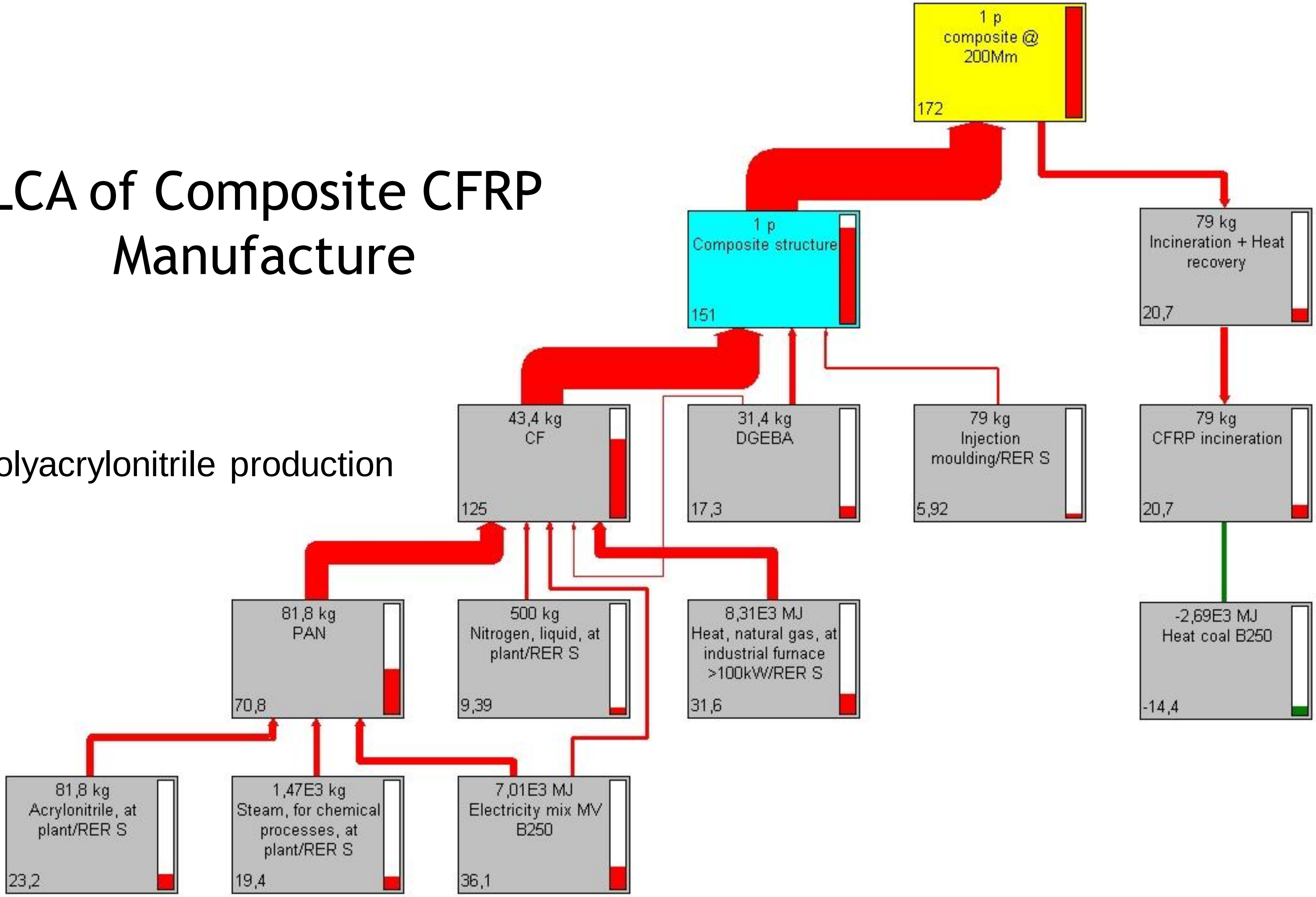
"Trends In Composites Development From An Environmental Perspective: An LCA Based Study", Joost Duflou, Deng Yelin, Wim Dewulf, and Karel Van Acker, KU Leuven (Belgium)

"Measurements, Standards and Data Activities to Support Industry Sustainability Efforts", Dianne Poster, Michael Fasolka, Ellyn Beary, and Rich Cavanagh, Materials Measurement Laboratory, National Institute of Standards and Technology, Gaithersburg, MD

"Trends In Composites Development From An Environmental Perspective: An LCA Based Study", J. Duflou et al (KU Leuven Belgium)

LCA of Composite CFRP Manufacture

Polyacrylonitrile production



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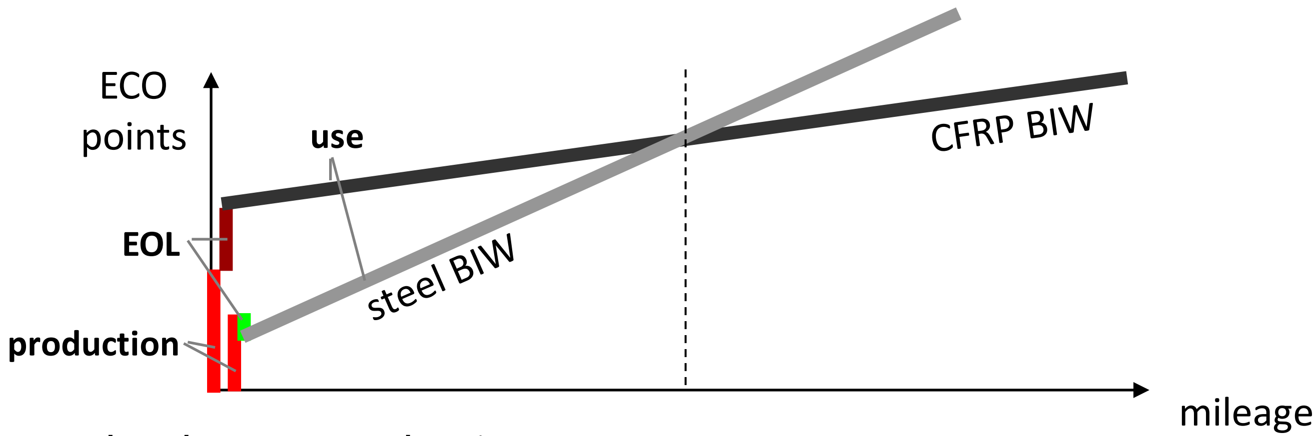
"Trends In Composites Development From An Environmental Perspective: An LCA Based Study", J. Duflou et al (KU Leuven Belgium)

- The choice of CFRP instead of steel for automotive applications depends on the intensity of the use phase: breakeven point is at 132000 km



- Second order mass reductions:
  - don't have a significant impact on the production phase (8.8 Pt)
  - do have an important impact on the use phase:
    total saving is 0.76 l/100km, instead of 0.42 l/100km without second order mass reduction (= gain of 80%)
- Effect of PAN production is predominant in production phase
  - anticipated further reduction of energy consumption in the PAN production of 50% means a breakeven point at 86000 km

MRS Bulletin Special Issue
"Materials for Sustainable Development"

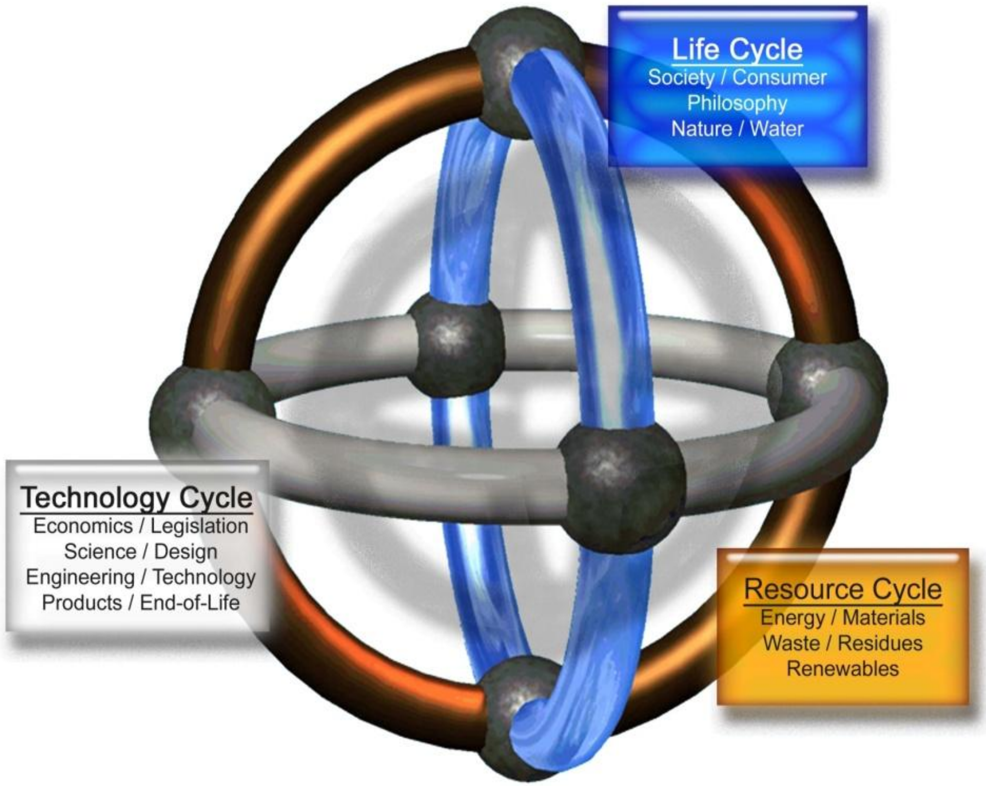
- ***Sub-Topic: Recycling***

"Limits of Design for Recycling and 'Sustainability': A Review", Markus Reuter, Outotec Ausmelt Ltd. (Australia)

"To Recycle or Not to Recycle: That Is the Question", Linda Gaines, Argonne National Lab

“Limits of Design for Recycling and ‘Sustainability’: A Review”

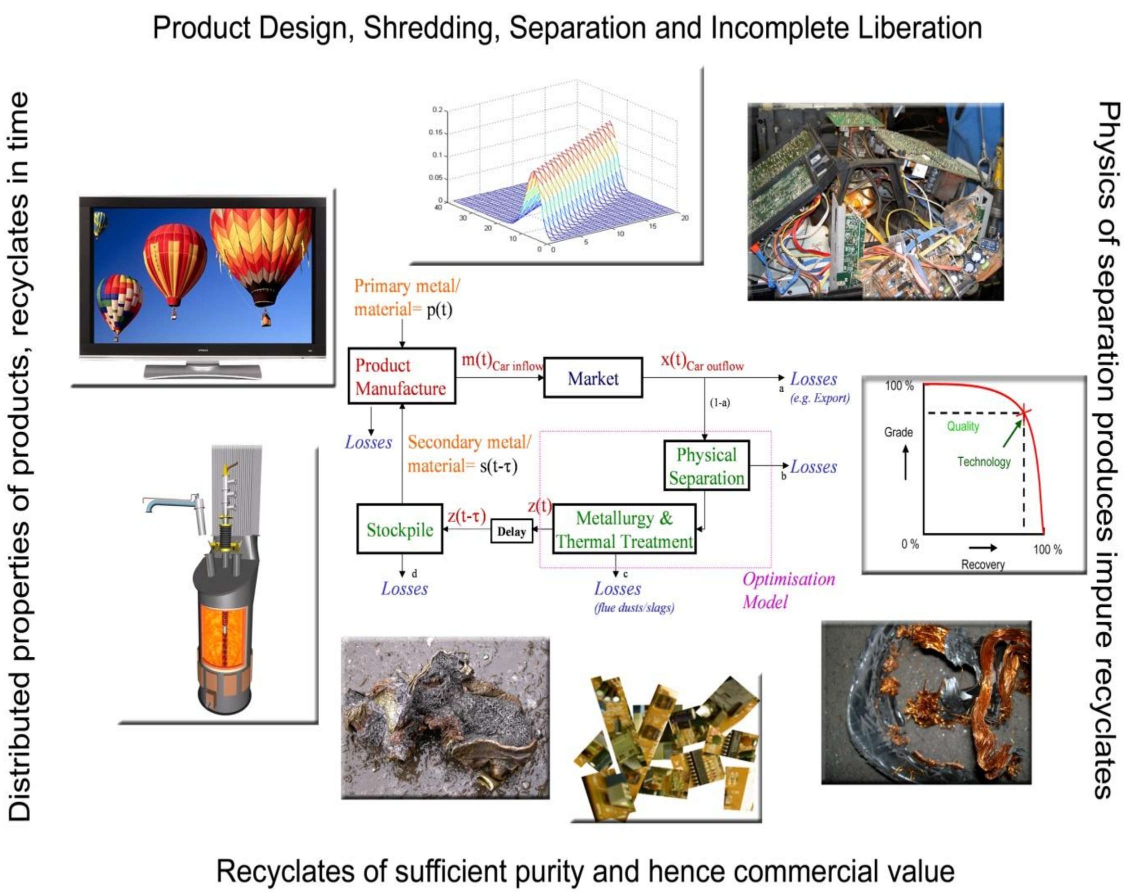
Markus Reuter (Outotec Ausmelt Ltd.)



The driving Vision and Mission of our work is to connect the various aspects in the above symbol with first-principles models i.e. the resource cycle, the water cycle and technology with detail as described - Our models have linked these three cycles on a fundamental basis.

“Limits of Design for Recycling and ‘Sustainability’: A Review”

Markus Reuter (Outotec Ausmelt Ltd.)



A summary of aspects that affect recycling rate of EoL-products as included in the recycling models: time and property distribution, product design, degree of liberation, separation physics, solution thermodynamics, recycling technology etc.

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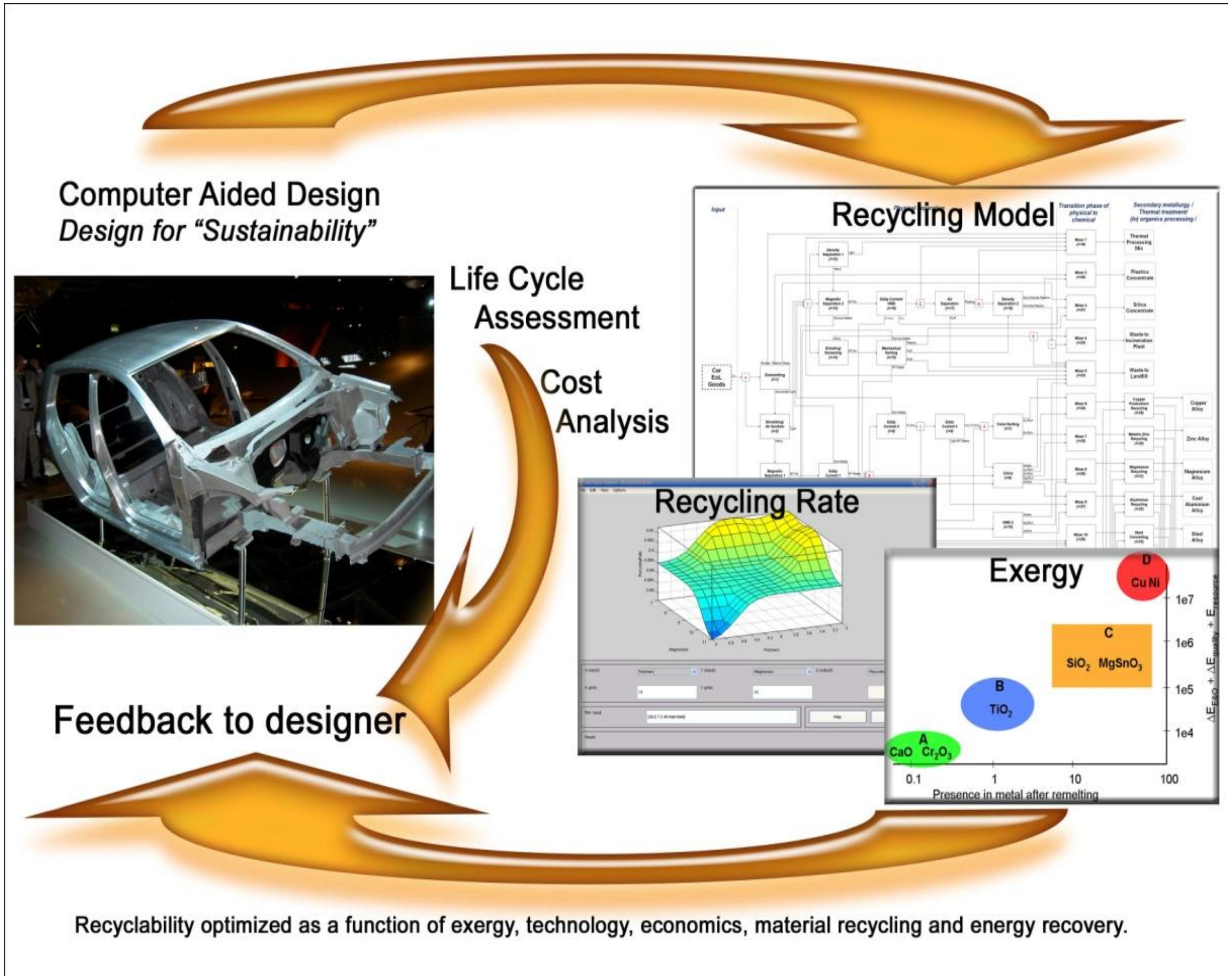

Link between CAD, LCA and recycling rate calculations

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"To Recycle or Not to Recycle: That Is the Question", Linda Gaines, Argonne National Lab

"Reduce, Reuse, Recycle" may not be the way to go

- Combustion is the best option for office paper
  - Production uses byproduct fuel
  - Recycling uses fossil fuel, degrades fibers
  - Combustion displaces coal with cleaner fuel
  - Trees can be replanted on plantations
- Recycled aluminum cans have lower impacts than refillable glass bottles
  - Aluminum energy-intensive but cans light
    - Material does not degrade
  - Can be recycled with low impacts
  - Glass bottles heavy and inconvenient
    - Washing and transport take energy
    - Some break during reuse cycles
    - Need to be used 7 times to compete with recycled cans
    - US consumers value convenience

“To Recycle or Not to Recycle: That Is the Question”
Linda Gaines (ANL)