Sustainable Electronics –
The Canary in the Coal Mine for Planet Earth

Carol A. Handwerker

Purdue University
Materials Engineering
Environmental & Ecological Engineering

Purdue – Mexico Workshop on Sustainability
29-30 April 2013

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Pb-Free and Next Generation Electronics

- **Tin whiskers - John Blendell**
  - **Wei-Hsun Chen, Nick Clore, John Koppes, Aaron Pedigo, Pylin Sarobol, Ying Wang**
- **Pb-free solders - Ganesh Subbarayan (ME) and Mysore Dayananda**
  - **Santosh Kumar, Jon Tucker, John Holaday, and Yuvraj Singh**
- **Nanoparticle-enabled electronics and solar cells- Eric Stach, Elliott Slamovich and Rakesh Agrawal (ChE)**
  - **Milea Kammer, Suk Jun Kim, Tony Muza, Luthfia Syarbaini, Yan Guo, Ruihong Zhang**

Sustainable Electronics

- **Anthropology: Kory Cooper, Riall Nolan**
- **Chemistry: Jon Wilker**
- **Forestry and Natural Resources: Marisol Sepulveda**
- **Management: Ananth Iyer, Susan Watts**
- **Political Science: Leigh Raymond**
- **Engineering: Agricultural/Biological – Bernie Tao, Civil – Inez Hua, Education – Monica Cox, Electrical/Computer – Dimitri Peroulis, Environmental/Ecological – John Sutherland, Materials – Carol Handwerker, John Howarter, Robert Moon, Jeffrey Youngblood, Mechanical – Karthik Ramani, Fu Zhao**

Sustainable Electronics

In close collaboration with Tuskegee University Materials Science & Engineering Ph.D. program faculty

- **Mahesh Hosur**
- **Melissa Reeves**
- **Michael Curry**
- **Vijaya Rangari**
- **Tamara Floyd-Smith**

Sustainable Electronics

- **Recycling LCD TVs:** Fu Zhao and Kory Cooper
  - 18 undergraduates from MSE, ME, Communications, and Anthropology (2009-2012)- Electronic TakeBack Coalition
  - Current: 5 EEE undergraduates – EPA P3 project (Zhao – PI)
- **NSF IGERT: Global Traineeship in Sustainable Electronics:** Inez Hua, Ananth Iyer, Karthik Ramani, Mahesh Hosur (Tuskegee)
- **DOE Critical Materials Institute:** Ananth Iyer, John Sutherland, and Fu Zhao
  - DOE Energy Innovation Hub starting April 2013, with Ames

Welsh miner Charlie Williams, with canary, in Dinas mine, Rhonda Valley, in 1965

*"**Sustainable development** is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.*

It contains within it two key concepts:

- the concept of **needs**, in particular the essential needs of the world's poor, to which overriding priority should be given; and
- the idea of **limitations** imposed by the state of technology and social organization on the environment's ability to meet present and future needs.“

UN World Commission on Environment and Development (WCED). *Our common future*. Oxford: Oxford University Press, 1987 p. 43.

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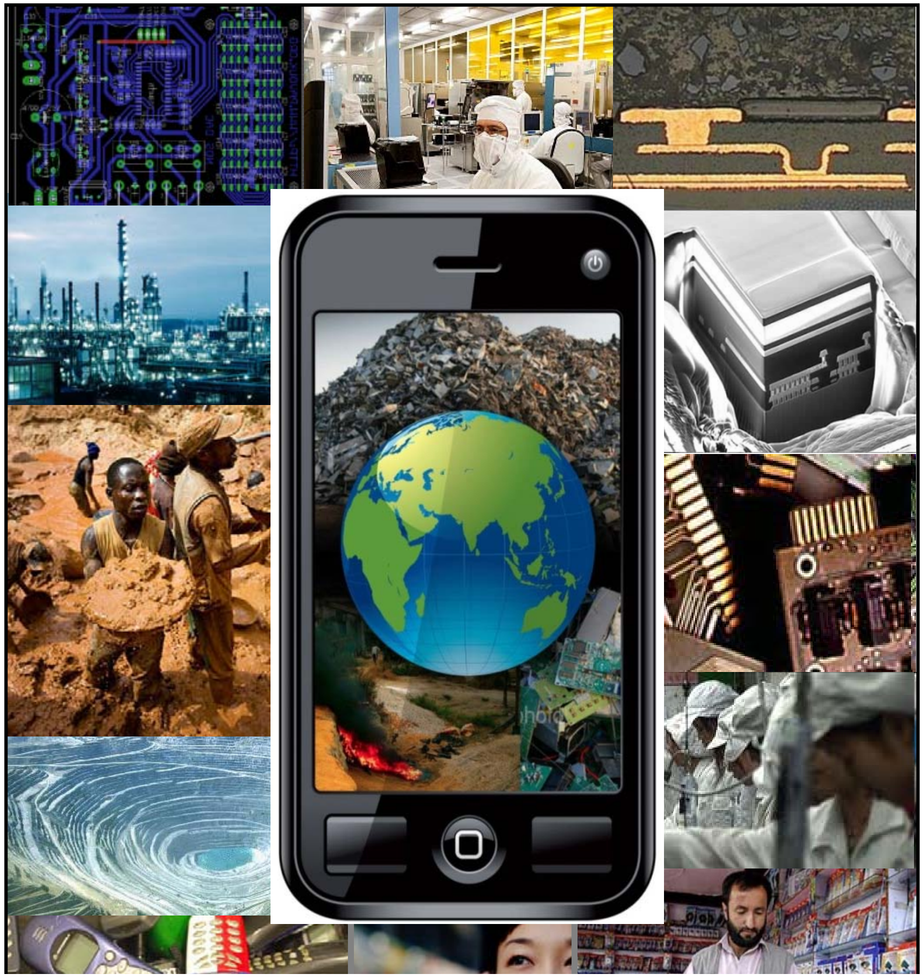


•Definition of global sustainability for electronics

Are there guiding principles?

How do we realistically measure what happens?

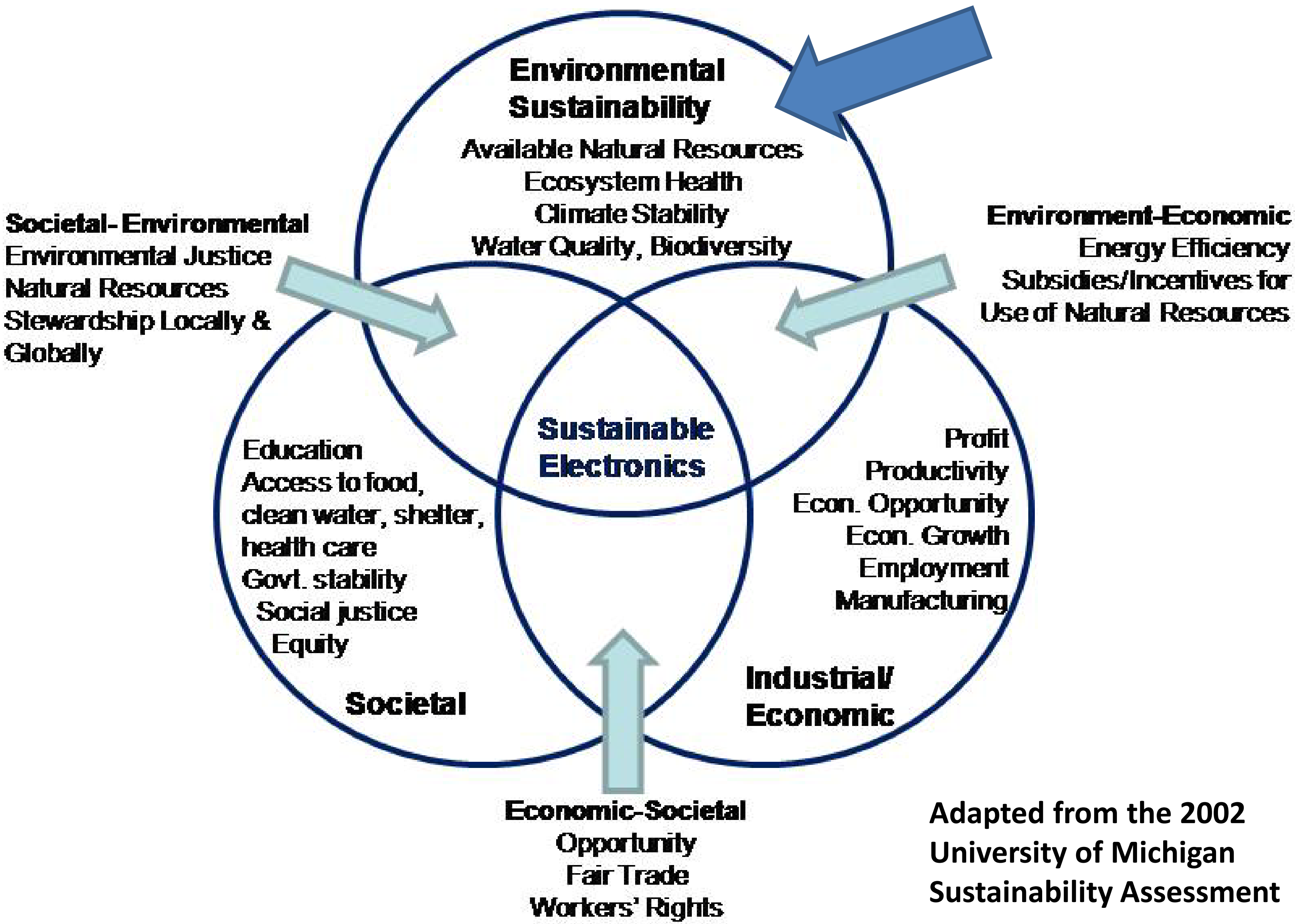
How do we frame the right questions?

What are the tradeoffs?

What data are not there?

How do we apply this at the research stage?

- We don’t know what this looks like yet.
- We want to understand.
- We want to eliminate barriers.
- We want to build bridges - to industry, NGO’s, government, educators.



Adapted from the 2002 University of Michigan Sustainability Assessment

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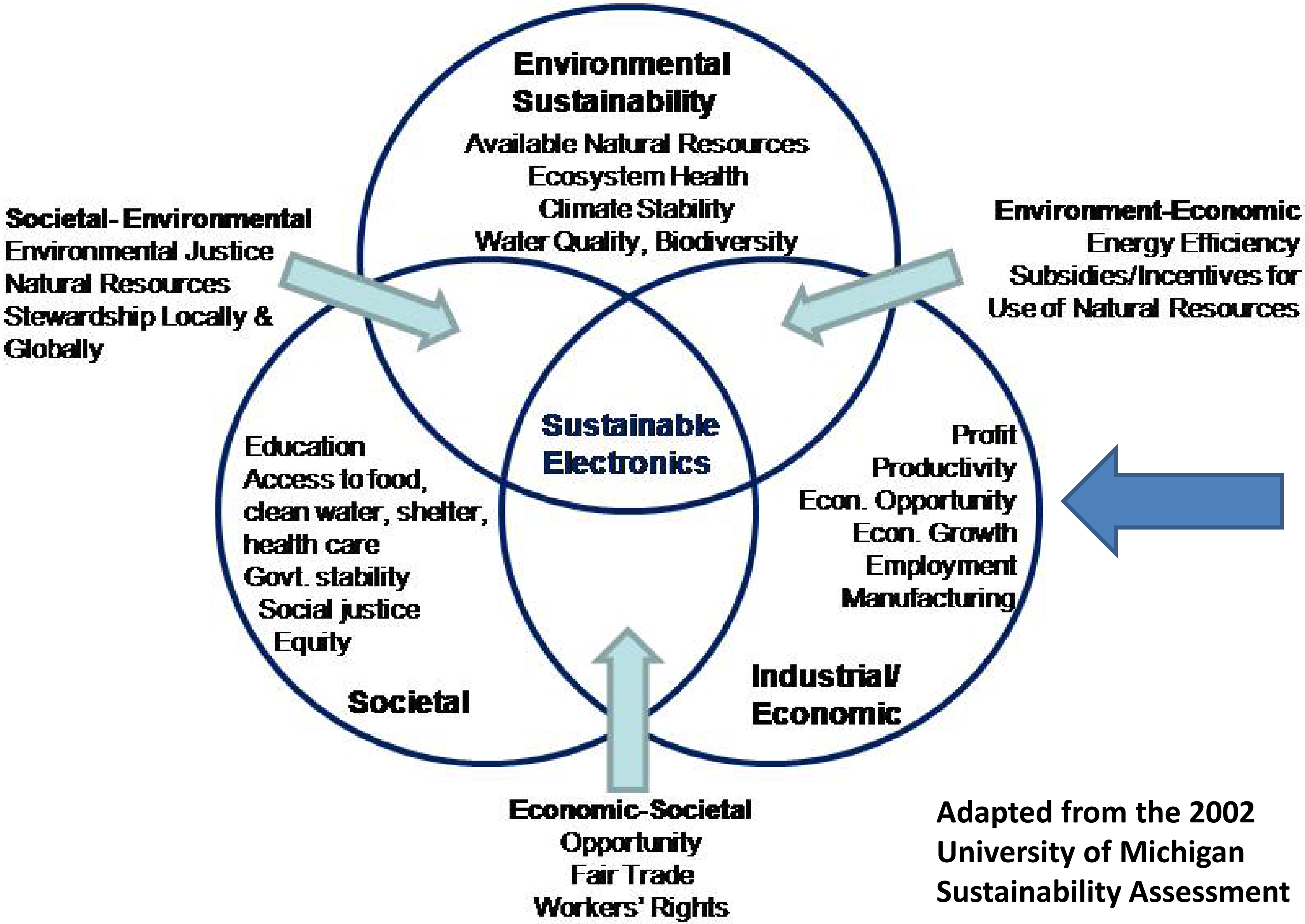

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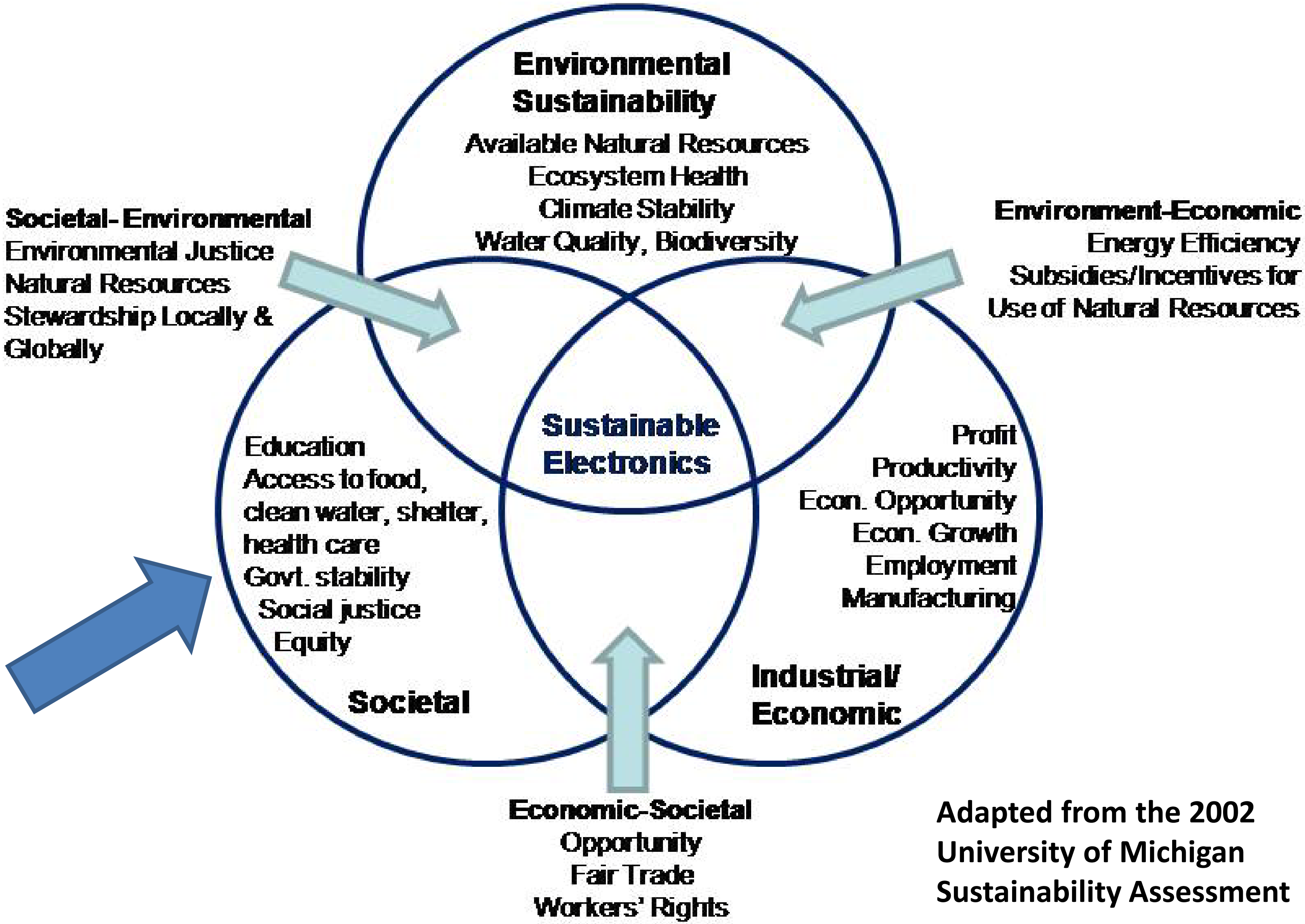

Adapted from the 2002
University of Michigan
Sustainability Assessment

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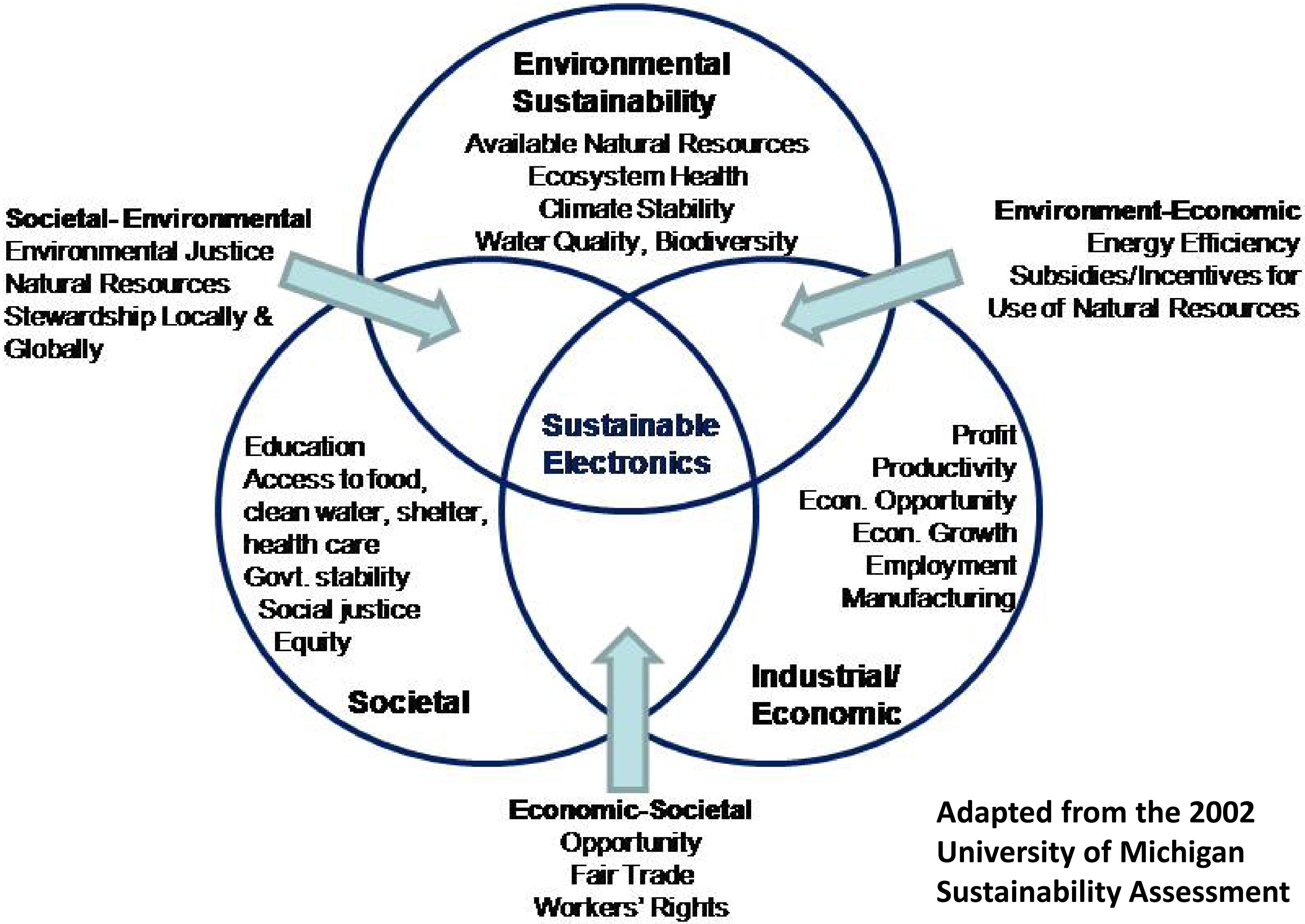

Adapted from the 2002 University of Michigan Sustainability Assessment

Sustainability

- Sustainable development:
  - meeting the needs of the present without compromising the ability of future generations to meet their own needs
- Economic – Societal - Environmental
- Sustainable for whom?
- Sustainable over what time?
- (Impact) X (number of people)

1.6B global 3G subscribers
6B mobile subscriptions worldwide in 2011 – *78/100* people in developing countries
Total population of 6.9B

Simplified Supply Chain Map for an OEM

http://greeningit.wordpress.com/2011/08/09/electronic-industry-citizenship-coalition-pilots-carbon-reporting-system/

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Environmental impact = population * (impact per person)

Impact to have needs met

Food

Shelter

Water

Safety

Community

…

Four Factors Determine the Amount of CO_2 Emissions

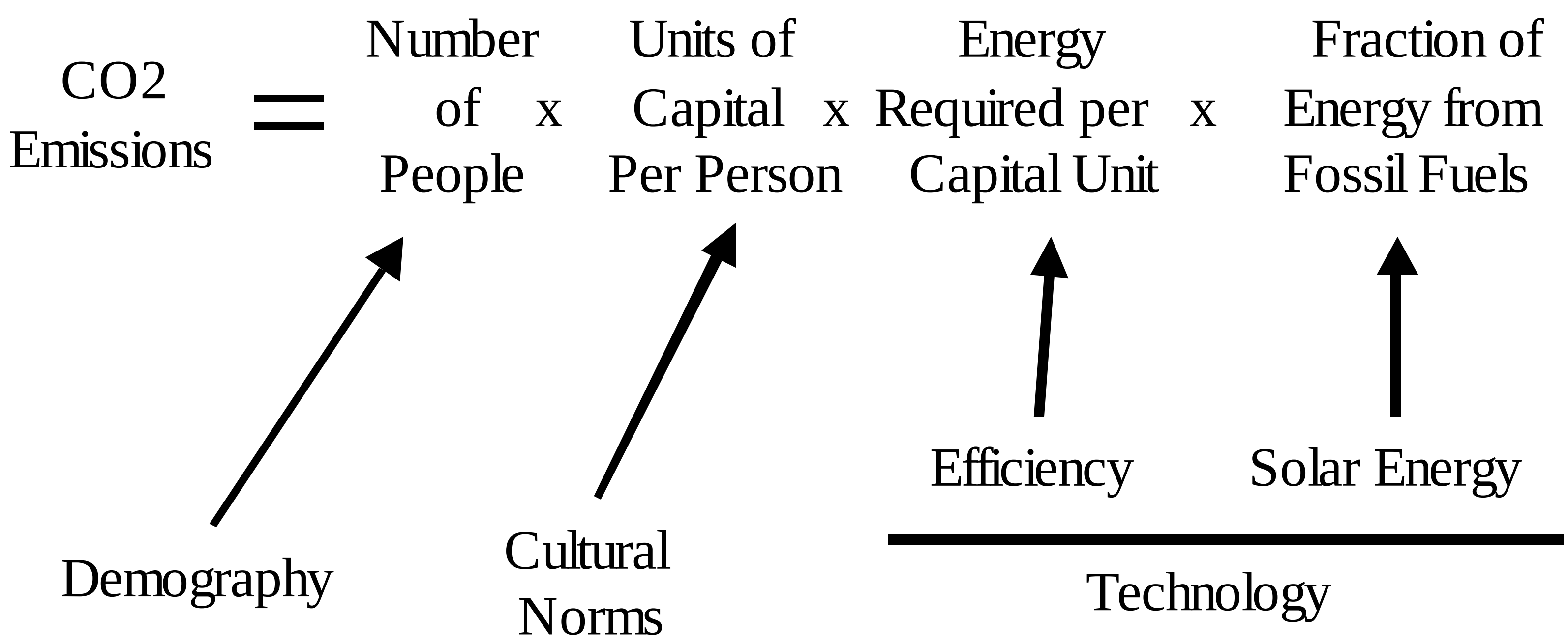
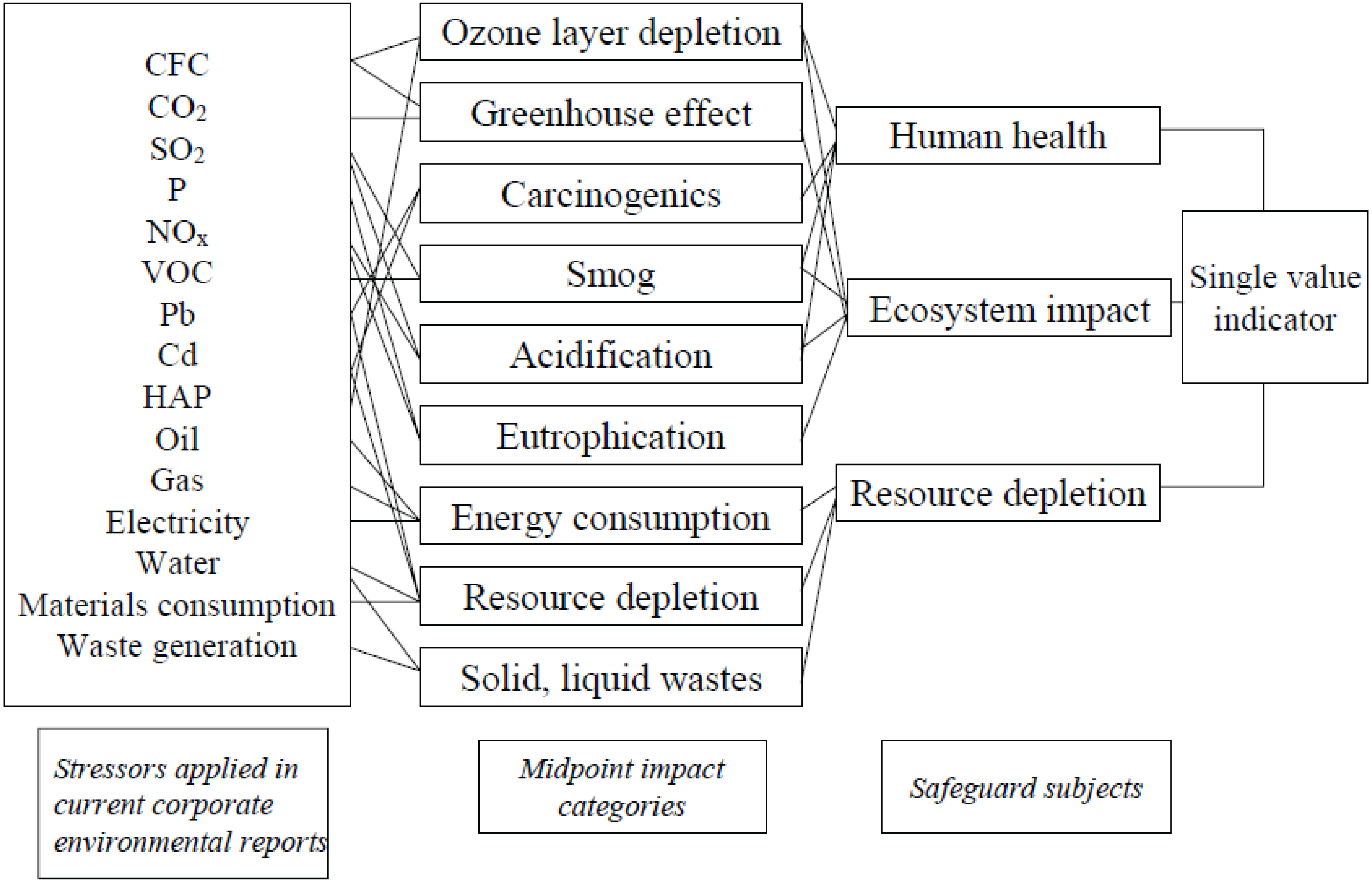


Fig. 2. Impact chain in environmental performance assessment. CFC: chlorofluorocarbons; VOC: volatile organic compounds; HAP: hazardous air pollutants



Sustainable Electronic Product Design: A Comparison of Environmental Performance Assessment Tools Derived from Life Cycle Thinking, **Xiaoying Zhou, Julie M. Schoenung,** *University of California – Davis, USA* , in: Web-Based Green Products Life Cycle Management Systems: Reverse Supply Chain Utilization, Ed. Hsiao-Fan Wang, IGI Global, 2009.

iphone 3G

http://www.likecool.com/cate-Gear-256.html

TABLE II. WEIGHT VERSUS VALUE DISTRIBUTION

weight-%	Fe	Al	Cu	plastics	Ag [ppm]	Au [ppm]	Pd [ppm]
TV-board	28%	10%	10%	28%	280	20	10
PC-board	7%	5%	20%	23%	1000	250	110
mobile phone	5%	1%	13%	[illegible]	1380	350	210
portable audio	23%	1%	21%	[illegible]	150	10	4
DVD-player	62%	2%	5%	24%	115	15	4
calculator	4%	5%	3%	61%	260	50	5

value-share	Fe	Al	Cu	sum PM	Ag	Au	Pd
TV-board	4%	11%	42%	43%	8%	27%	8%
PC-board	0%	1%	14%	85%	5%	65%	15%
mobile phone	0%	0%	7%	93%	5%	67%	21%
portable audio	3%	1%	77%	20%	4%	13%	3%
DVD-player	13%	4%	36%	48%	5%	37%	5%
calculator	0%	5%	11%	84%	7%	73%	4%

Improving metal returns and eco-efficiency in electronics recycling

- a holistic approach for interface optimisation between pre-processing and integrated metals smelting and refining

Christian Hagelüken
Umicore Precious Metals Refining

Sum of Precious Metals

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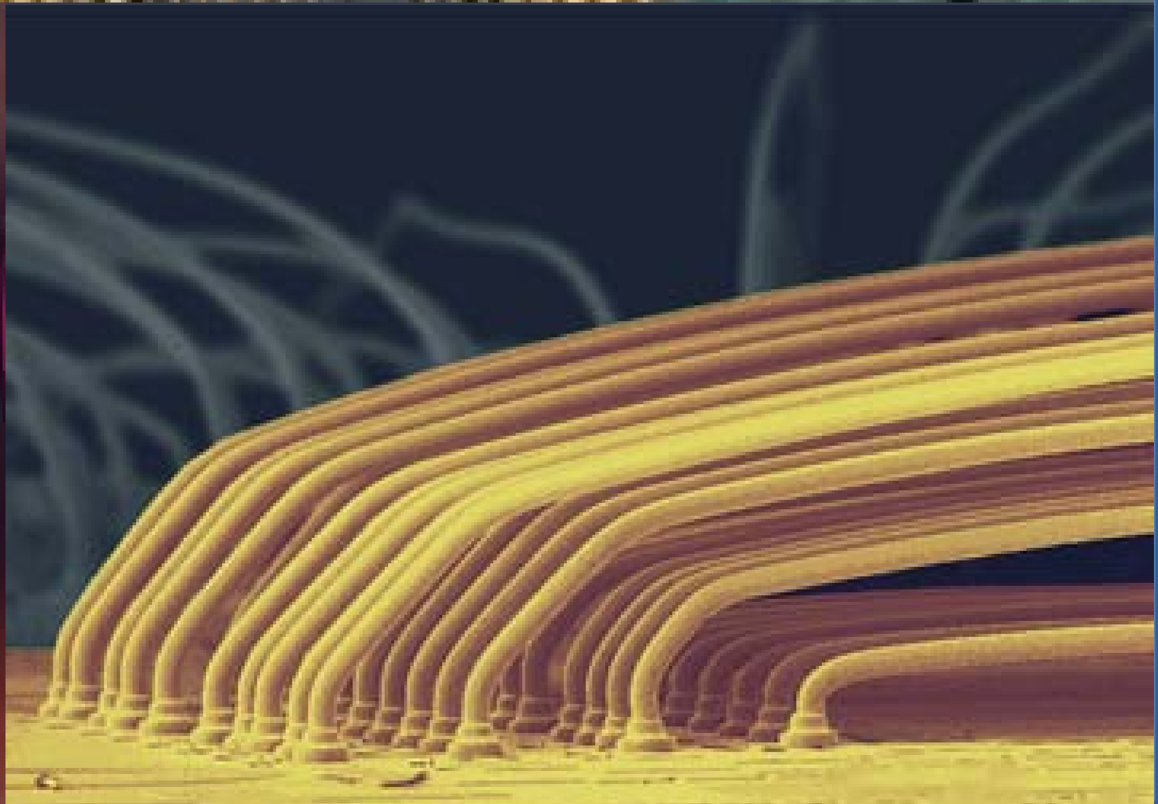
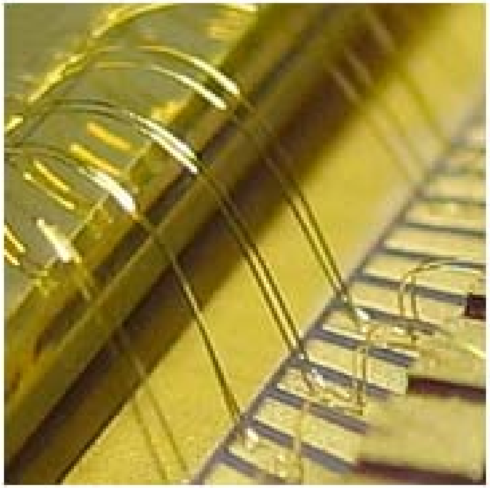


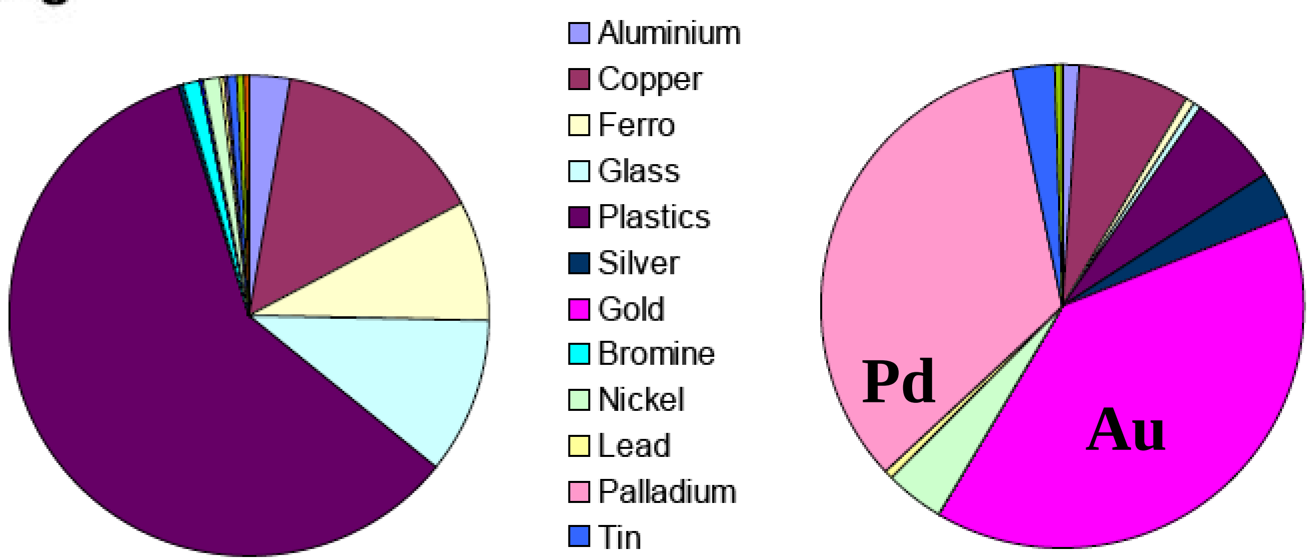
Environmental Impact – It is not how much is in the final product



Gold Wire Bonding

WEEE Recast - Huisman and Magalini

NVMP – StEP Summerschool on WEEE
Philips HTC 2009-09-10



polymers

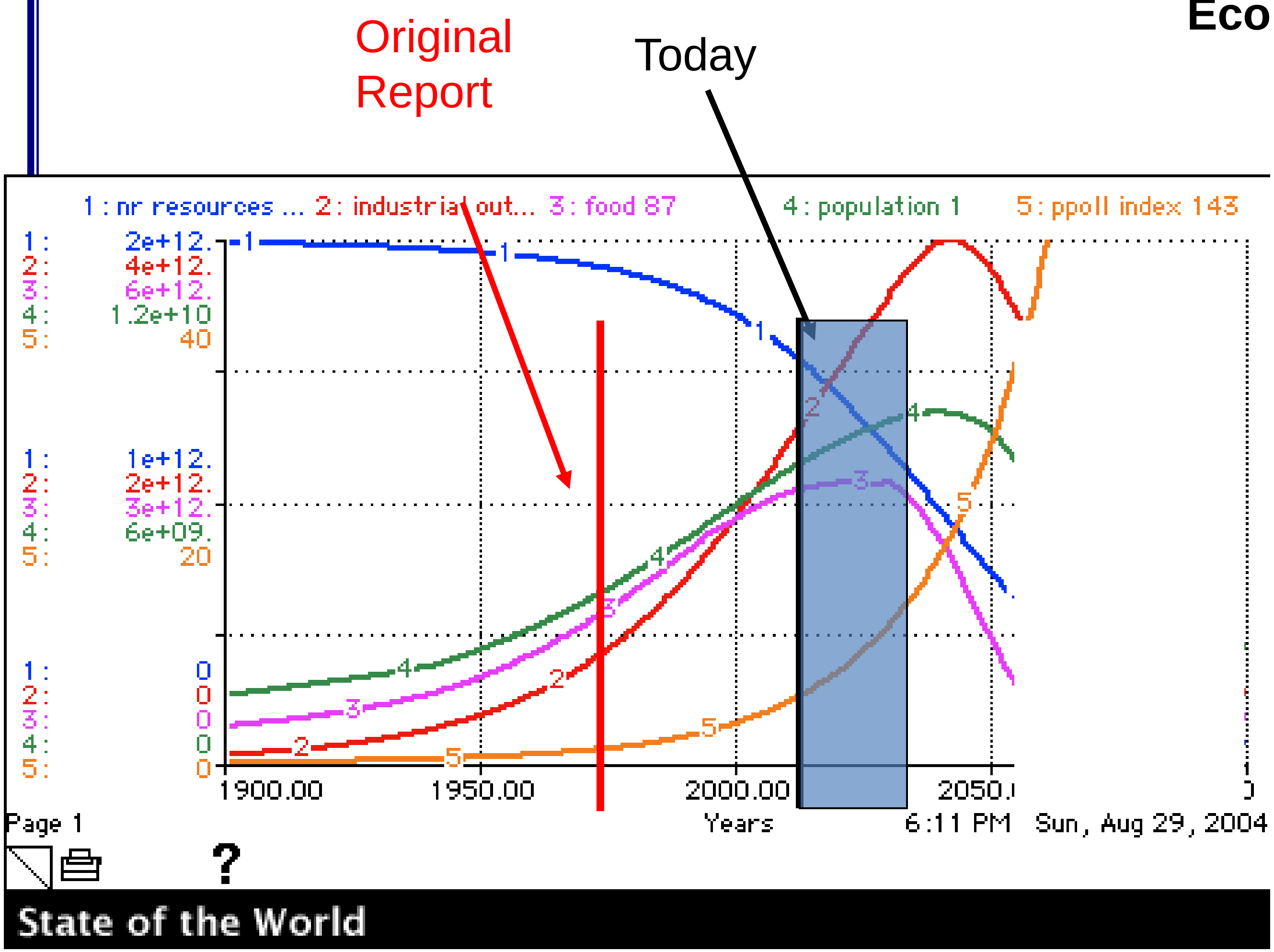
by weight

by environmental impact




The Reference Scenario: Club of Rome's Limits to Growth

Economics and Limits to Growth: What's Sustainable?
Dennis Meadows
Washington, DC
October 6, 2009



Industrial Output
Population
Pollution
Resources
Food

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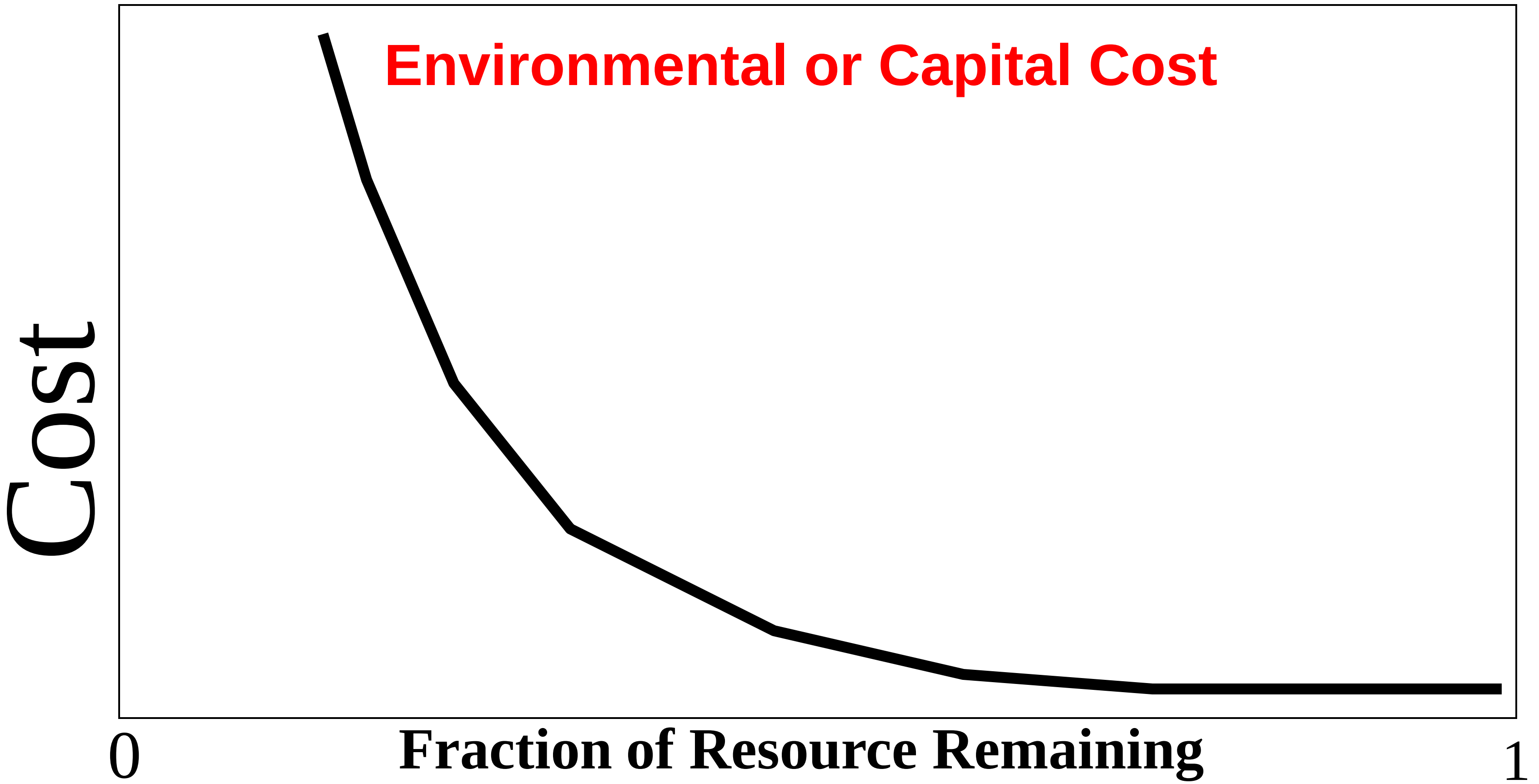
Capital Cost of Discovery



Economics and Limits to Growth: What's Sustainable?

Dennis Meadows

Washington, DC

October 6, 2009

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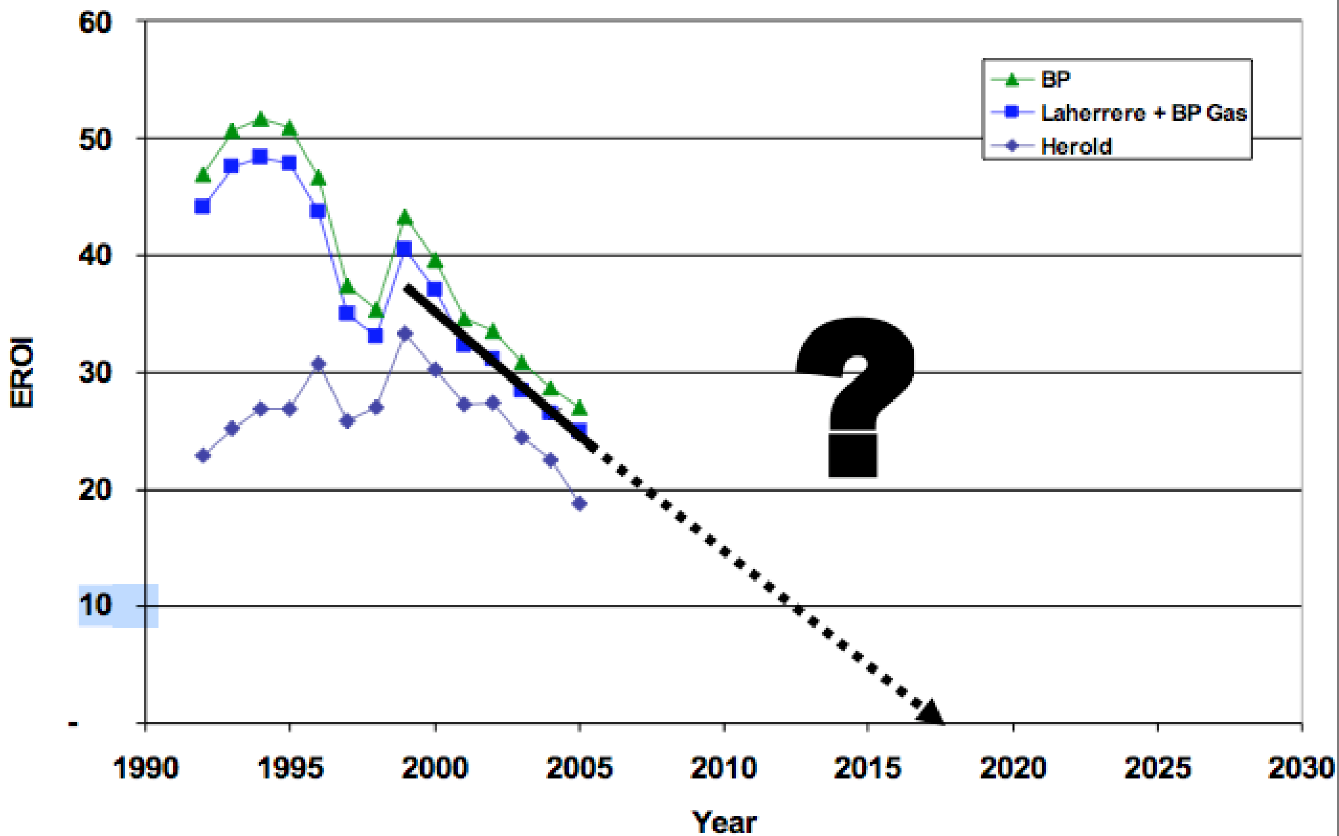
Energy Return on Investment



Economics and Limits to Growth: What's Sustainable?
Dennis Meadows
Washington, DC
October 6, 2009

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Dennis Meadows:

Main Points of His Speech

- Growth has continued until we are now past sustainable levels.
- The global society will change more over the next 20 years than in the past 100. Design policies for what is coming, not what has been.
- The main forces for change will be climate change and resource scarcity - especially fossil fuels and water.
- The end of growth does not result from total depletion, but from rising capital costs.
- The most important scarcity is the absence of a longer-term perspective.

Economics and Limits to Growth: What's Sustainable?
Dennis Meadows
Washington, DC
October 6, 2009

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iNEMI

(International Electronics Manufacturing Initiative)

An industry-led research and development consortium of 100+ major electronic firms, suppliers, industry associations and consortia, government agencies and universities.

- **roadmaps** the needs of the global electronics industry, identifies gaps in the technology infrastructure, and establishes implementation projects to eliminate these gaps (both business and technical).

- works with government, universities and funding agencies to **set priorities for R&D initiatives**.

- has been instrumental in providing the reliability and manufacturing knowledge necessary for the world-wide conversion to Pb-free electronics and continues to serve that role as replacement materials for electronics systems continue to be required due to environmental or human health bans or material shortages.

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iNEMI members

Agilent Technologies

Alcatel·Lucent

Cochlear™

Boston Scientific
Delivering what's next.™

CISCO

DELPHI

DELL

hp invent

HUAWEI

Celestica™

FLEXTRONICS

FOXCONN®

JUNIPER NETWORKS

IBM®

RIM®

MED-EL MEDICAL ELECTRONICS

lenovo

intel®

IEC electronics
Absolutely, Positively, Perfect and On-Time(sm)

Microsoft®

PLEXUS®

VALTRONIC™

SANMINA-SCI®

MICRO SYSTEMS ENGINEERING

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Supplier Members

ASE GROUP

ASSET
Driving Embedded Instrumentation

Amkor Technology

akrometrix

CORELIS
An EWA Company

DOW
Electronic Materials

Henkel

INDIUM CORPORATION OF AMERICA

Cookson Electronics
A Division of Cookson Group plc

HOVER-DAVIS

Heraeus

INVENTEC
PERFORMANCE CHEMICALS

IHS

ICHIMURA

NIHON SUPERIOR CO., LTD.

NAMICS

MICRONIC MYDATA

株式会社 日鉄マイクロメタル
NIPPON MICROMETAL CORPORATION

iST INTEGRATED SERVICE TECHNOLOGY

TE

PVI SYSTEMS

STATSChipPAC

Speedline technologies

TEXAS INSTRUMENTS

Senju Comtek

TERADYNE

Universal Instruments

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Research Institutes and University Members

ASU Arizona State University

Berkeley University of California

Fraunhofer IZM

Georgia Institute of Technology

IEEC

imec

ITRI Industrial Technology Research Institute

Rochester Institute of Technology R·I·T 1829

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NIST National Institute of Standards and Technology

Peking University 1898

MIT Massachusetts Institute of Technology

ncms National Center for Manufacturing Sciences

Purdue University

Sustainable Electronics – 2012 EPA & 2013 iNEMI Roadmaps

- Business decisions are aligned with sustainability objectives
- All life cycle costs are internalized in the products

  "Externalities are *impacts generated by one economic actor, which are felt by others, but the market doesn't bring these impacts back to affect the actor that originated them*. " Neva Goodwin
- Decisions are transparent
- Companies, consumers, and all people in the supply chain are accountable
- ICT enables smarter use of natural resources

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Sustainable Electronics – 2012 EPA & 2013 iNEMI Roadmaps

- All ICT hardware is manufactured in facilities with best-in-class health, safety, and environmental standards globally with employees earning a living wage, no forced labor, no forced overtime, no child labor, no discrimination, and workers have freedom of association
- No chemical or materials selection is made without an alternatives assessment, or the substance is on the "good" list
- Hazardous emissions to air, water, land are eliminated
- Resources are not wasted
- People and communities benefit

NSF Integrated Education and Research Traineeship Program

IGERT: Global Traineeship in Sustainable Electronics

Purdue University and Tuskegee University in close collaboration with the global electronics industry - iNEMI plus 5 corporate members - and

International Academic Partners - Fraunhofer IZM - Berlin, Shanghai Jiao Tong University, Tsinghua University – Beijing, Indian Institute of Management – Udaipur, Universidad EAFIT – Medellin

Vision

Create a new integrative, collaborative model for graduate research and education needed to enable *meaningful and measurable improvements in the global sustainability of electronics*.

Funded by NSF in June 2012

$3.2M for 28 two-year fellowships over 5 years

External Advisory Board and opportunities for collaboration with industry, NGOs, research institutions

NSF Integrated Education and Research Traineeship Program

IGERT: Global Traineeship in Sustainable Electronics

Three Research Thrusts

1. Polymers from Nature for Construction & Disassembly
   - **Natural Nanocomposites for Structural Applications in Casings and Boards**,
   - **Bio-based Lignin and Soy-based Resins for Circuit Board Construction**
   - **Biomimetic Marine-Derived Bioadhesives for Device Construction & Disassembly**
   - **Green Replacements for Brominated Flame Retardants**
2. Sustainable Product Design and Manufacturing
   - **Novel LCA Approach for Electronic Products**
   - **Electronic Product Manufacturing Process Characterization and Improvement**
   - **LCA-based Design of Electronics**
   - **Recycling and Reuse of Electronic Devices**
3. System and Supply Chain Issues
   - **Integrating Sustainability Indicators across the Supply Chain**
   - **Corporate Sustainability Behavior – Stakeholder Perception – Corporate Valuation**
   - **Consumer Behavior**
   - **System-wide Effects of Laws and Regulations**

NSF Integrated Education and Research Traineeship Program

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IGERT will creates a Ph.D. graduate education and research traineeship to:

(1) Educate, train and empower scientists, engineers, product developers, economists, and managers as decision-makers, using input f... e interdependent dynamic ... ,

(2) ... ural ... be ...

(3) ... nciples of ... academic institutions, ... and industry experts), teamwork, and interdisciplinary breadth,

(4) Develop a curriculum with our industry and international university partners in Germany, Colombia, India, and China and disseminate it widely through Purdue's globalHUB cyberinfrastructure to positively influence the global stakeholders who impact electronics sustainability.

How to agree upon common goals
to have difficult, yet productive conversations
to make progress

NSF Integrated Education and Research Traineeship Program

IGERT: Global Traineeship in Sustainable Electronics

Sara Beasley – Leigh Raymond

Bill Bernstein* – Karthik Ramani

Alexandra Bruce – John Howarter, Inez Hua

Kristy Crews – Michael Curry (T), Robert Moon

Michael Laird Johnston – Jon Wilker, John Blendell

Milea Kammer – Carol Handwerker, Fu Zhao

Mike McCoy – Karthik Ramani

Gamini Mendis – John Howarter, Jeffrey Youngblood, Inez Hua

Shane Peng – Jeffrey Youngblood, Robert Moon

Vertonica Powell-Rose – Mahesh Hosur (T)

Devarajan Ramanujan* – Karthik Ramani

Eldon Trigg – Mahesh Hosur (T)

Aditya Vendantum* - Ananth Iyer

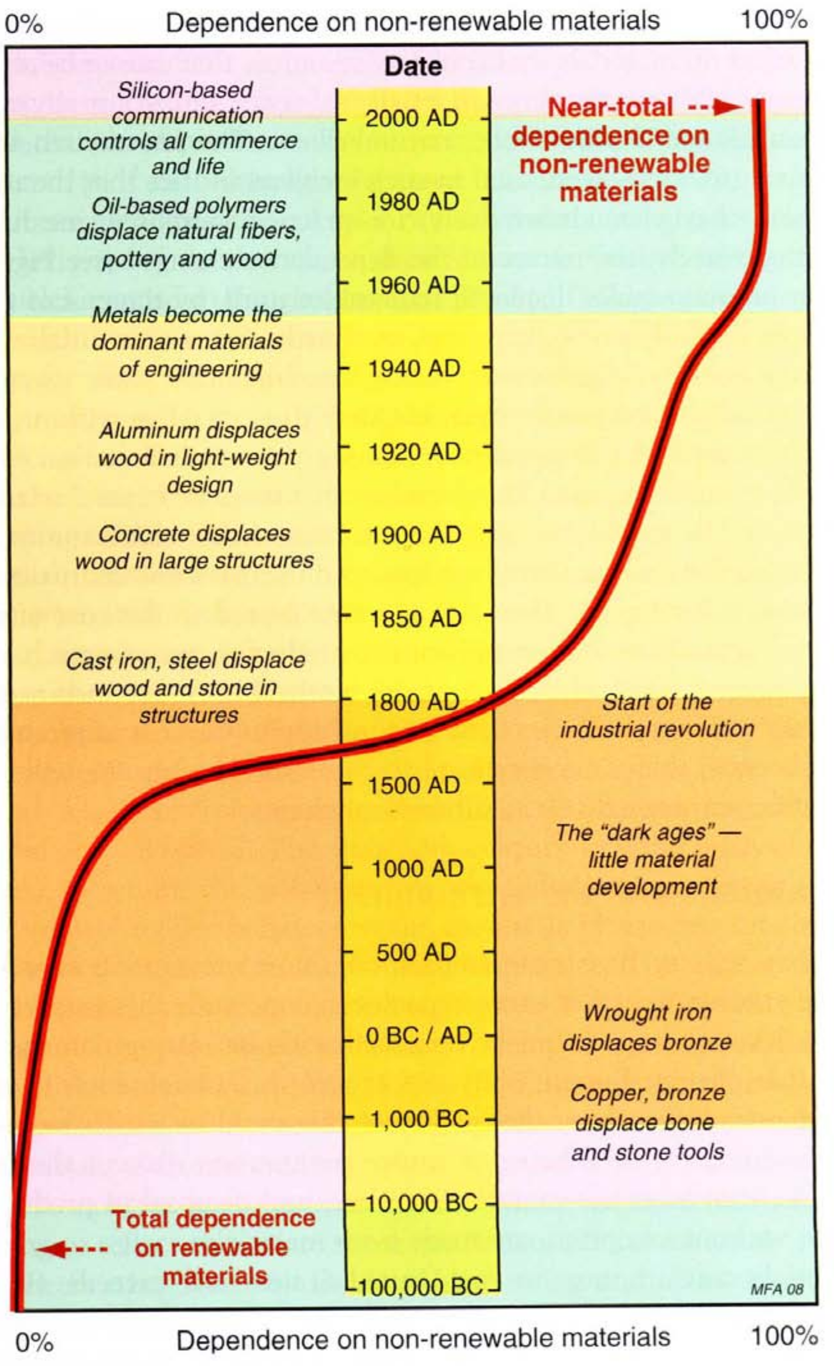
***IGERT Associates**

Pb-Free Electronics

- Waste shipped to China and developing countries
  - Concentrates recycled electronics in countries with weakest recycling and environmental regulations
- Ultimately may reduce Pb-poisioning during informal recycling – but not yet
- Tin whiskers are reliability problem
- Pb-free electronics are less impact-resistant
  - Higher processing temperatures
  - Circuit boards are more brittle
  - Stronger solder leads to more damage to the board
- More Sn mined – Conflict mineral
- More Ag mined

Anthropology: Materials Development

Ashby, Shercliff, Cebon
Materials – Engineering, Science, Processing, and Design, 2010



Journal of Archaeological Science (2000) **27**, 771–778
doi:10.1006/jasc.1999.0580, available online at http://www.idealibrary.com on IDEAL®

An Imperial Legacy? An Exploration of the Environmental Impact of Ancient Metal Mining and Smelting in Southern Jordan

F. B. Pyatt*

Extensive wastes from the copper mining and smelting activities of the Nabatean, Roman and Byzantine periods in the Wadi Faynan in the southern Jordanian desert continue to exert a profound influence upon the environment, mainly through processes of bioaccumulation. It is suggested that in antiquity both producers and consumers (plants and animals) would have similarly been subjected to enhanced bioaccumulation of potentially toxic heavy metals such as lead and copper, whose consequences are explored in this account.

J. P. Grattan

Institute of Geography and Earth Sciences, The University of Wales, Aberystwyth SY23 3DB, U.K.

C. O. Hunt

Department of Geographical and Env
U.K.

S. McLaren

Department of Geography, Universit

(Gilbertson *et al.*, 1997). Small wonder then that in Romano-Byzantine times the mines of Phaino were seen as a place to send recalcitrant criminals. Eusebius of Caesarea in his "Martyrs of Palestine" describes such a scene; "they demanded that he should be sent away to the mines, and not just any mines but to that of Phaino where even a condemned murderer is hardly able to live a few days".

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- How innovative are we prepared to be?
- How resilient are we to change?

Welsh miner Charlie Williams, with canary, in Dinas mine, Rhonda Valley, in 1965

Richard Heinberg

Post Carbon Institute - September 2009

Antimony	China	Thermoelectric/paraelectric materials
Barium	China	Thermoelectric/paraelectric materials
Bismuth	China, Mexico	Thermoelectric/paraelectric materials
Cobalt	Kinshasa, Australia	Photovoltaics
Gallium	China	Photovoltaics
Germanium	Belgium, Canada	Photovoltaics
Indium	China, Canada	Photovoltaics, thermo/paraelectric mat'ls
Manganese	Gabon, S. Africa	Photovoltaics
Nickel	Canada	Fuel cells
Platinum	S. Africa	Fuel cells, thermoelectric materials
Rare Earths	China	Fuel cells, magnets, thermoelectric materials
Tellurium	Belgium, Germany	Solar cells, semiconductors
Titanium	Australia, S. Africa	Solar cells
Zinc	Canada, Mexico	Photovoltaics, fuel cells

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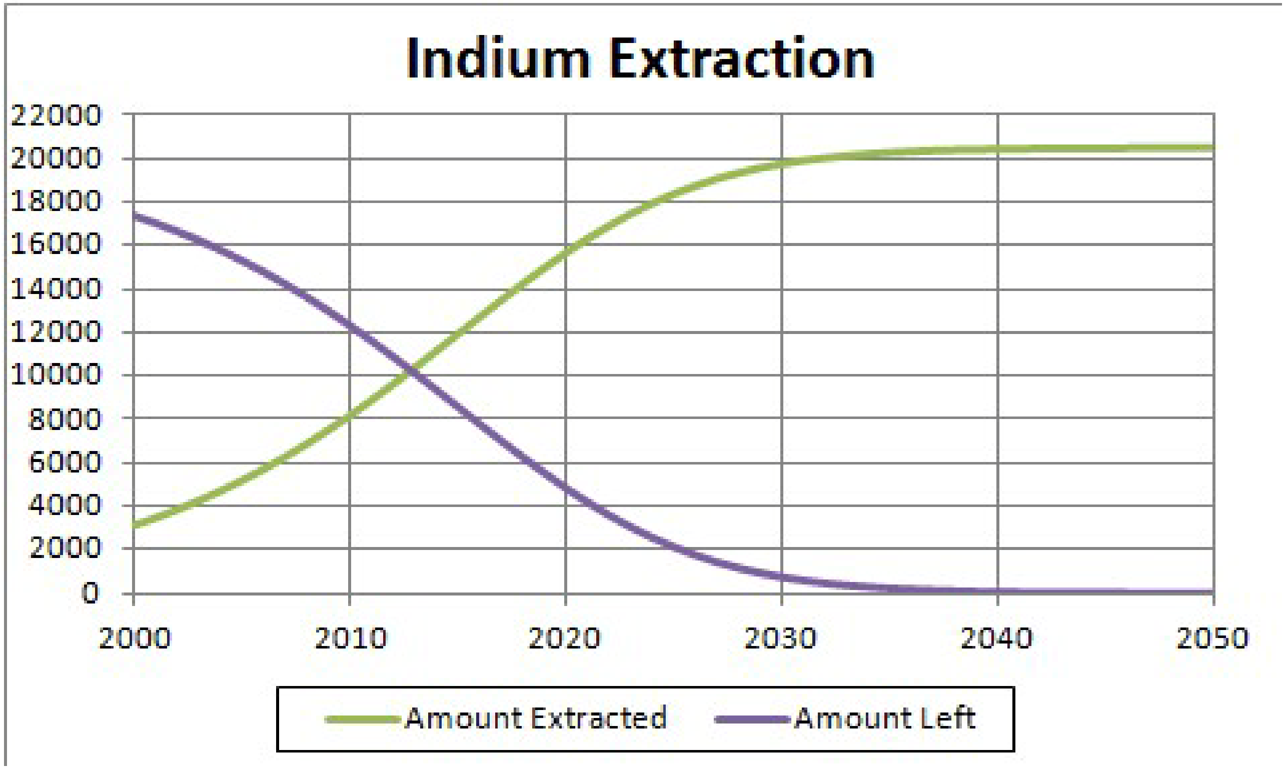
Indium Depletion



- Deposits of tin and tungsten have the highest known concentrations of Indium (Tolcin)
- By 2040 all currently known Indium deposits will have been mined (Roper)

Roper, David L. Indium Depletion Including Recycling. http://arts.bev.net/RoperLDavid/20 March, 2010

Tolcin, Amy C. *USGS Mineral Resources Program. 2011*. http://minerals.usgs.gov/minerals/pubs/commodity/indium/mcs-2008-indiu.pdf

Energy Analysis for a Coffeemaker

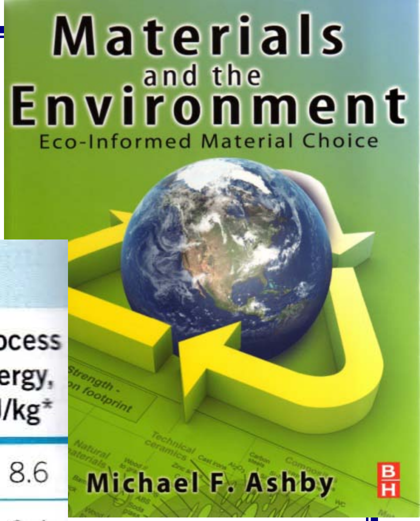


Table 7.6 Coffee maker142 bill of materials, life: five years

Component	Material	Process	Mass, kg	Material energy, MJ/kg*	Process energy, MJ/kg*
Housing	Polypropylene	Polymer molding	0.91	94	8.6
Small steel parts	Steel	Def. processing	0.12	81	3.4
Small aluminum parts	Aluminum	Def. processing	0.08	210	2.6
Glass jug	Glass (Pyrex)	Molded	0.33	25	8.2
Heating element	Ni-Cr alloy	Def. processing	0.026	130	2.6
Electronics and LED	Electronics	Assembled	0.007	3000	130
Cable sheath, 1 meter	PVC	Polymer extrusion	0.12	66	7.6
Cable core, 1 meter	Copper	Def. processing	0.035	71	2.0
Plug body	Phenolic	Polymer molding	0.037	90	13
Plug pins	Brass	Def. processing	0.03	72	2.3
Packaging, padding	Polymer foam	Polymer molding	0.015	110	11
Packaging, box	Cardboard	Construction	0.125	28	0.5
Other components	*Proxy material:* Polycarbonate	*Proxy process:* Polymer molding	0.04	110	11
		Total mass	**1.9**		

**From the data sheets of Chapter 12 and Table 6.4.*

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(2) Prepare grad … ural … be

(3) … inciples of p … g … , and interdisciplinary b …

How to agree upon common goals

to have difficult, yet productive conversations

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(4) Develop a curriculum with our industry and international university partners in Germany, Colombia, India, and China and disseminate it widely through Purdue's globalHUB cyberinfrastructure to positively influence the global stakeholders who impact electronics sustainability.

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Material Recycling at Product End-of-Life

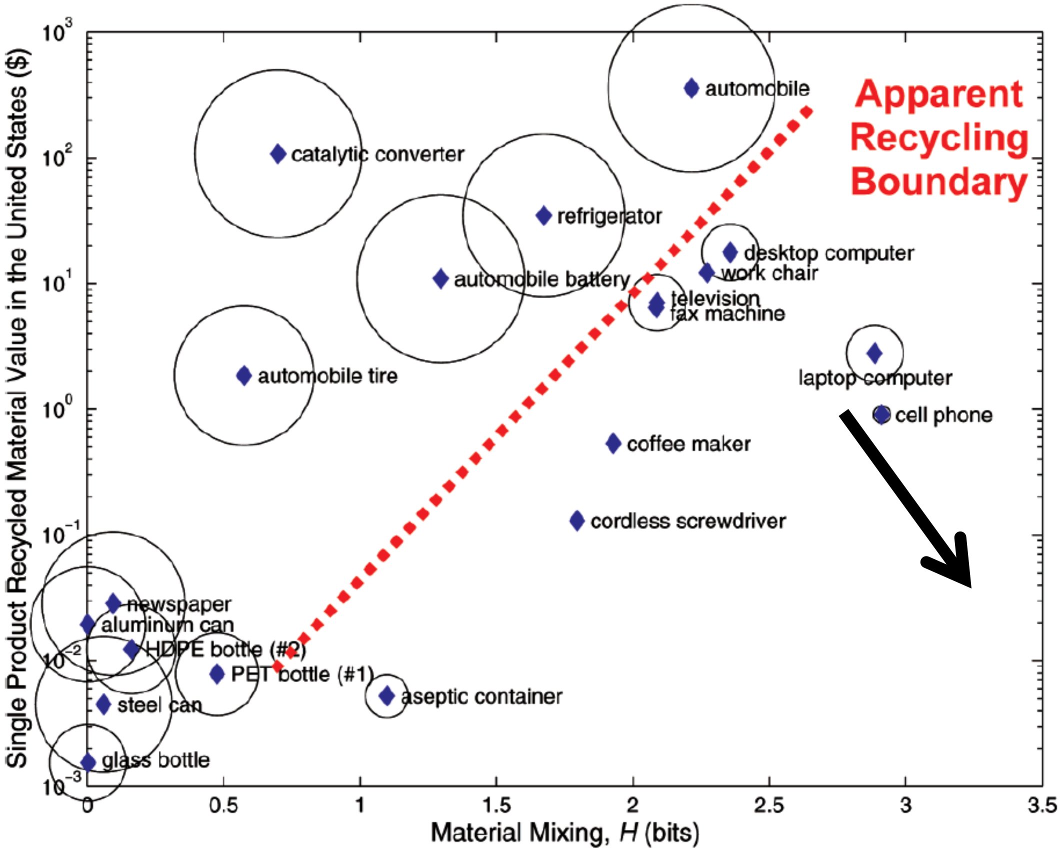

FIGURE 4. A plot of single product recycled material values ($\sum m_i k_i$), material mixing (H), and recycling rates (indicated by the area of the circles) for 20 products in the U.S. The "apparent recycling boundary" is shown.

"However, while recycling technologies may improve, design trends seem to be pushing products towards lower material value and greater material mixing. Designers are constantly motivated to reduce material costs in products, either by using less material or by using less expensive materials. At the same time, materials are being used in new and different applications, presenting designers with increasingly wider selections of potential materials."

Material Recycling at Product End-of-Life
Jeffrey B. Dahmus and Timothy G. Gutowski
ENVIRONMENTAL SCIENCE & TECHNOLOGY / VOL. 41, NO. 21, 2007

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Maslow's Hierarchy of Needs

- Sustainable for whom?
- Sustainable over what time?

Polymeric Materials Used in Electronic Packaging

Adhesive
Acrylic, Epoxy silicone, Epoxy novalac, Epoxy bisphenol A, Epoxy polyimide, Epoxy polyurethane, Polyimide, Silicones

Encapsulation
Polyetherketone, Polyetheretherketone, Polysulfone, Polyethersulfone, Polyester Epoxy and filled epoxy Silicones and filled silicones

Substrate
Bis-maleimide triazine (BT) resin, BT-Epoxy E-glass laminate, Epoxy-E-glass laminate,Polyimide-E-glass laminate, Poly(tetrafluoroethylene)-E-glass laminate, Polyimide-E-glass laminate, Polyester film, Polyimide film, Poly(tetrafluoroethylene) film, Polyamide film, Poly(vinyl chloride) film, Poly(vinyl fluoride) film, Polyethylene film, Polypropylene film, Polycarbonate film, Polysulfone film, Poly(parabanic acid) film, Poly(ethersulfone) film

Stress buffer coating
Poly(amide-imide), Poly(benzocyclobutene)–BCB, Polybenzoxazole, PolyimideRTV Silicone

Interlayer dielectric
Poly(benzocyclobutene)–BCB, Polybenzoxazole, Polyimide, Poly(norbornene), Triazine blend resin

from http://www.scribd.com/doc/101919564/Electronic-Packaging

NNI – Face of US Nanotechnology

"The vision of the NNI is a future in which the ability to understand and control matter at the nanoscale leads to a revolution in technology and industry that benefits society.

The NNI expedites the discovery, development, and deployment of nanoscale science, engineering, and technology to serve the public good, through a program of coordinated research and development aligned with the missions of the participating agencies."

From 2011 National Nanotechnology Initiative Strategic Plan

Definitions of NNI Success

THE NATIONAL ACADEMIES

- Frontiers of knowledge are being substantially advanced, commensurate with the scale of funding.
- An appropriate, world-class scientific and technical workforce is being trained and educated in the US.
- Vibrant, competitive and sustainable industry sectors evolve in the USA that use nanotechnology to enable the creation of new products, skilled employment and economic growth.
- NNI infrastructure meets the users’ needs.
- Businesses of all sizes are aware of potential risks of nanomaterials and know where to obtain current information about properties and best practices for handling them.