Panel 7:
Sustainable Nanomaterials and Nanomanufacturing

2013 NSF Nanoscale Science and Engineering Grantees Conference

December 4-6, 2013

Westin Hotel - Arlington, VA

Panel 7: Path Forward

Moderators

- **Jackie Isaacs**, Northeastern University
- **Nora Savage**, EPA

Panelists

- **Jackie Isaacs**, Northeastern University
  - Mechanical and Industrial Engineering
- **Matt Eckelman**, Northeastern University
  - Civil and Environmental Engineering
- **Gabrielle Gaustad**, Rochester Institute of Technology
  - Golisano Institute for Sustainability

It's All About Definitions…

sus·tain·a·ble

/səˈstānəbəl/

adjective

adjective: **sustainable**

1. able to be maintained at a certain rate or level.
   "sustainable fusion reactions"
   - conserving an ecological balance by avoiding depletion of natural resources.
     "our fundamental commitment to sustainable development"
2. able to be upheld or defended.
   "sustainable definitions of good educational practice"

Translate sustainable to Choose language

Use over time for: sustainable

nan·o·ma·te·ri·al

/ˈnanōməˌti(ə)rēəl/

noun

plural noun: **nanomaterials**

1. a material having particles or constituents of nanoscale dimensions, or one that is produced by nanotechnology.

Translate nanomaterials to Choose language

Use over time for: nanomaterials

and

/and/

conjunction

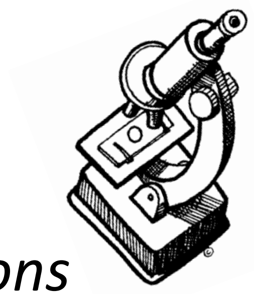
1. used to connect words of the same part of speech, clauses, or sentences that are to be taken jointly.
   "bread and butter"
   synonyms: together with, along with, with, as well as, in addition to, also; More

nanomanufacturing

Web definitions

Nanomanufacturing is both the production of nanoscaled materials, which can be powders or fluids, and the manufacturing of parts "bottom up" from nanoscaled materials or "top down" in smallest steps for high precision, used in several technologies such as laser ablation, etching and others. ...
http://en.wikipedia.org/wiki/Nanomanufacturing

A Closer Look at Sustainability…



Sustainable Development has many definitions…
Most commonly quoted is:

Development that meets the needs of current generations without compromising the ability of future generations to meet their needs and aspirations.

WCED*, in Brundtland Report, 1987

What is done now to improve the quality of life should not degrade the environment or its resources such that future generations are put at a disadvantage.

*WCED is the United Nations-sponsored World Commission on Environment and Development

USDA on Sustainable Development

RIO+20 Commitments

USDA highlighted nine commitments to sustainable development at the United Nations conference on Sustainable Development (Rio+20). Photo: U.S. Delegation to Rio+20

Sustainable Development

The U.S. Department of Agriculture is committed to working with partners and stakeholders toward sustainability of diverse agricultural, forest and range systems. USDA seeks to balance the goals of:

- Satisfying human needs;
- Enchancing environmental quality, the resource base, and ecosystem services;
- Sustaining the economic viability of agriculture;
- Enhancing the quality of life for farmers, ranchers, forest mangers, workers and society as a whole.

USDA integrates these goals into its policies and programs, particularly through interagency collaboration, partnership and outreach at both domestic and international levels.

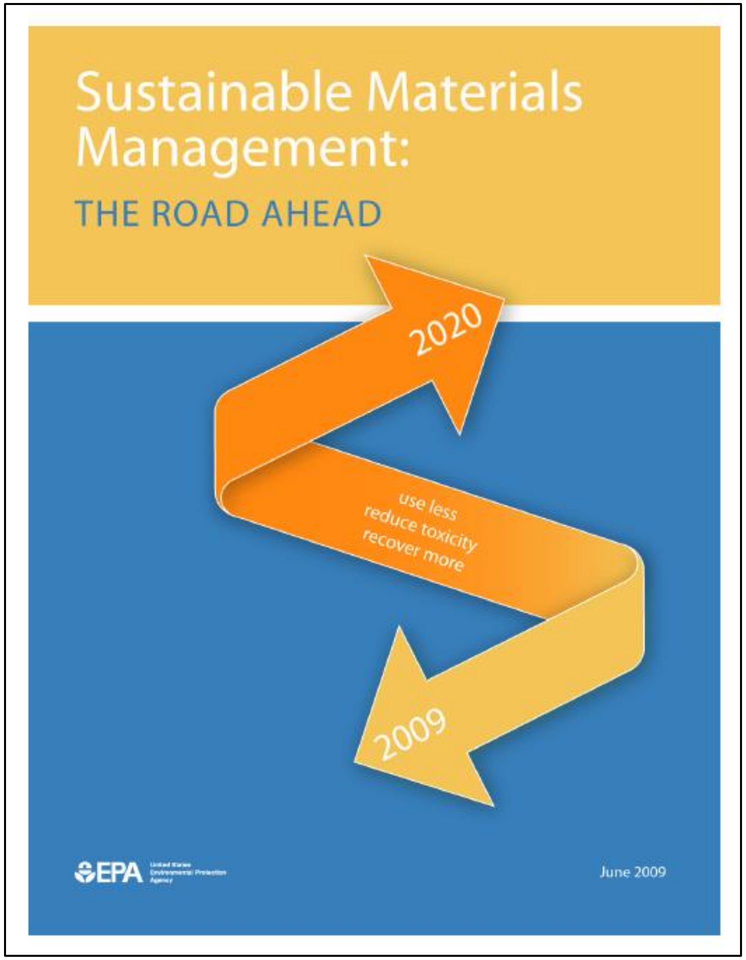
USDA encourages the development and adoption of place-and-scale-appropriate management, production, distribution, and information systems that advance continuous, integrated progress toward all of these goals across landscapes, supply chains and markets. USDA also supports the principles of "reduce, reuse, and recycle" in relation to efficient product handling, processing, transportation, packaging, trade, consumption and waste management.

2011 National Academies Report

http://sites.nationalacademies.org/PGA/sustainability/EPA/index.htm

US EPA Vision on Sustainable Materials…

"We live in a material world. How our society uses materials is fundamental to many aspects of our economic and environmental future. If we want to be competitive in the world economy, the sustainable use of materials must be our goal. Our key message is simple."



http://www.epa.gov/epawaste/conserve/smm/vision.htm

Implementation of Green Design

Green Chemistry Principles		Designing Greener Nanomaterial and Nanomaterial Production Methods		Practicing Green Nanoscience
P1.	Prevent waste	Design of safer nanomaterials (P4,P12)	→	Determine the biological impacts of nanoparticle size, surface area, surface functionality; utilize this knowledge to design effective safer materials that possess desired physical properties; avoid incorporation of toxic elements in nanoparticle compositions
P2.	Atom economy			
P3.	Less hazardous chemical synthesis	Design for reduced environmental impact (P7,P10)	→	Study nanomaterial degradation and fate in the environment; design material to degrade to harmless subunits or products. An important approach involves avoiding the use of hazardous elements in nanoparticle formulation; the use of hazardless, bio-based nanoparticle feedstocks may be a key.
P4.	Designing safer chemicals			
P5.	Safer solvents/reaction media	Design for waste reduction (P1,P5,P8)	→	Eliminate solvent-intensive purifications by utilizing selective nanosyntheses - resulting in greater purity and monodispersity; develop new purification methods, e.g. nanofiltration, that minimize solvent use; utilize bottom-up approaches to enhance materials efficiency and eliminate steps
P6.	Design for energy efficiency			
P7.	Renewable feedstocks	Design for process safety (P3,P5,P7,P12)	→	Design and develop advanced syntheses that utilize more benign reagents and solvents than used in "discovery" preparations; utilize more benign feedstocks, derived from renewable sources, if possible; identify replacements for highly toxic and pyrophoric reagents
P8.	Reduce derivatives			
P9.	Catalysis	Design for materials efficiency (P2,P5,P9,P11)	→	Develop new, compact synthetic strategies; optimize incorporation raw material in products through bottom-up approaches, use alternative reaction media and catalysis to enhance reaction selectivity; develop real-time monitoring to guide process control in complex nanoparticle syntheses
P10.	Design for degradation/Design for end of life			
P11.	Real-time monitoring and process control	Design for energy efficiency (P6,P9,P11)	→	Pursue efficient synthetic pathways that can be carried out at ambient temperature rather than elevated temperatures; utilize non-covalent and bottom-up assembly method near ambient temperature, utilize real-time monitoring to optimize reaction chemistry and minimize energy costs
P12.	Inherently safer chemistry			

Sustainable Nanotechnology Organization
Research | Education | Responsibility

Karn, 2014 SNO Annual Conference, Santa Barbara
Dahl et al Greener Nano Synthesis, Chem. Rev. 2007 107:2228

US National Nanotechnology Initiative

Goal 1: Advance a world-class nanotechnology research and development program;

Goal 2: Foster the transfer of new technologies into products for commercial and public benefit;

Goal 3: Develop and sustain educational resources, a skilled workforce, and the supporting infrastructure and tools to advance nanotechnology; and

Goal 4: Support responsible development of nanotechnology

Goal 4: Objectives

4.1. Support the creation of a comprehensive knowledge base for evaluation of the potential risks and benefits of nanotechnology to the environment and to human health and safety.

4.2. Create and employ means for timely dissemination, evaluation, and incorporation of relevant EHS knowledge and best practices.

4.3. Develop the national capacity to identify, define, and responsibly address concepts and challenges specific to the ethical, legal, and societal implications (ELSI) of nanotechnology

4.4. Incorporate sustainability in the responsible development of nanotechnology.

> **How do you measure success?**

Five NNI Signature Initiatives

"To accelerate nanotechnology development in support of national priorities and innovation strategy, OSTP and NNI member agencies identified areas ripe for significant advances …on critical challenges and R&D gaps."

1. **Nanotechnology for Solar Energy Collection and Conversion: Contributing to Energy Solutions for the Future**
2. **Sustainable Nanomanufacturing: Creating the Industries of the Future**
3. **Nanoelectronics for 2020 and Beyond**
4. **Nanotechnology Knowledge Infrastructure**
5. **Nanotechnology for Sensors and Sensors for Nanotechnology: Improving and Protecting Health, Safety, and the Environment**

NSTC COMMITTEE ON TECHNOLOGY
SUBCOMMITTEE ON NANOSCALE SCIENCE, ENGINEERING, AND TECHNOLOGY

National Nanotechnology Initiative Signature Initiative:

Sustainable Nanomanufacturing – Creating the Industries of the Future

Final Draft, July 2010

Collaborating Agencies[1]: *NIST, NSF, DOE, EPA, IC, NIH, NIOSH, OSHA, USDA/ Forest Service*

National Need Addressed

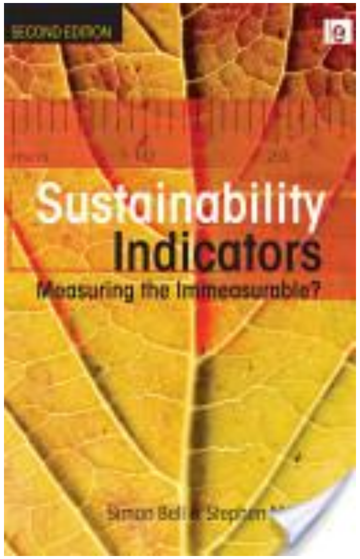
This interagency initiative will establish manufacturing technologies for economical and sustainable integration of nanoscale building blocks into complex, large-scale systems.

A decade of research under the National Nanotechnology Initiative has led to remarkable discoveries of nanoscale materials with unique properties, laboratory demonstrations of a range of innovative nanoscale devices, and introduction of a limited number of nanotechnology-based products into the marketplace. For this investment to become the basis for high-value industries, methods must be established to efficiently assemble products that integrate together billions of nanoscale devices with disparate functions. Current manufacturing methods such as those used in the semiconductor industry will not be economical at these scales; radically new approaches are needed. Moreover, for such products to be ubiquitous in the nation's future economy without causing long-term negative environmental or health impacts, these new approaches and the resulting products must be inherently sustainable by design.

A long-term vision for nanomanufacturing is to create flexible, "bottom-up" or "top-down/bottom-up" continuous assembly methods that can be used to construct elaborate systems of complex nanodevices. Moreover, these systems by design will reduce the overall environmental and health impacts over their full life cycle; for example, by minimizing any release of harmful nanomaterials or substances, and reducing energy consumption. To create the foundation for achieving this vision, over the next decade this initiative will first establish sustainable industrial-scale manufacturing of functional systems with relatively limited complexity based on manufactured nanoparticles with designed properties. The organized assemblies of nanoparticles manufactured here will be designed to control and manipulate

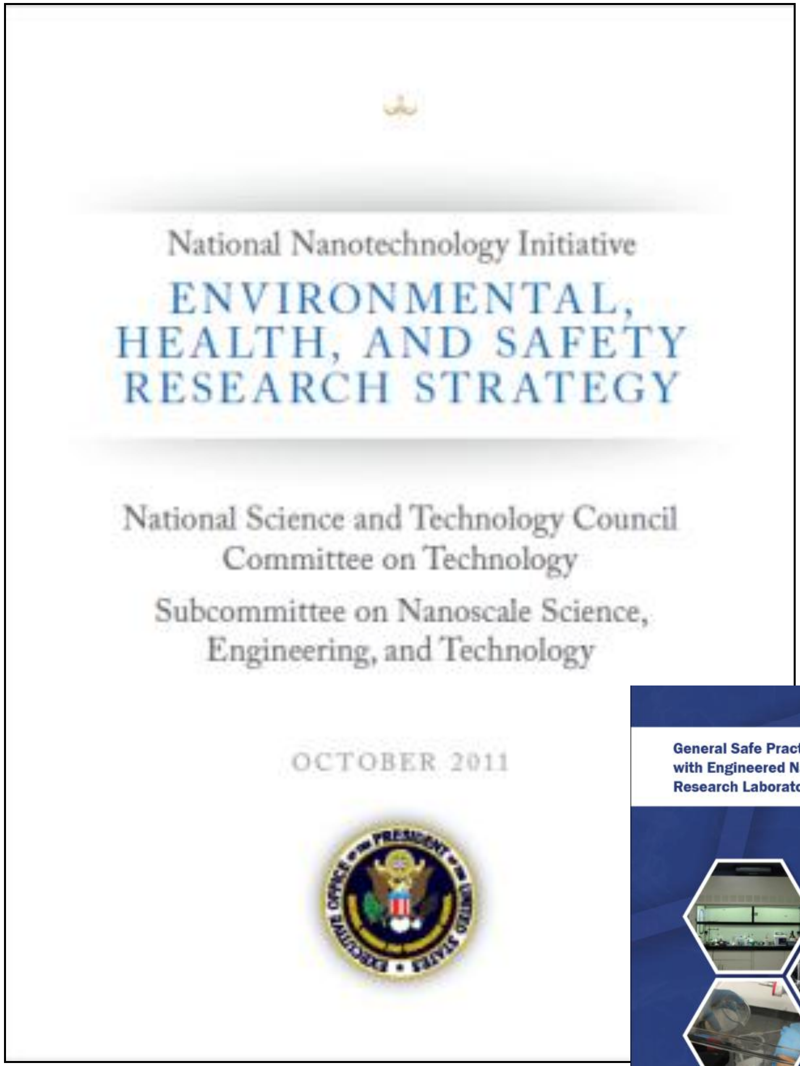
Chicken and Egg Problem

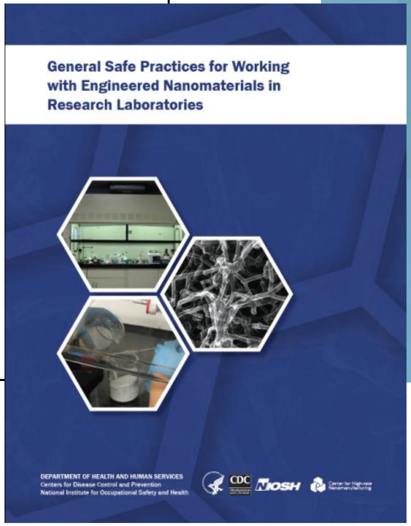
"Indeed, sustainability is not a "thing" that can be measured.... sustainability becomes defined by the parameters that can be measured, rather than the other way around."

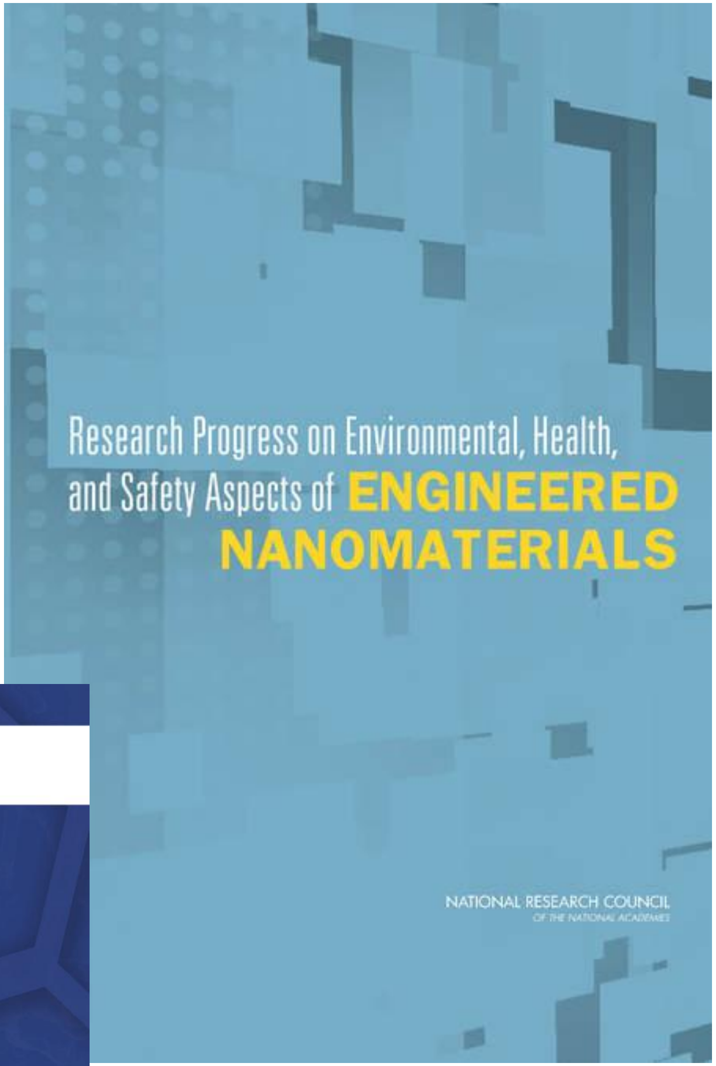


From book entitled
"Sustainability Indicators: Measuring the Immeasurable?"
Simon Bell and Stephen Morse, 2008

Recent NNI and NRC Guidance Documents…

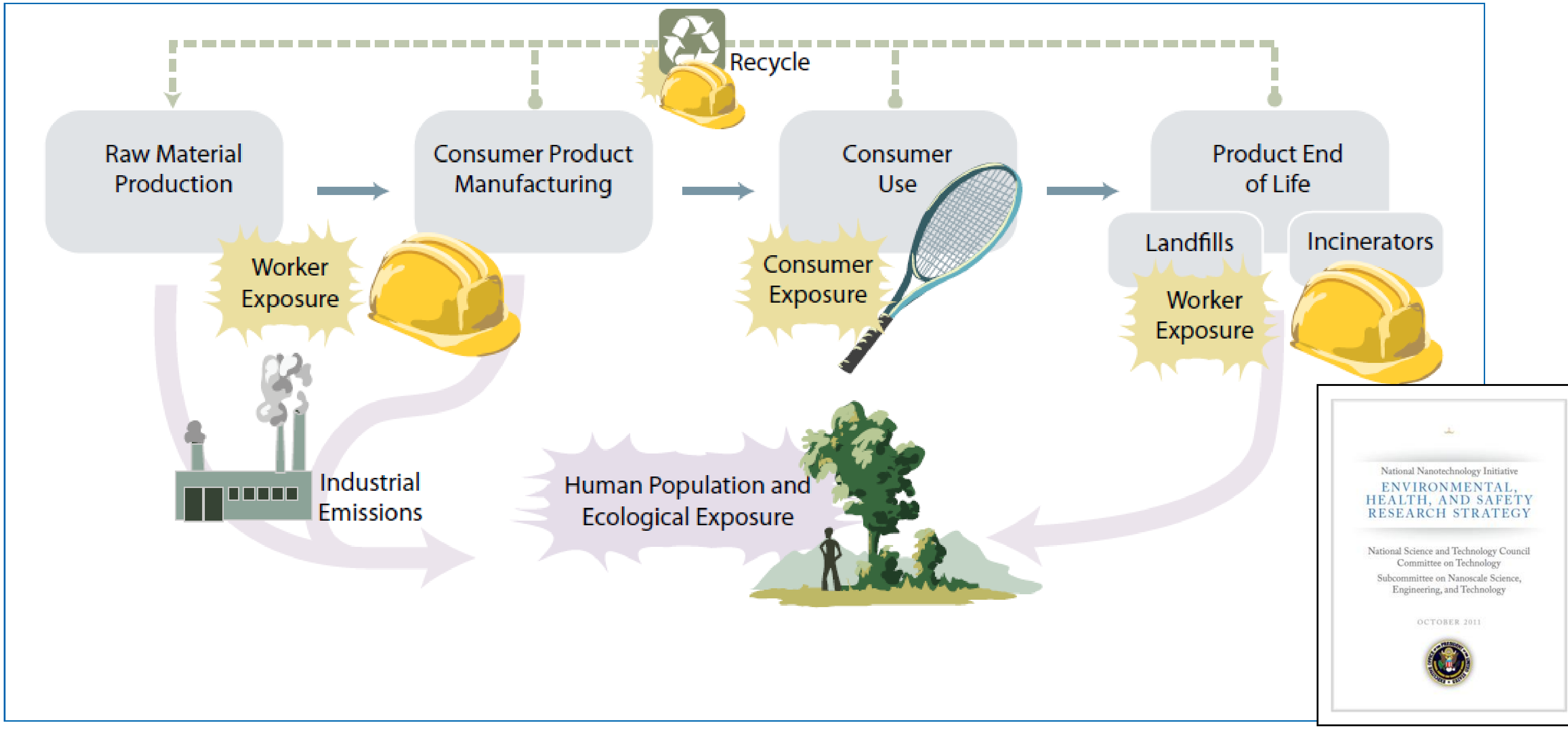






…and NIOSH

Increased Emphasis on Life Cycle Perspective



National Nanotechnology Initiative
ENVIRONMENTAL, HEALTH, AND SAFETY RESEARCH STRATEGY
National Science and Technology Council
Committee on Technology
Subcommittee on Nanoscale Science, Engineering, and Technology
OCTOBER 2011

Figure 1-5. The life cycle perspective on risk assessment. Life cycle assessment supports sound product development, responsible nanomanufacturing (scaling up), and protection of public health.

Source: EPA 100/B07/001, February 2007, http://epa.gov/osa. N.R. Fuller of Sayo-Art provided revised image graphics.

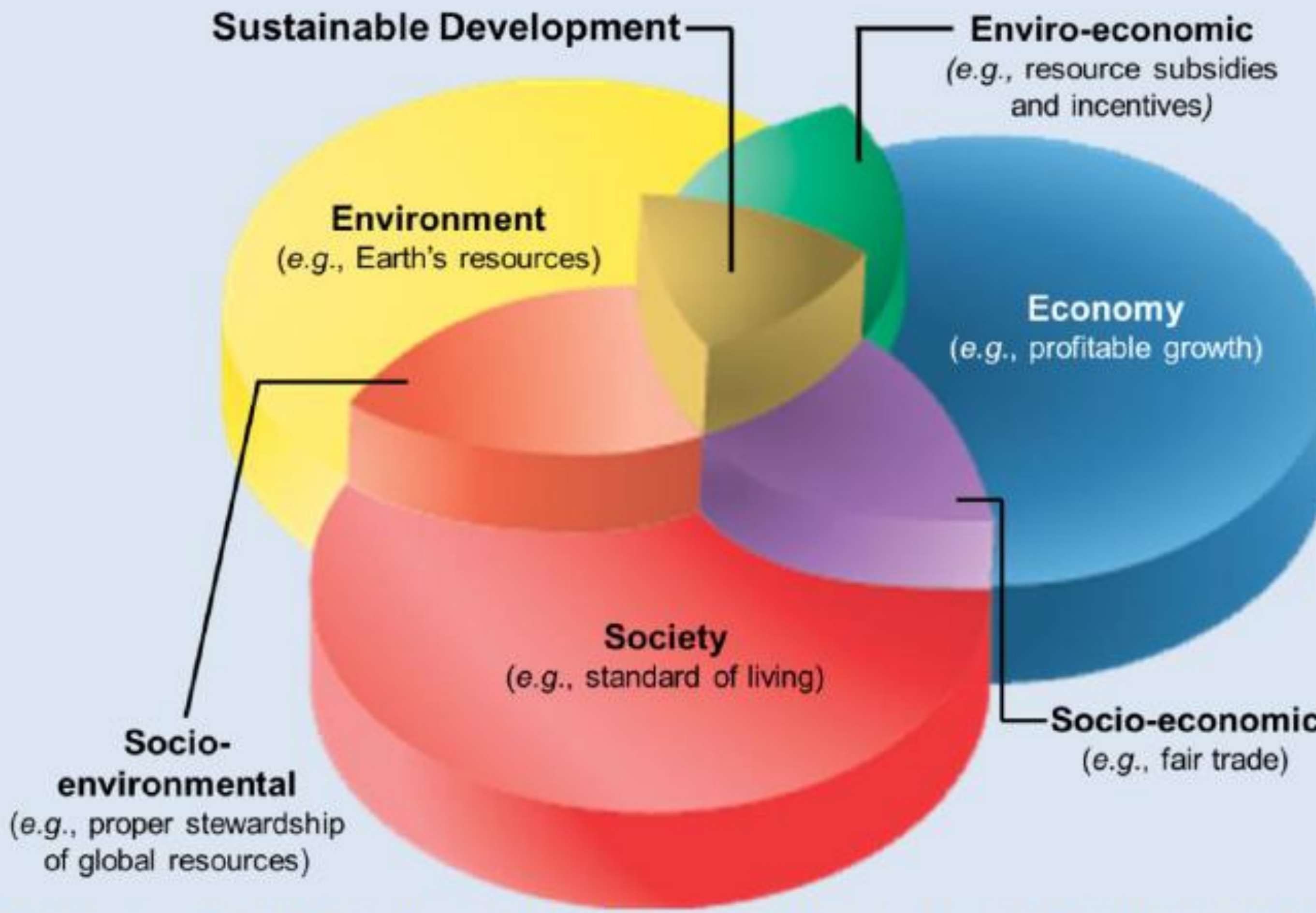
Same figure used in Draft 2014 NNI Strategic Plan…

Center for High-rate Nanomanufacturing

2014 Draft NNI Strategic Plan

Sustainability

The development of sustainable ENMs, NEP manufacturing, and end-of-life processes must incorporate societal, economic, and environmental considerations.



Source: Martin L. Green, NIST; figure adapted from "Materials for Sustainable Development", MRS Bulletin 37(4), 304 (2012).

EPA United States Environmental Protection Agency

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Assessing Nanomaterials Potential Impact with a Life Cycle Approach

Issue:

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Materials that incorporate particles manufactured at the nano scale (nanomaterials) may have many potential benefits to society with their development and deployment in science, engineering and technology. Their benefits, however, need to be weighed with any potential cost to the environment and public health. As a result, scientists at the U.S. Environmental Protection Agency have recognized the need to develop risk assessment processes to study the potential health and environmental impacts of nanomaterials.

In addition, scientists want to understand how the manufacture, use, and waste management of these nanomaterials could potentially contribute to ongoing environmental problems during their life-cycle from cradle to grave, including recycling. For example, is there the potential for nanomaterials to impact global warming, stratospheric ozone depletion, acidification (formation of acid rain) or eutrophication (the increase of chemical nutrients in water)?

Scientific Objective:

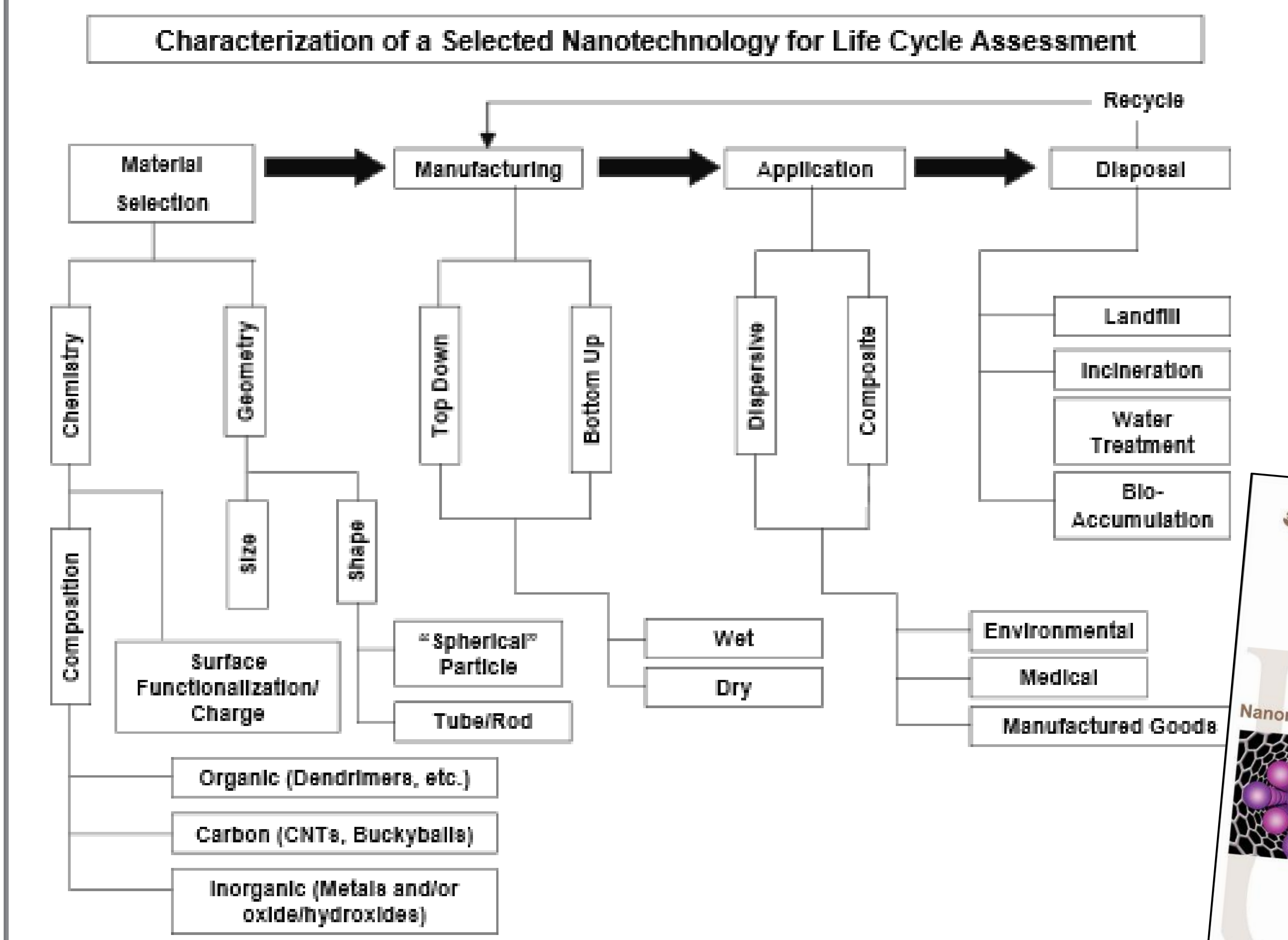
EPA's Nanotechnology Research Program in the Office of Research and Development is conducting a series of Life Cycle Assessments (LCAs) on various products made from nanomaterials to gain knowledge about potential release into the environment. The assessments are holistic and comprehensive and track a product from its inception (cradle) through its final disposal (grave). LCAs are essential to analyze, evaluate, understand, and manage the overall health and environmental impacts of products.

LCA experts worldwide agree that existing LCA tools are capable of supporting the development of decisions on the manufacture and use of nanomaterials as long as uncertainties and data gaps are clearly stated (Kloepffer et al 2007).

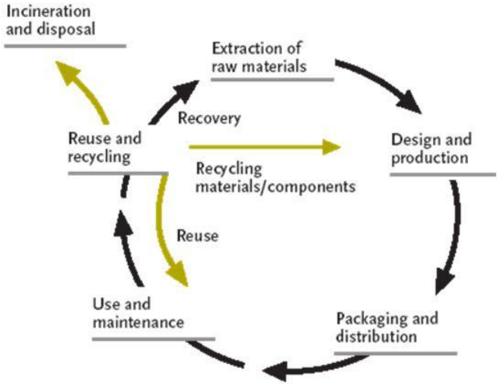
Google "EPA Nanotech LCA"
http://www.epa.gov/nanoscience/quickfinder/lifecycle.htm18

Figure 4-8 Characterization of a Selected Nanotechnology for Life Cycle Assessment

Characterization of nanotechnologies for life cycle assessment is challenging because of the various aspects of the material that can significantly influence the traditional impact categories.



LCA: Needs and Challenges



Why Life Cycle Thinking?

- Help reduce material and energy consumption
- Quantify emissions and reduce environmental burden
- Compare nanoproducts with alternatives
- Identify sources of inefficiencies (Energy or Impact)

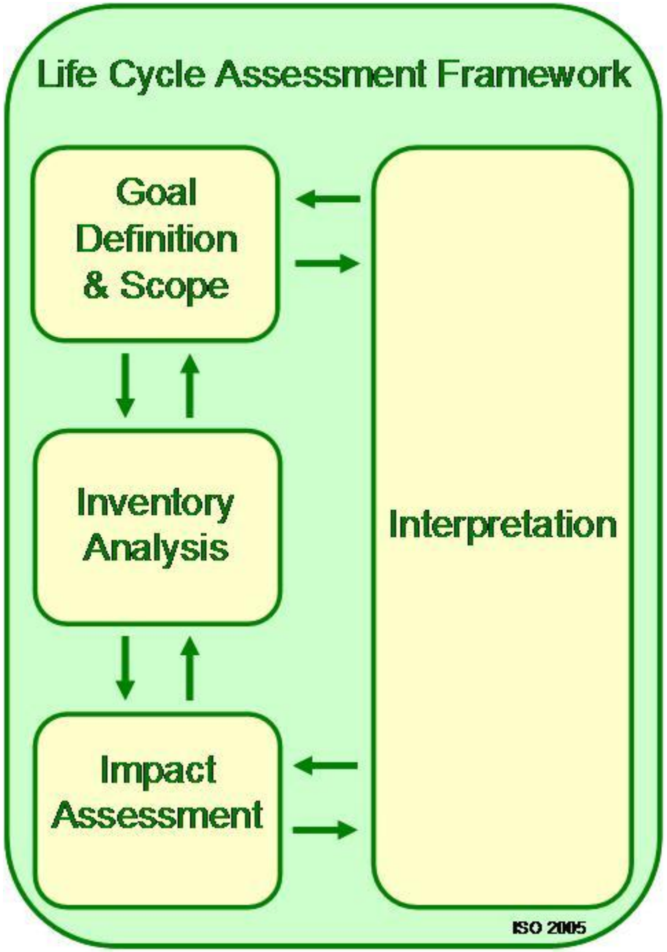
Challenges

- Collecting inventories for nanomaterials and nanoprocesses
- Quantifying impact of engineered nanomaterials on humans and ecosystems
- Predicting life cycle processes and activities while processes and products are still in nascent stages

Methodology: Life Cycle Assessment (LCA)

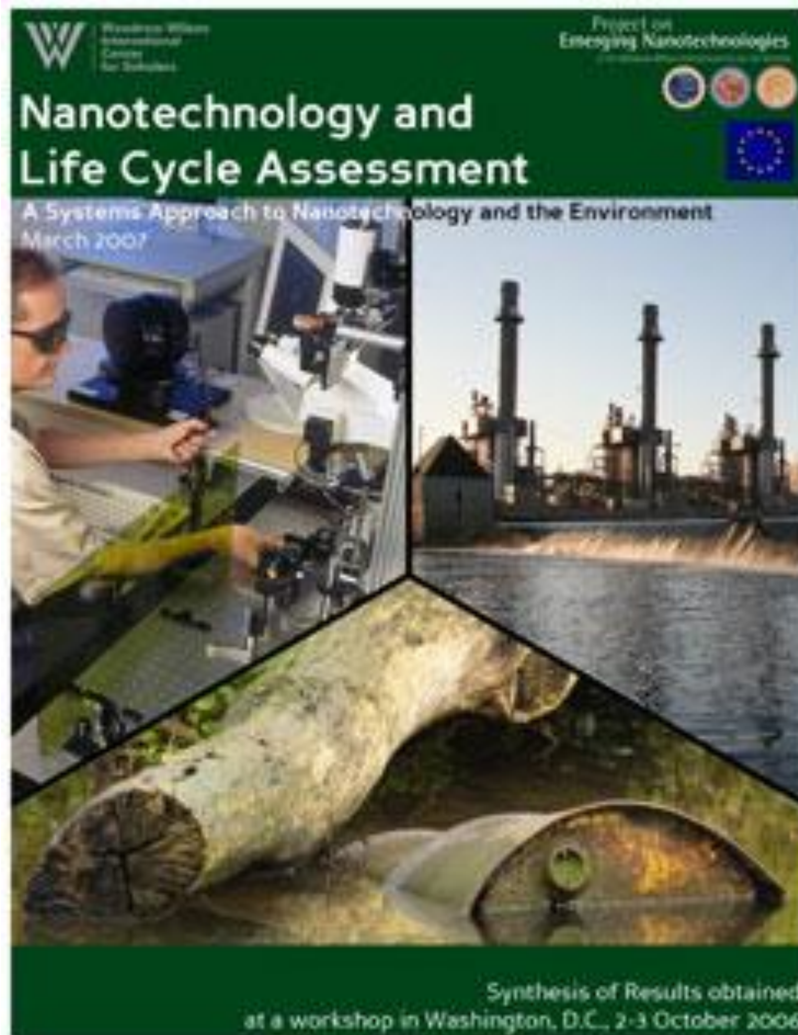
LCA techniques used to investigate environmental impacts associated with a product's life cycle

- ***Scope:*** Sets boundaries and assumptions, e.g., phases of product life cycle to include
- ***Inventory Analysis:*** Input data (materials, energy usage, labor) and output data (emissions to land, water, air) collected for lab-scale processes
- ***Impact Assessment: S***oftware used to determine preliminary environmental impact
- ***Interpretation:*** Valuation, weighting, preferences, sensitivity analyses…



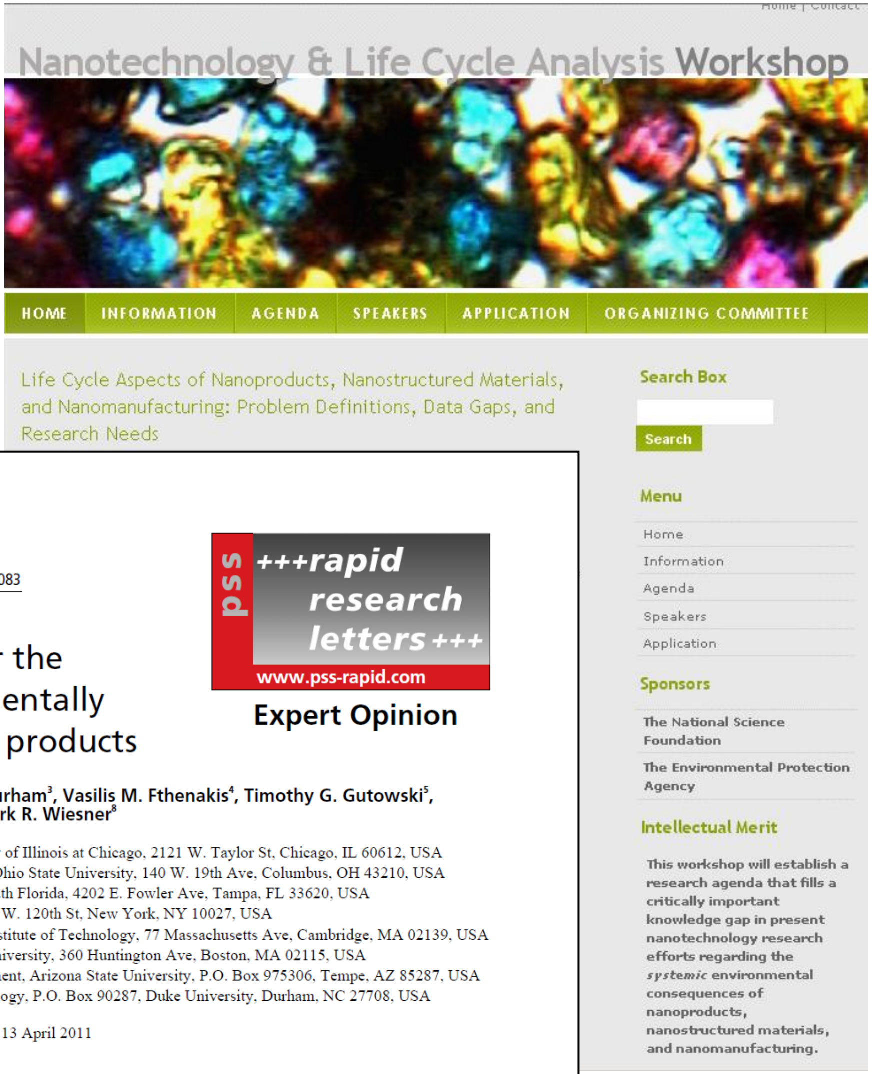
2007 D.C. Report: Nanotechnology & LCA

- EPA Workshop in October 2006
- Breakout discussions on how to use LCA in light of limited impact data
- Participants from
  US and Europe
- LCA experts & nano experts
- Report released in Feb 2007
- Report hosted on web site of Wilson Center,
  Project on Emerging Nanotechnologies
- www.nanotechproject.org



2009 Chicago Workshop: Nanotech & LCA

- Workshop in November 2009
- Breakout discussions on how to use LCA in light of limited impact data
- Participants from US
- LCA experts & nano experts
- Findings published in April 2011



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citable using Digital Object Identifier – **DOI**)

Phys. Status Solidi RRL, 1–6 (2011) / **DOI** 10.1002/pssr.201105083

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Expert Opinion

A life cycle framework for the investigation of environmentally benign nanoparticles and products

Thomas L. Theis[*,1], Bhavik R. Bakshi[2], Delcie Durham[3], Vasilis M. Fthenakis[4], Timothy G. Gutowski[5], Jacqueline A. Isaacs[6], Thomas Seager[7], and Mark R. Wiesner[8]

[1] Institute for Environmental Science and Policy, University of Illinois at Chicago, 2121 W. Taylor St, Chicago, IL 60612, USA
[2] Department of Chemical and Biomolecular Engineering, Ohio State University, 140 W. 19th Ave, Columbus, OH 43210, USA
[3] Department of Mechanical Engineering, University of South Florida, 4202 E. Fowler Ave, Tampa, FL 33620, USA
[4] Center for Life Cycle Analysis, Columbia University, 500 W. 120th St, New York, NY 10027, USA
[5] Department of Mechanical Engineering, Massachusetts Institute of Technology, 77 Massachusetts Ave, Cambridge, MA 02139, USA
[6] Center for High-rate Nanomanufacturing, Northeastern University, 360 Huntington Ave, Boston, MA 02115, USA
[7] School of Sustainable Engineering and the Built Environment, Arizona State University, P.O. Box 975306, Tempe, AZ 85287, USA
[8] Center for the Environmental Implications of Nanotechnology, P.O. Box 90287, Duke University, Durham, NC 27708, USA

Received 26 January 2011, revised 11 April 2011, accepted 13 April 2011
Published online 18 April 2011

Keywords nanoparticles, nanoproducts, life cycle analysis, environmental quality

[*] Corresponding author: e-mail theist@uic.edu, Phone: +1 312 996 1081, Fax: +1 312 355 0760

2011 Barcelona Workshop: NanoLCA

SAFETY ISSUES OF NANOMATERIALS ALONG THEIR LIFE CYCLE is a two days Symposium that will be held on the 4th and 5th May 2011 at LEITAT Technological Center, Barcelona (Spain).

It is jointly organized by the coordinators of three European FP7 Projects NANOPOLYTOX, NEPHH and HINAMOX. The organizers are representing three Spanish institutions actively working in the field of nanotechnology: LEITAT Technological Center (Barcelona), Ekotek (Bilbao) and CIC BiomaGUNE (San Sebastian), respectively.

The aim of the Symposium is to discuss about the human and environmental impacts of nanomaterials along their life cycle from their production through their processing, use, and end of life (recycling and/or disposal). Therefore, the tools and methodologies proposed for the risk assessment (RA) and Life Cycle Assessment (LCA) of nanomaterials will be one of the main topics of discussion in this symposium.

A panel of experts at international level have been invited as speakers and lectures will be organized into six different sessions:

- Session 1 International, national and regional initiatives on Nanotechnology / Nanosafety
- Session 2 Nanomaterials: Synthesis, characterization and applications
- Session 3 Human health impact of Nanomaterials
- Session 4 Environmental impact of Nanomaterials
- Session 5 Risk assessment of Nanomaterials
- Session 6 Life cycle assessment of Nanomaterials

This Scientific Program will be complemented with a poster session thus allowing the presentation of relevant scientific outcomes in the areas above.

Registration & Abstract submission:
www.leitat.org/nanoLCA
e-mail: nanoLCA@leitat.org

Date and Venue
4th/5th May 2011

Safety issues of nanomaterials along their life cycle

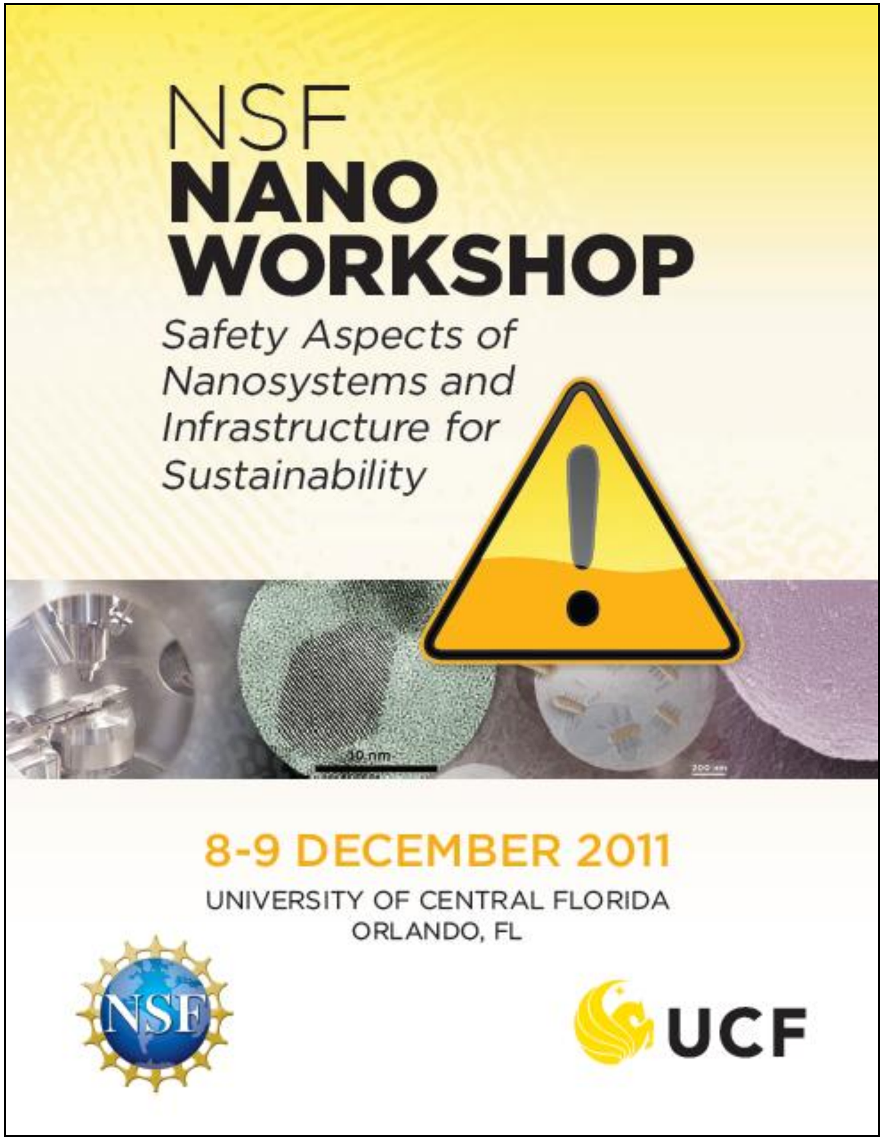
Leitat Technological Center
C/ de la Innovació 2, 08225 Terrassa. Barcelona(Spain)
www.leitat.org/nanoLCA

Symposium jointly organized by:

nanopolytox

The research leading to these results has received funding from European Community´s Seventh Framework Programme (FP7/2007 – 2013) under Grant Agreements n. 247899, 228536 & 228825

2011 UCF Workshop: Safety Aspects



…

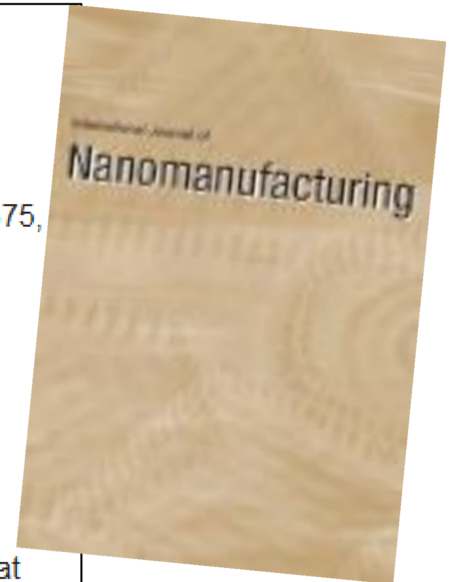
Implementing Nanotech: Nanomfg

Title: Nanomanufacturing: path to implementing nanotechnology

Author: Khershed P. Cooper; Ralph F. Wachter

Address: Materials Science and Technology Division, Naval Research Laboratory, Washington, DC 20375, USA ' Division of Computer and Network Systems, National Science Foundation, Arlington, VA, 22230, USA

Journal: Int. J. of Nanomanufacturing, 2013 Vol.9, No.5/6, pp.540 - 554



Abstract: Research and development work in nanoscience and nanotechnology has generated new fundamental understanding of physical phenomena and material behaviour at the nano-scale. This knowledge has resulted in discoveries of new materials, structures and devices. It is believed that these basic research investments should now lead to new products and applications. The general feeling is that nanotechnology needs to move from fundamentals to practice, from the laboratory to the marketplace. The broad consensus is that we need accelerated research and development investments in nanomanufacturing science to step up transition of nanotechnology and to hasten technology transfer. Such an effort will fulfil nanotechnology's promise, which to bring about economic and societal benefits. This paper will define and discuss our perspective on nanomanufacturing, describe our manufacturing science programmes ongoing research and development efforts, list manufacturing challenges and discuss how these are being met through our basic research programmes.

Keywords: nanoscience; nanotechnology; nanomaterials; nanodevices; nanosystems; nanofabrication; roll-to-roll processing; R2R; large area processing; nanomanufacturing; research and development; R&D investment; technology transfer.

Immediate Concerns for Nanomanufacturing

- Technical feasibility
- Economic viability
- Intellectual property issues
- Regulatory issues
- Workforce health and safety
  - Appropriate workforce training
    - Knowledge of researchers
    - knowledge of "first responders"
  - Appropriate waste handling and disposal
- Public health and environmental impact

Tradeoffs in light of many uncertainties…

And then "sustainable" nanomanufacturing?

Bosso, Isaacs, Kay, Sandler, "Leaving the Laboratory: Regulatory and Societal Issues Confronting Nanotechnology Commercialization" in The Handbook of Nanomanufacturing, Busnaina, ed. Taylor and Francis/CRC Press, 2006

OECD Sustainable Mfg Indicators

Inputs

- **I1** Non-renewable materials intensity
- **I2** Restricted substances intensity
- **I3** Recycled/reused content

Operations

- **O1** Water intensity
- **O2** Energy intensity
- **O3** Renewable proportion of energy
- **O4** Greenhouse gas intensity
- **O5** Residuals intensity
- **O6** Air releases intensity
- **O7** Water releases intensity
- **O8** Proportion of natural land

Products

- **P1** Recycled/reused content
- **P2** Recyclability
- **P3** Renewable materials content
- **P4** Non-renewable materials intensity
- **P5** Restricted substances content
- **P6** Energy consumption intensity
- **P7** Greenhouse gas emissions intensity

Note: Indicators O1, O2 and O4 can be extended to measure the impact associated with your supply chain as well as your facility: namely, water and energy consumed and greenhouse gas emissions caused during the production of inputs.

NIST Sustainable Mfg Portal

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Engineering Laboratory

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NIST Home > EL > Systems Integration Division > Life Cycle Engineering Group > Sustainability of Unit Manufacturing Processes Project

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Sustainability of Unit Manufacturing Processes Project

Summary:

To advance sustainable manufacturing practices and promote resource efficiency, U.S. industries need reliable measurement methods to evaluate a number of process-related sustainability performance metrics. The most important of these metrics are energy consumption and material use, emissions, waste, and water usage of manufacturing processes. However, current practice involves the use of ad-hoc methods to compute and unstructured data to report these metrics. These practices cannot effectively support the development of the needed reliable measurement methods and tools. Under the Methodologies for Characterizing Sustainable Processes and Resources Thrust of the program, this project will develop a science-based methodology and the associated structured information models for computing sustainability metrics for unit manufacturing processes. Project results will facilitate industry's evaluation of sustainability performances and adoption of resulting standards.

Description:

Objective: Provide the measurement science and methodology to evaluate sustainability performance metrics (such as energy and material consumption, emissions, waste, and water usage) of unit manufacturing processes by 2014.

Start Date:

October 1, 2011

Lead Organizational Unit:

EL

Staff:

Principal Investigator: Kevin Lyons

Co-Investigator(s): Mahesh Mani

Related Programs and Projects:

Sustainable Manufacturing Program

Sustainability Characterization for Product Assembly Processes Project

Sustainability Metrics for Design and Manufacturing Project

…

It's All About Key Words…

sus·tain·a·ble

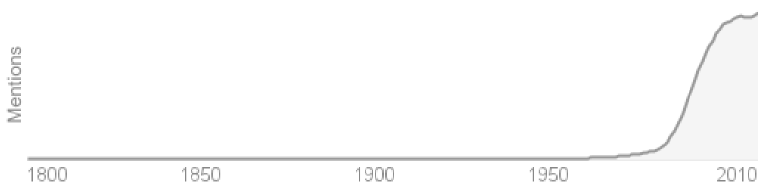
/səˈstānəbəl/

adjective
adjective: **sustainable**

1. able to be maintained at a certain rate or level.
   "sustainable fusion reactions"
   - conserving an ecological balance by avoiding depletion of natural resources.
     "our fundamental commitment to sustainable development"
2. able to be upheld or defended.
   "sustainable definitions of good educational practice"

Translate sustainable to Choose language

Use over time for: sustainable



nan·o·ma·te·ri·al

/ˈnanōməˌti(ə)rēəl/

noun
plural noun: **nanomaterials**

1. a material having particles or constituents of nanoscale dimensions, or one that is produced by nanotechnology.

Translate nanomaterials to Choose language

Use over time for: nanomaterials

life cycle assessment

Web definitions

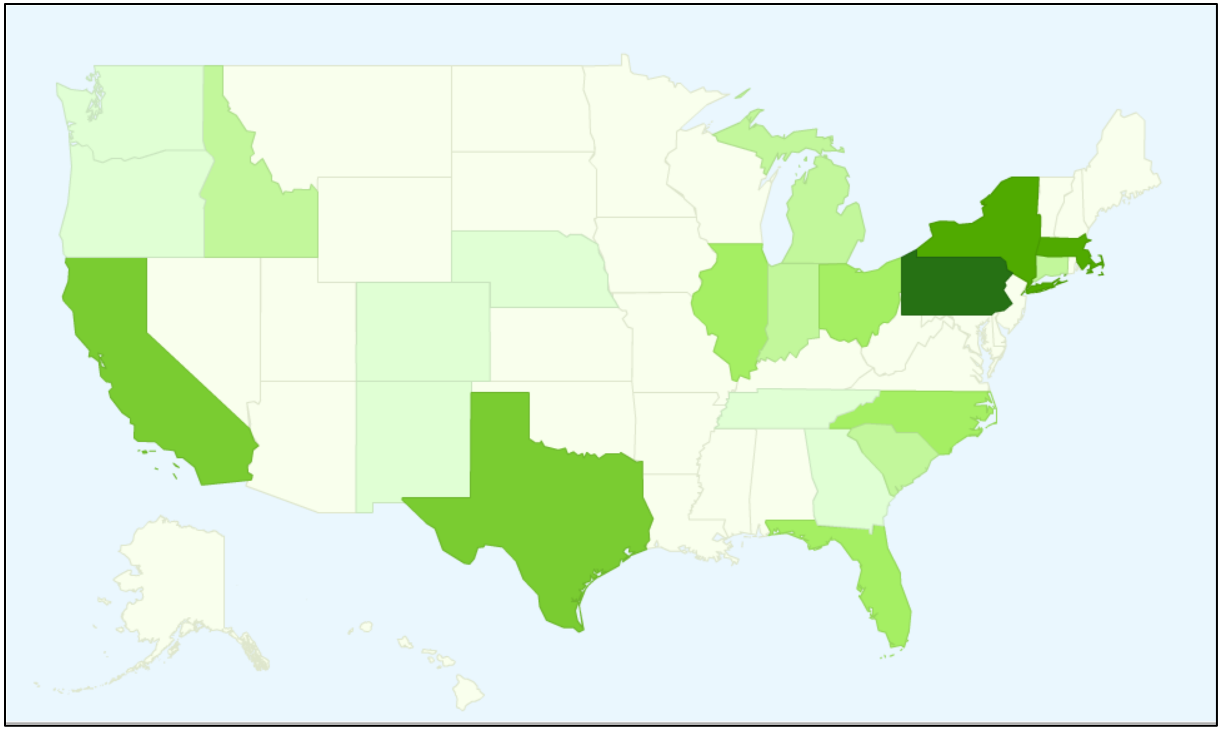
Life-cycle assessment is a technique to assess environmental impacts associated with all the stages of a product's life from-cradle-to-grave. ...
http://en.wikipedia.org/wiki/Life-cycle_assessment

nanomanufacturing

Web definitions

Nanomanufacturing is both the production of nanoscaled materials, which can be powders or fluids, and the manufacturing of parts "bottom up" from nanoscaled materials or "top down" in smallest steps for high precision, used in several technologies such as laser ablation, etching and others. ...
http://en.wikipedia.org/wiki/Nanomanufacturing

NSF Scalable Nanomanufacturing Awards

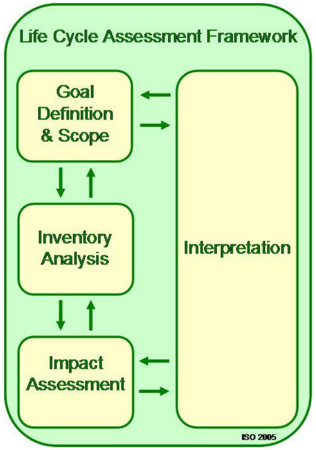


US – Pennsylvania	7
US – Massachusetts	5
US – New York	5
US – California	4
US – Texas	4
US – Florida	3
US – Illinois	3
US – North Carolina	3
US – Ohio	3
US – Connecticut	2
US – Idaho	2
US – Indiana	2
US – Michigan	2
US – South Carolina	2

- 55 NSF SNM Active Awards listed (2007-2013)
- 8 have “societal” (or some variant) in abstract
- 4 have “sustainable” (or some variant) in abstract
- 2 have “societal” and “sustainable” in abstract
- 1 has “life cycle assessment” in abstract

NSF Awards "Life Cycle Assessment"

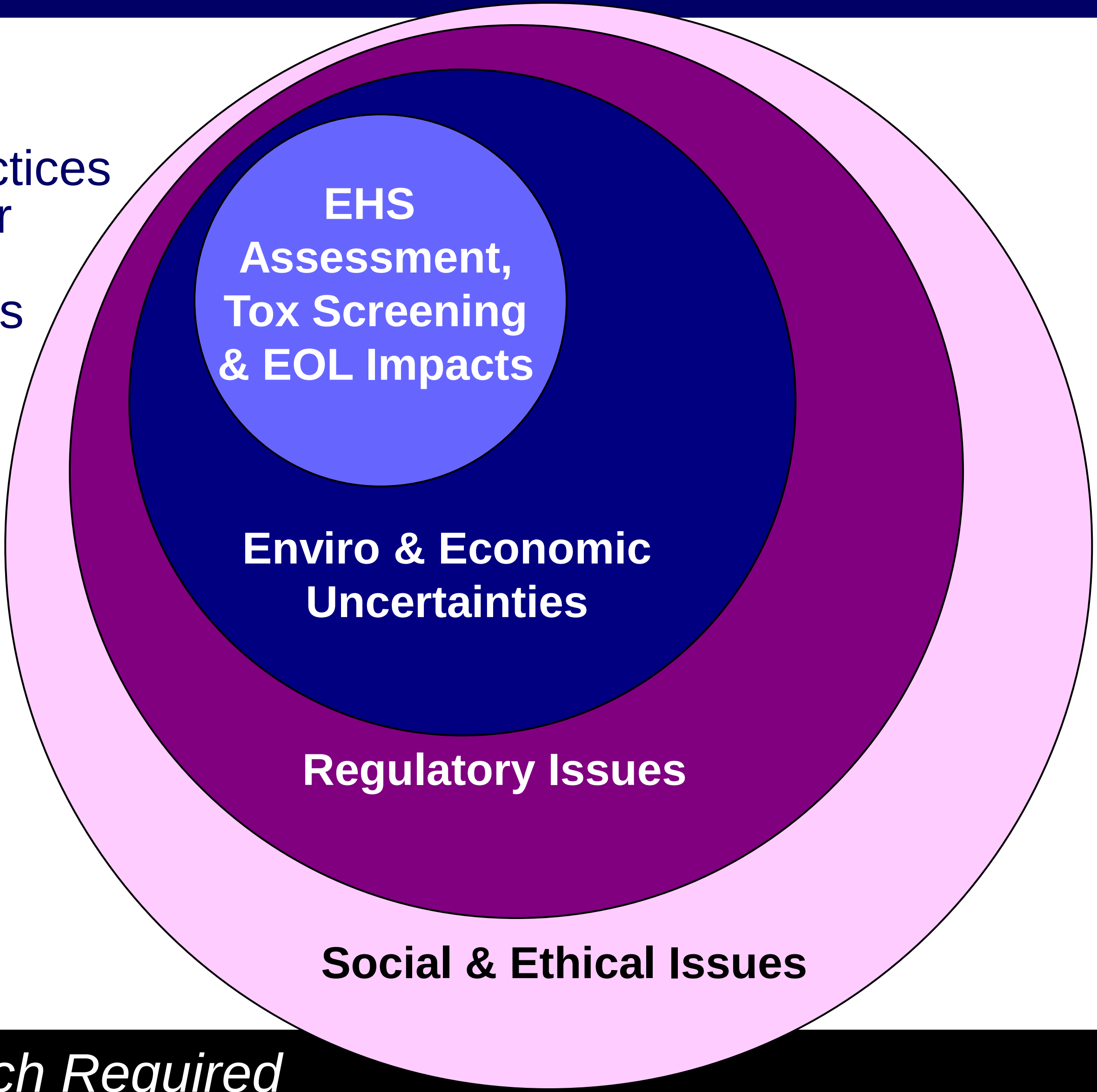
- Search shows 111 awards for "Life Cycle Assessment"
- Searching within this award set resulted in 18 awards with "nano" in the…
  - Title or
  - Abstract or
  - Program classification:
    - "Enviro Health & Safety of Nano" or
    - NANOSCALE: INTRDISCPL RESRCH T, NANO EHS CORE, SOCIETAL IMPLICATIONS OF NANO or
    - NANTOXICOLOGY
  - 4 of the 18 are conferences
  - 6 awards where nano issues are addressed using LCA methods



(This is not the "definitive list" of LCA-nano projects.)

Responsible Nanomanufacturing

- Measure and control to determine best safety practices and screening methods for nanomaterials as well as impact of possible releases
- Perform assessment of developing processes / products and evaluate tradeoffs for EHS (environmental health and safety) with costs
- Promote informed policymaking
- Advocate productive public discourse



Integrated Systems Approach Required for Appropriate and Efficient Commercialization

Setting Stage for Discussion

- What aspects of sustainability need to be addressed?
  - How will we know whether it’s “sustainable”?
- Are there standard methods or metrics can be used to assess nanomanufacturing as it develops?
  - Can we use current metrics developed for sustainable manufacturing?
- Can LCA be used as an effective tool for evaluating nano-enabled products throughout their life cycles?
  - Given uncertainties in potential EHS effects of nanomaterials, can we determine life cycle impacts…?
- How can we encourage innovators (in industry or academia) to adopt life cycle thinking?
  - Is there some way to be proactive for end-of-life Product Stewardship, in light of uncertainties?

Panel 7: Topics for Discussion

Moderators

- **Jackie Isaacs**, Northeastern University
- **Bruce Hamilton**, NSF

Panelists

- **Jackie Isaacs**, Northeastern University
  - **Manufacturing Phase / Life Cycle Inventories**
- **Matt Eckelman**, Northeastern University
  - **Use Phase / Life Cycle Impact Assessment**
- **Gabrielle Gaustad**, Rochester Institute of Technology
  - **End-of-Life Phase /**

Panel 7:
Sustainable Nanomaterials and Nanomanufacturing

Manufacturing Phase / Life Cycle Inventories

Jackie Isaacs

Assoc Director, CHN, NSF NSEC

Professor, Mechanical and Industrial Engineering

Northeastern University

2013 NSF Nanoscale Science and Engineering Grantees Conference

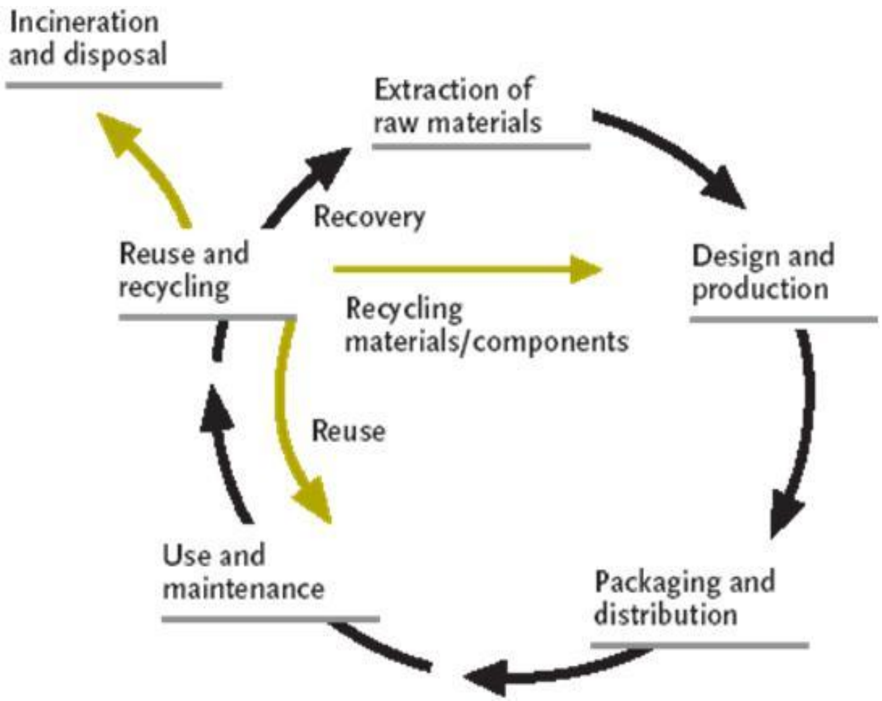
December 4-6, 2013

Westin Hotel - Arlington, VA

How can industry develop
new nanotechnologies in a
responsible, sustainable manner?

**How can we ensure
nanomanufacturing processes and
products remain safe for workers,
consumers and the environment?**

Nano-Enabled Product Lifecycle



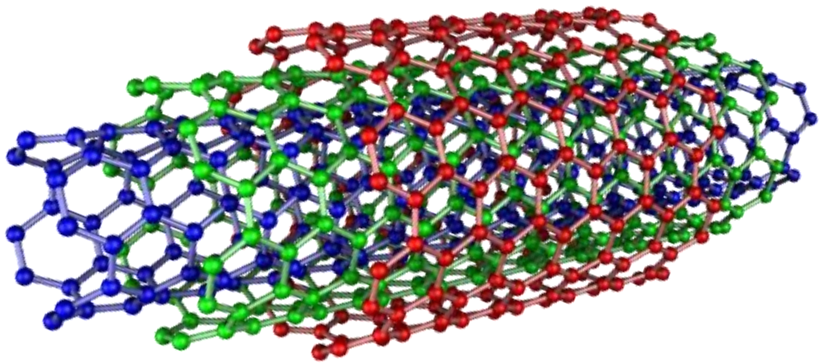
- Where can we gather data for inventories?
  - Literature
  - Laboratory
  - Estimates
  - LCI Databases
  - Industrial data
  - ….

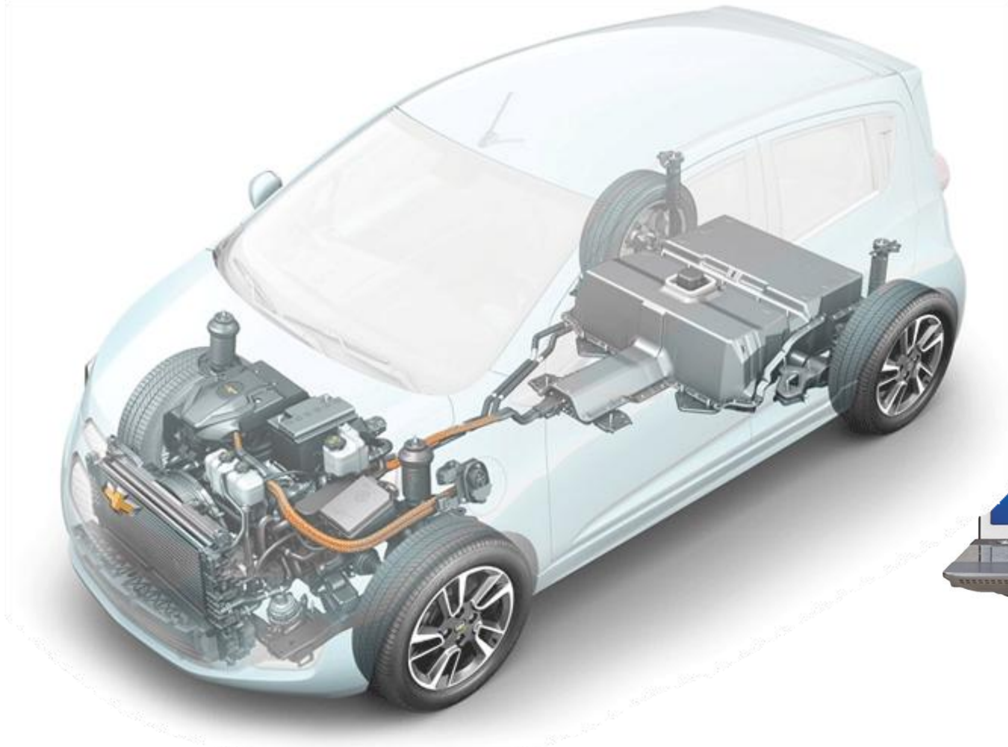
…Carbon Nanotube Enabled Batteries

Outstanding Properties

Expanding Global Market

Potential Environment Issues





Design for the Environment An EPA Partnership Program

Partnership for "Application of Life-Cycle Assessment to Nanoscale Technology: Lithium-ion Batteries for Electric Vehicles"

About This Project | Publications | Partners

This partnership was led by EPA's Design for the Environment (DfE) Program, in the Office of Pollution Prevention and Toxics, and the National Risk Management Research Laboratory, in EPA's Office of Research and Development.

The partnership conducted a screening-level life-cycle assessment (LCA) of currently manufactured lithium-ion (Li-ion) battery technologies for electric vehicles, and a next generation battery component (anode) that uses single-walled carbon nanotube (SWCNT) technology.

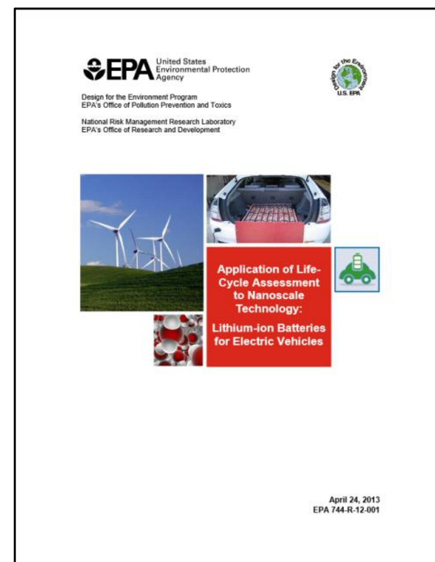
A quantitative environmental LCA of Li-ion batteries was conducted using primary data from both battery manufacturers and recyclers--and the nanotechnology anode currently being researched for next-generation batteries.

This type of study had not been previously conducted, and was needed to help grow the advanced-vehicle battery industry in a more environmentally responsible and efficient way. The LCA results are expected to mitigate current and future impacts and risks by helping battery manufacturers and suppliers identify which materials and processes are likely to pose the greatest impacts or potential risks to public health or the environment throughout the life cycle of their products. The study identifies opportunities for environmental improvement, and can inform design changes that will result in the use of less toxic materials and reduced overall environmental impacts, and increased energy efficiency.

The opportunities for improving the environmental profile of Li-ion batteries for plug-in and electric vehicles identified in the draft LCA study have the potential to drive a significant reduction of potential environmental impacts and risks, given that advanced batteries are an emerging and growing technology.

Final LCA Report

April 29, 2013 – The final report for the life-cycle assessment (LCA) of current and emerging energy systems used in plug-in hybrid and electric vehicles conducted by the DfE/ORD Li-ion Batteries and Nanotechnology Partnership is now available. The LCA results will help to promote the responsible development of these emerging energy systems, including nanotechnology innovations in advanced batteries, leading to reduced overall environmental impacts and the reduced use and release of more toxic materials.



http://www.epa.gov/dfe/pubs/projects/lbnp/final-li-ion-battery-lca-report.pdf

Process Flow & Inventory Data: Li-ion Batteries for Vehicles

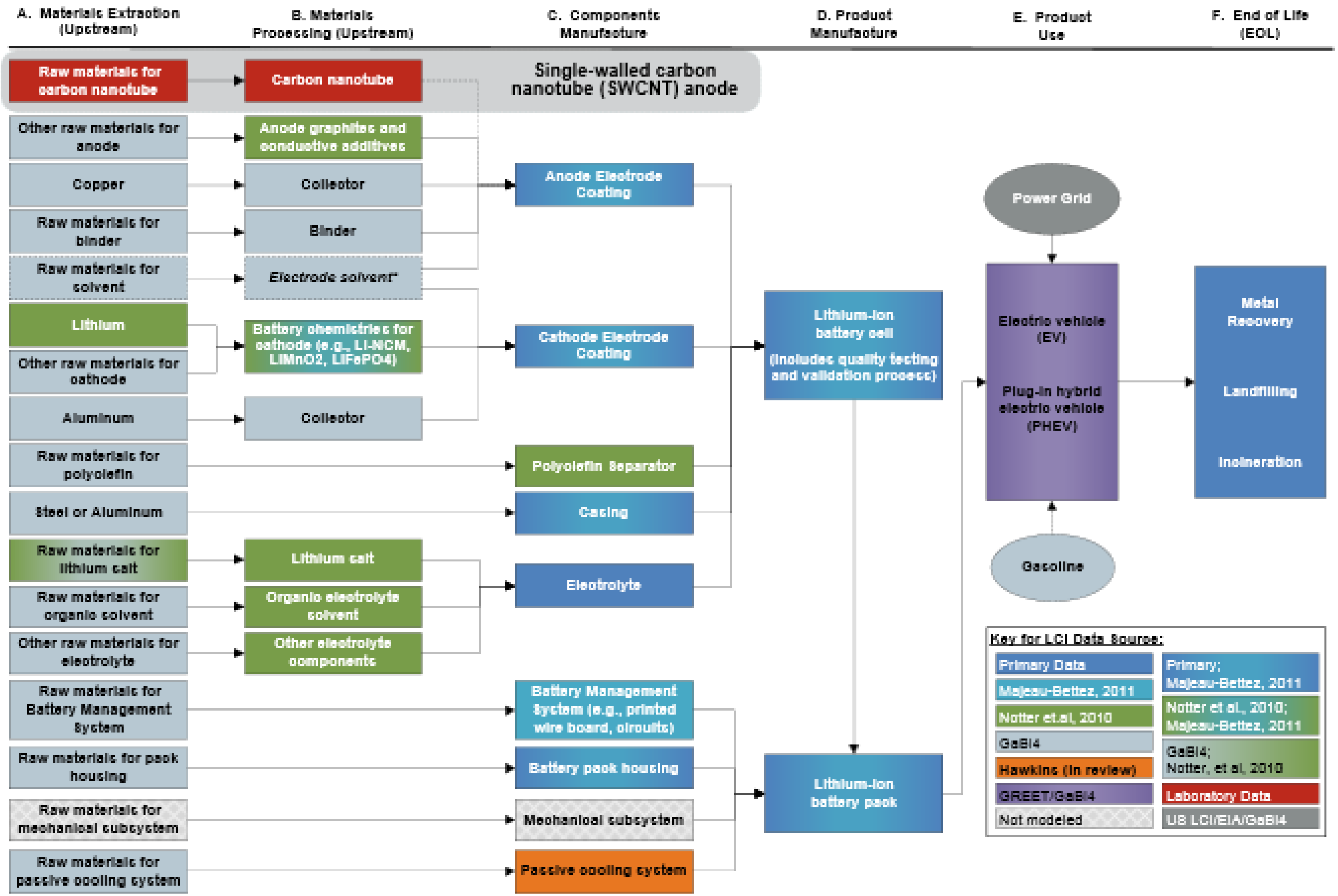


Figure 2-10. Generic Process Flow Diagram for Lithium-ion Batteries for Vehicles (color coded to present LCI data sources)

Sources: DfE/ORD Li-ion Batteries and Nanotechnology for Electric Vehicles Partnership; NEC/TOKIN (http://www.nec-tokin.com, 2010; Olapiriyakul, 2008; Ganter, 2009. Notes: Electrode solvent is an ancillary material used during manufacturing but not incorporated into batteries.

Flow Diagram for Battery Recovery

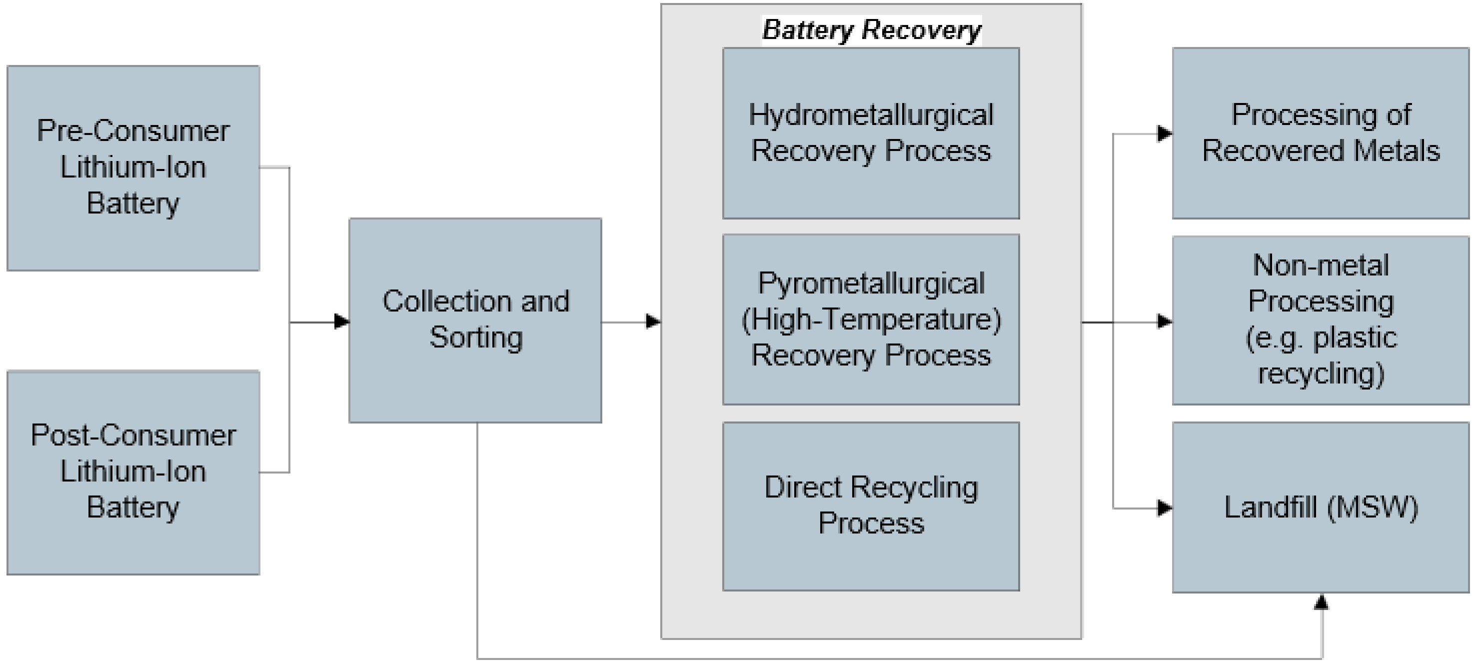


Figure 2-9. Generic Process Flow Diagram for End-of-Life (EOL) Management for Li-ion Batteries

Sources: EPA, DfE/ORD Li-ion Batteries and Nanotechnology for Electric Vehicles Partnership; Olapiriyakul, 2008.

"LCI data were based on current recycling processes, which do not recycle large volumes of Li-ion batteries for vehicles at present. Recovery and eventual disposition of materials will be better characterized as the volume of battery waste increases and markets for recovered/recycled materials emerge. "

How many different nanotechnologies are based on **resources that are limited** and on **non-renewable** precursors?

What are the projections of the growth of the nano-industry?

...the growth of world population?

...the decline of non-renewable resources?

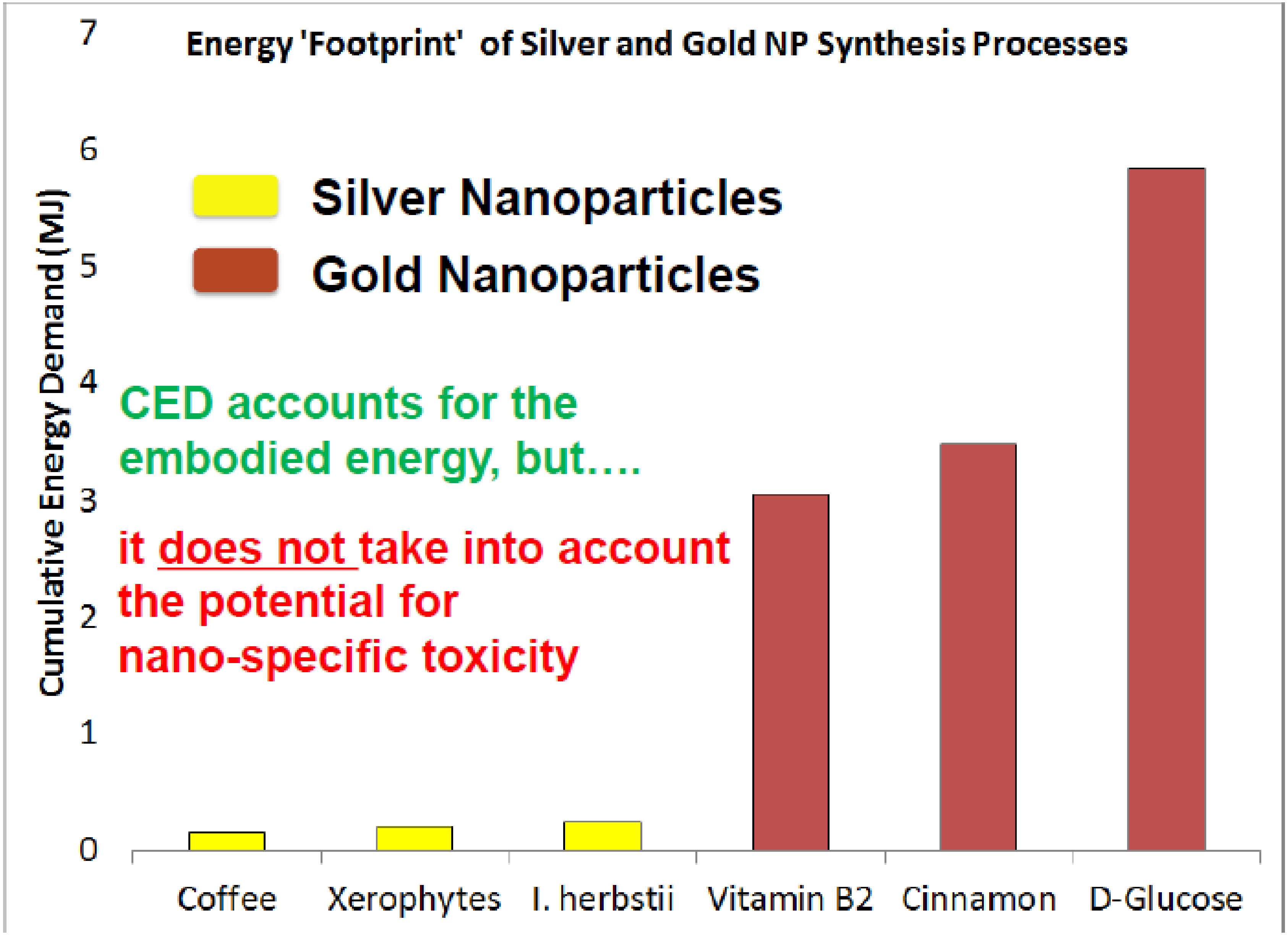
...and the synergistic effects of all of the above?

Of course life cycle thinking matters!

Sustainable Nanotechnology Organization
Research | Education | Responsibility

The LCA Toolbox

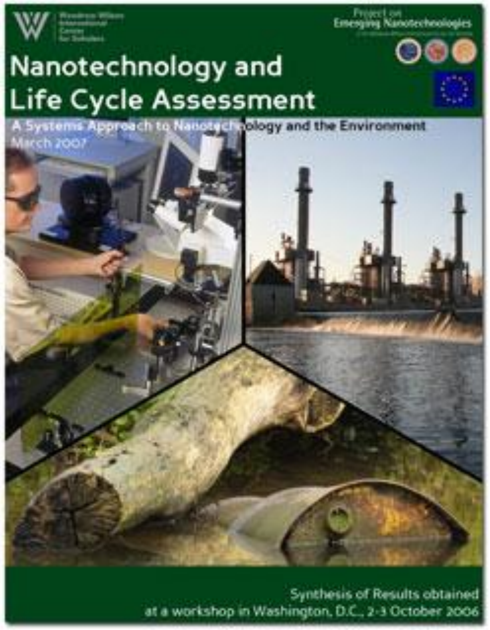
Databases	ecoinvent	U.S. LCI Database
Impact assessment methods	Cumulative Energy Demand, Global Warming Potential	Eco-Indicator, TRACI
LCA software	openLCA SimaPro	GaBi Product Sustainability Performance

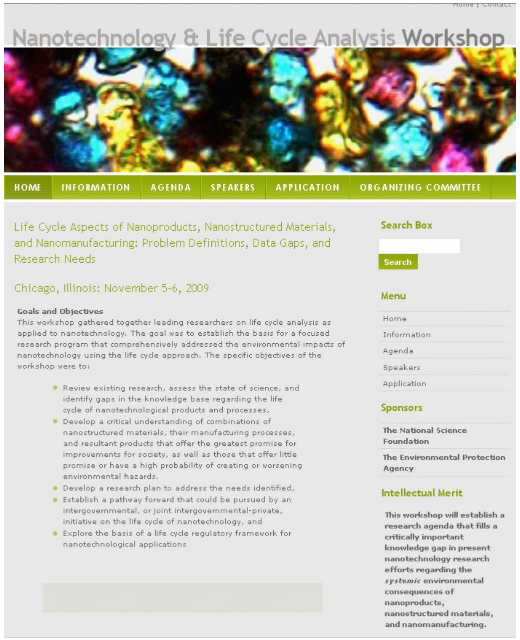


Pati, Vikesland, & McGinnis,2014 SNO Annual Conference, Santa Barbara

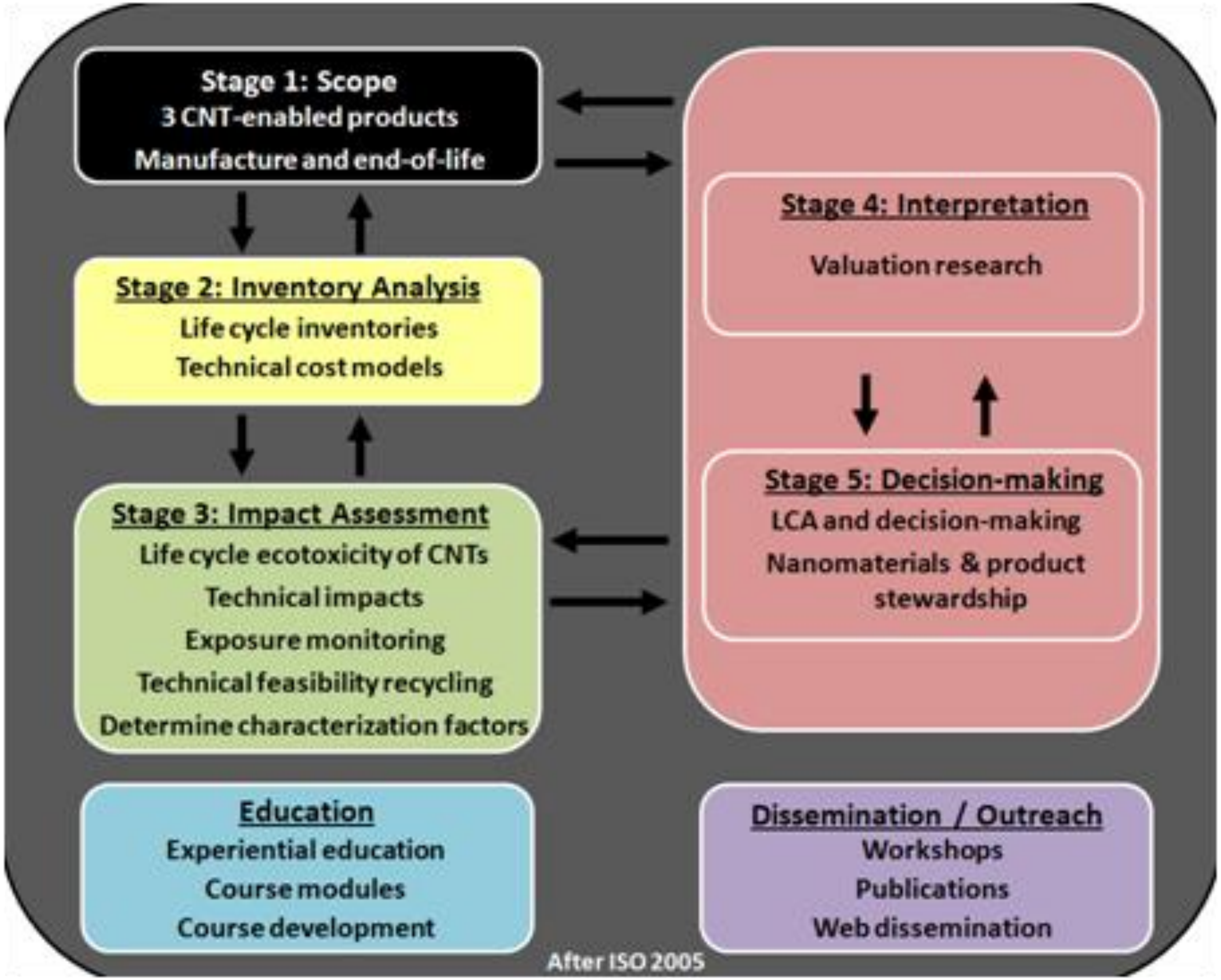
Results do not indicate effect of CNTs… …limited toxicological factors!

Same issues as in 2007, 2009…



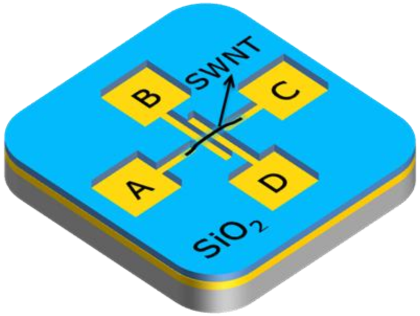


NSF SNM: Designing and Integrating LCA Methods for Nanomanufacturing Scale-up

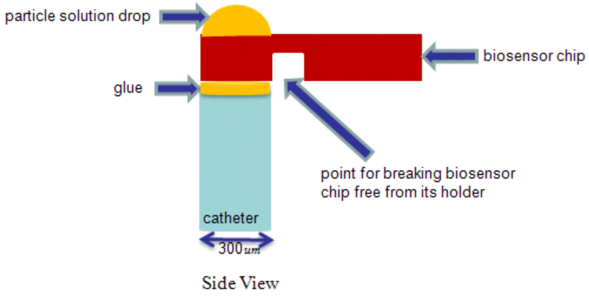


Applications Using CNTs

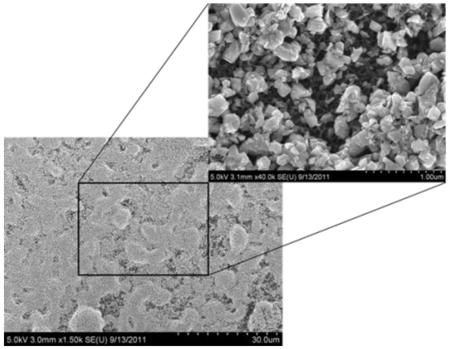
- SWNT Switch



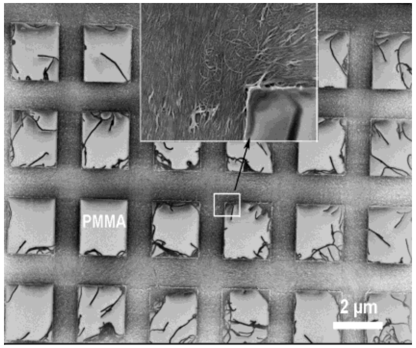
- Sensors



- Batteries



- EMI-Shielding



Isaacs, Bosso, Busnaina, Cullinane, Eckelman, Sandler : **Northeastern**
Mead, Bello: **U Mass Lowell;** Zimmerman: **Yale;** Nash: **Harvard**

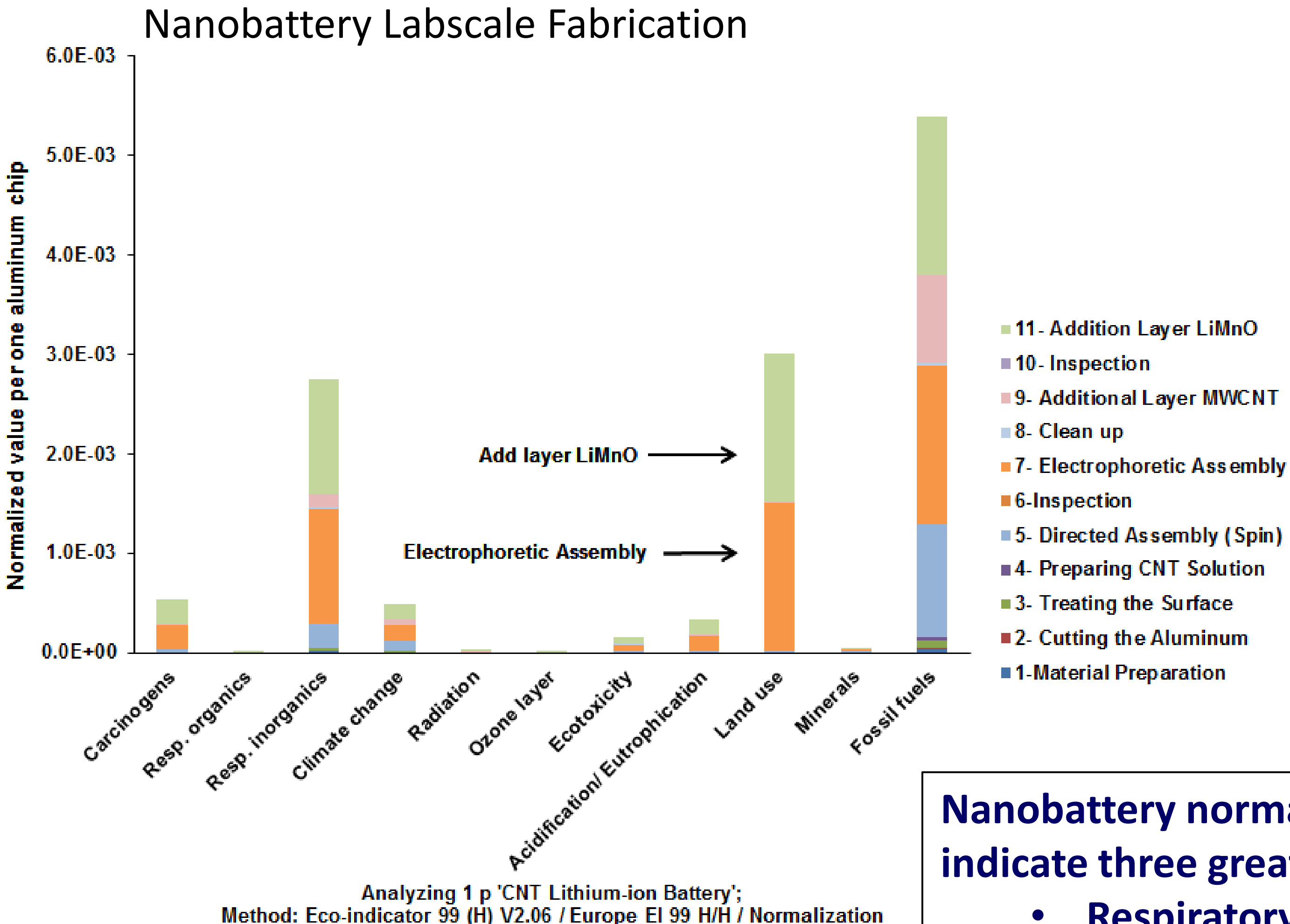
Life Cycle Inventories for CNT Cathodes/Anodes

1- Material preparation
↓
2- Cutting the Aluminum
↓
3- Treating the surface
↓
4- Preparing CNT solution
↓
5- Directed assembly (Spinning)
↓
6- Inspection
↓
7- Electrophoresis assembly
↓
8- Clean up
↓
9- Additional layer MWCNT
↓
10- Inspection
↓
11- Additional layer LiMnO

ENERGY	kWh
	1.073657
INPUT MATERIAL	**g/chip**
ethanol (200 proof)	15.78
Lithium Manganese Oxide Powder	0.1
Gold Chip	0.5576
N2 Gas	10.324
ethylene glycol	0.446
deionized water	5163.95
disposable lab materials (plastic and paper	10.48
MWCNT	0.00112
INPUT TOTAL	5201.639

OUTPUT MATERIAL	g/chip
mixed wastewater to treatment	5174.364
hazardous waste	16.276
emissions to air	10.324
MWCNT	0.00112
OUTPUT TOTAL	5200.964

Nanobattery Normalized Results



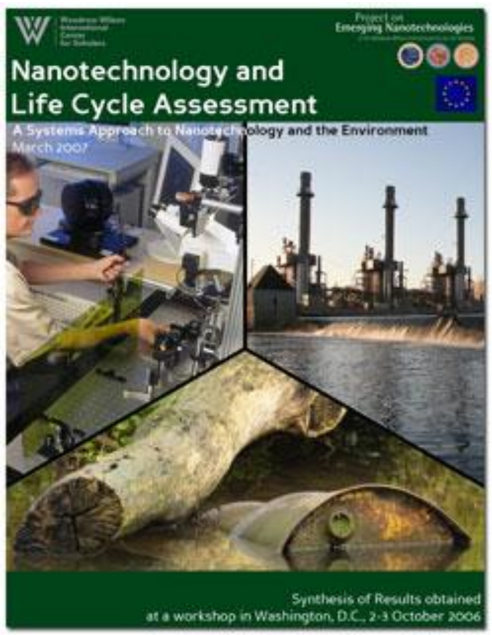
Nanobattery normalized result indicate three greatest contributors:

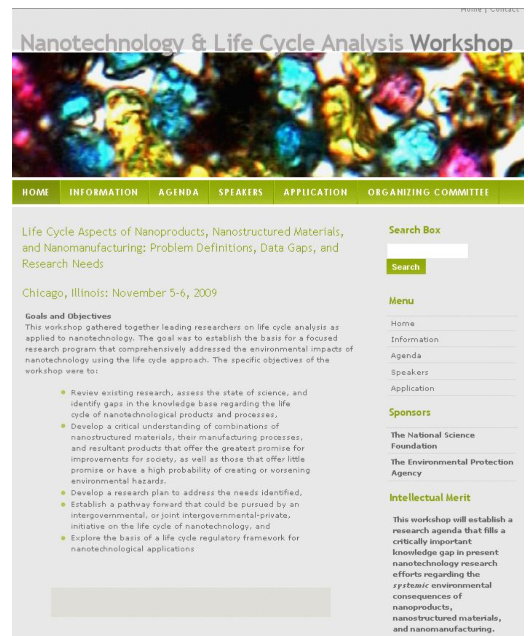
- **Respiratory inorganics**
- **Land use**
- **Fossil fuels**

Hakimian and Isaacs, Northeastern University

Results do not indicate effect of CNTs…
…limited toxicological factors!

Same issues as in 2007, 2009…





Environmental Science & Technology
Article
pubs.acs.org/est

Environmental Life Cycle Assessment of a Carbon Nanotube-Enabled Semiconductor Device

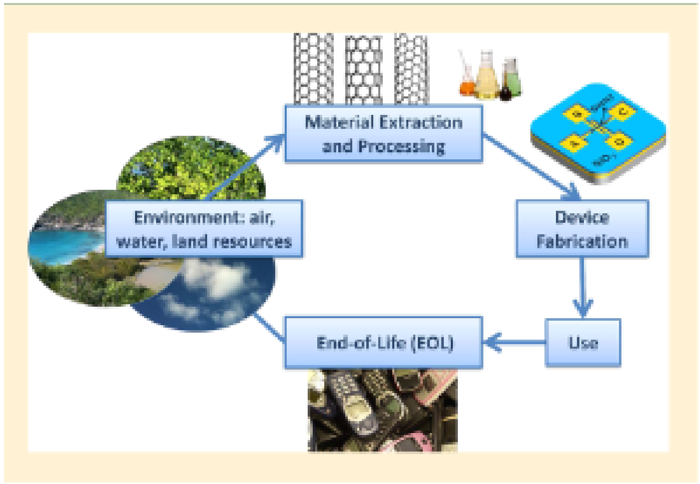
Lindsay J. Dahlben,[†,‡] Matthew J. Eckelman,[§] Ali Hakimian,[†] Sivasubramanian Somu,[†] and Jacqueline A. Isaacs*,[†]

[†]Department of Mechanical and Industrial Engineering and Center for High-rate Nanomanufacturing, Northeastern University, 360 Huntington Avenue, Boston, Massachusetts 02115, United States

[‡]Raytheon Company, Integrated Defense Systems, 350 Lowell Street, Andover, Massachusetts, 01810

[§]Department of Civil and Environmental Engineering, Northeastern University, 360 Huntington Avenue, Boston, Massachusetts 02115, United States

Estimates of inventories throughout the lifecycle offer insights on mass of nanomaterials for potential release at each stage…

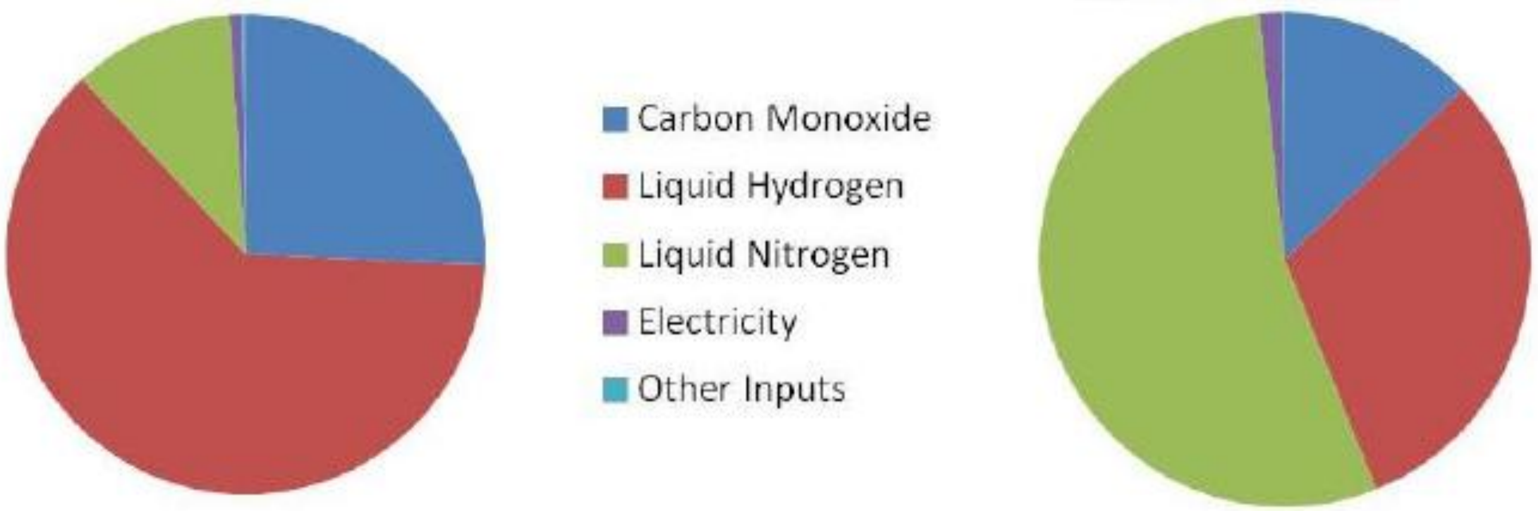


Scaling-up May Change Hot-Spots

For example : GW contributors

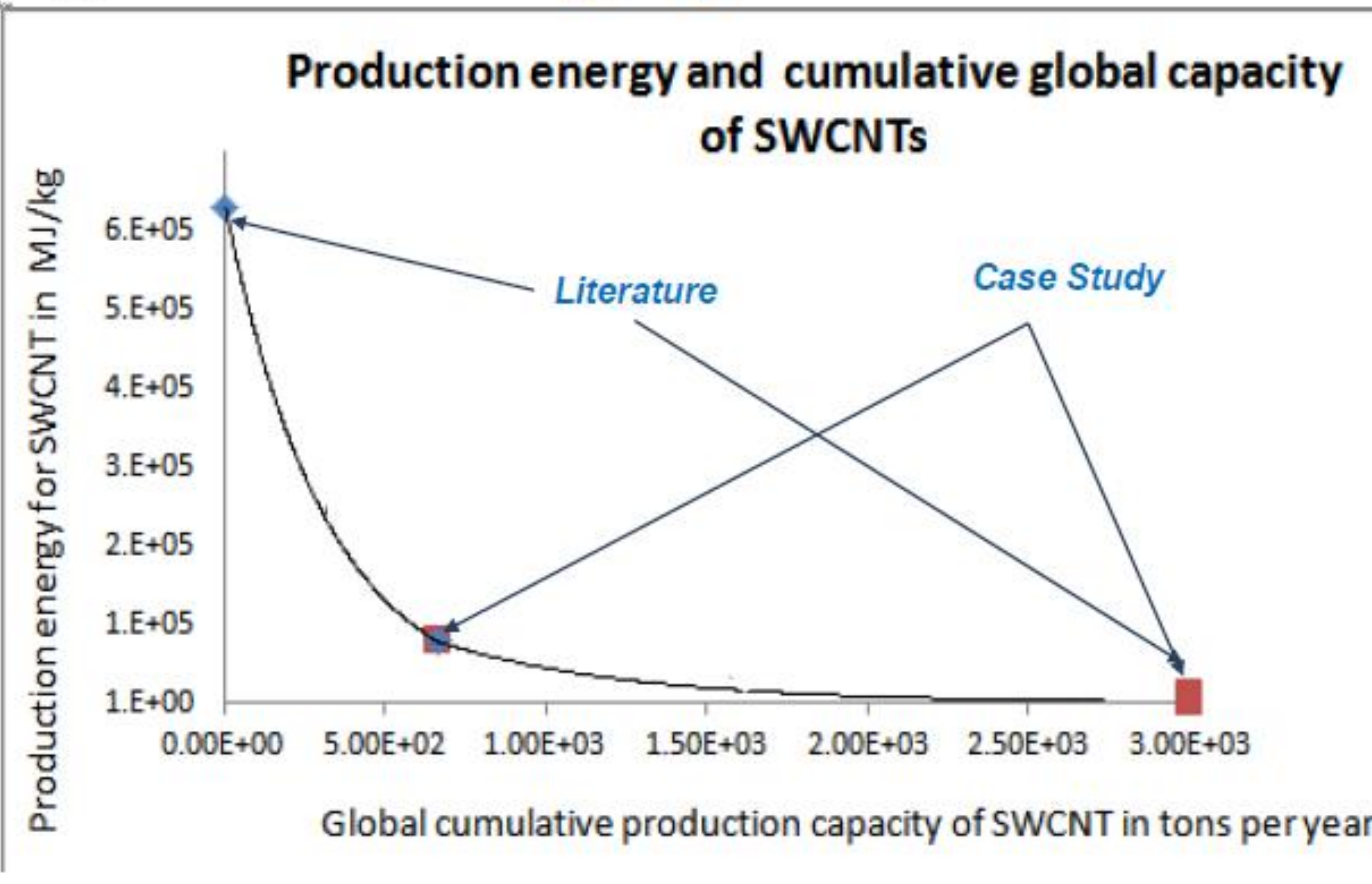
Small scale
1 Kg per month

Mass scale
1,000 Kg per month



Gavankar –Suh -- Keller (SNO 2013)

Scaling Up is Not Random



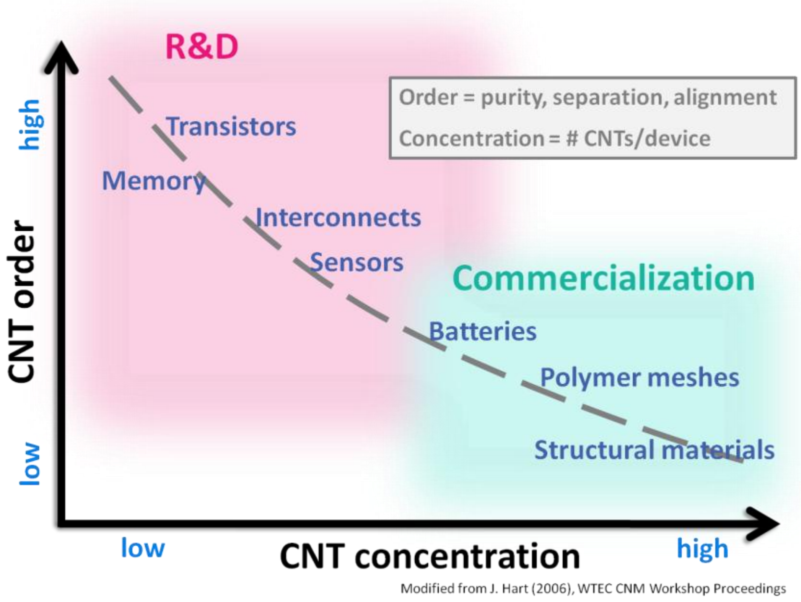
Gavankar –Suh -- Keller (SNO 2013)

Takeaway...

- Technological maturity and scale of manufacturing hold significance for the interpretation of early LCAs.
- Functional unit approach of LCA may not 'automatically' capture maturity and scale information.
- Using standardize maturity levels and establishing environmental learning curve will make LCAs more decision relevant.

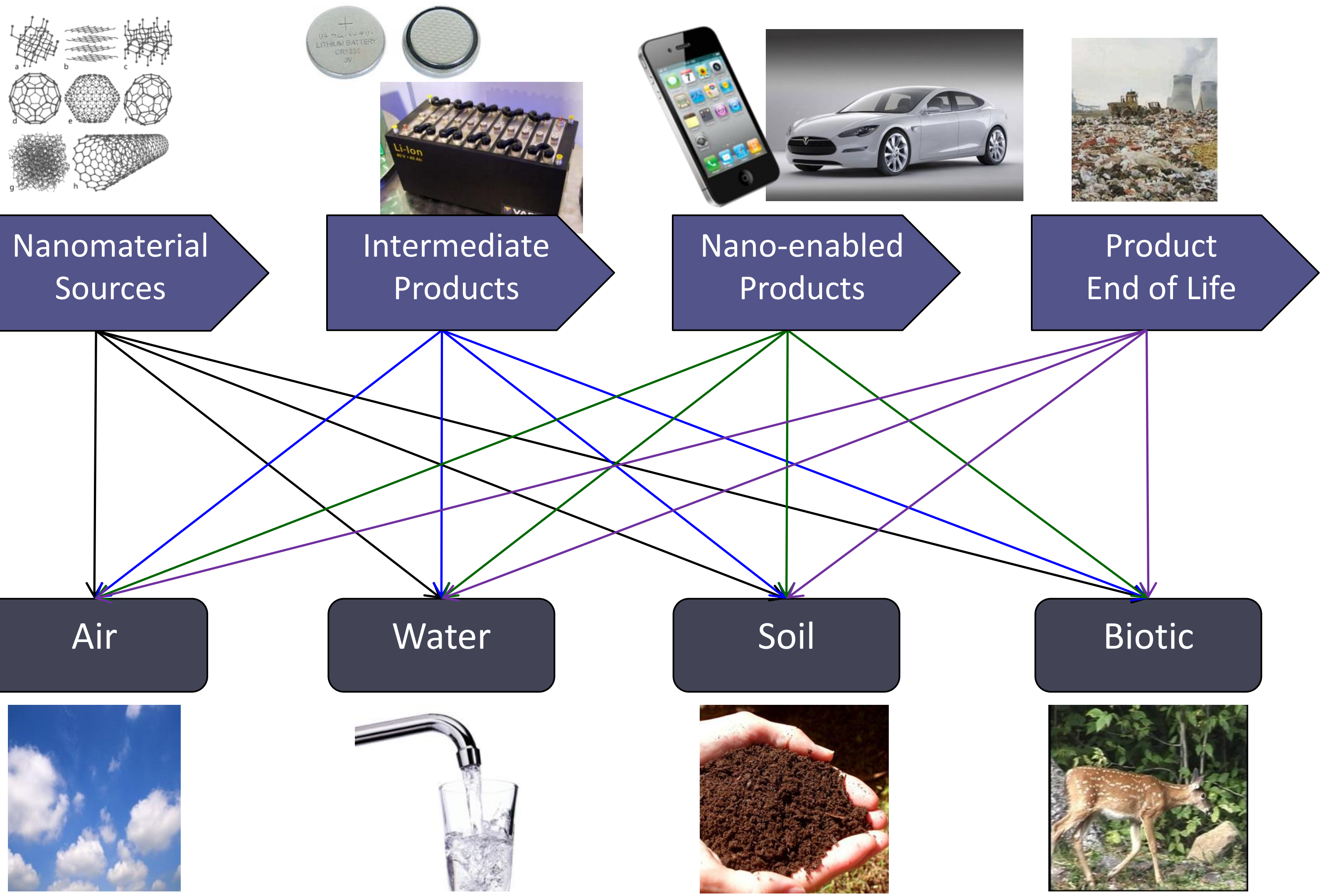
Inventory Collection Offers Value

- Process-based inventory collection applied to lab-scale fabrication of CNT applications
- Scale-up estimates allow approximation of possible CNT releases by series of nano-enabled products
  - Manufacturing
  - Use
  - End-of-Life decommission
- Opportunity to reduce environmental footprint of nano-fabrication
  - Greener design…
  - Early intervention…



Inventory collection and estimations through the lifecycle can provide data for influence diagrams and help prioritize subsequent research needs.

Nanomaterial Releases Through the Value Chain



Center for High-rate Nanomanufacturing

Adapted from Wiesner, 2011 ICEIN Plenary Talk

Product Stewardship Issues

"Product stewardship calls on those in the product life cycle—manufacturers, retailers, users, and disposers—to share responsibility for reducing the environmental impacts of products."

US Environmental Protection Agency

1. Can nano-enabled products be handled appropriately using the stewardship collection infrastructure developed for other products, or must manufacturers provide some form of special handling for products containing nanomaterials?

2. Does mixing of recyclate from nano-enabled products impact markets for recycled materials?

3. Does the collection of nano-enabled products pose particular challenges to household waste facilities run by municipalities in terms of costs, worker health and safety, or public perception?

Finding the Balance Between Social & Technical

- Materials scarcity (lithium, polymers…)?
- Energy for raw material production?
- Energy reduction during manufacture?
- Societal benefit (greater sensitivity) in product use?
- Dissipation issues at End-of-Life?
- How can businesses make decisions in light of all uncertainties (EHS, legal, regulatory, market…)?

System analysis needed to inform decisions -- although system can become quite broad and includes the social context into which the technology evolves…

Acknowledgements

Center for High-rate Nanomanufacturing

Northeastern University

University of New Hampshire

Museum of Science

UMASS LOWELL

YALE

HARVARD

National Science Foundation
WHERE DISCOVERIES BEGIN

Funded by NSF Award Numbers
EEC-0832785 and SNM-1120329

http://www.northeastern.edu/chn/

Setting Stage for Discussion

- What aspects of sustainability need to be addressed?
  - How will we know whether it's "sustainable"?

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  - Can we use current metrics developed for sustainable manufacturing?

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  - Given uncertainties in potential EHS effects of nanomaterials, can we determine life cycle impacts…?

- How can we encourage innovators (in industry or academia) to adopt life cycle thinking?
  - Is there some way to be proactive for end-of-life Product Stewardship, in light of uncertainties?