Analysis of Nanotechnology from an Industrial Ecology Perspective Part I:
Inventory & Evaluation of Life Cycle Assessments of Nanotechnologies

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1. Introduction

Research and development of nanotechnology has experienced tremendous growth in a short period of time. More than 800 companies worldwide now manufacture products with nano-scale components (Cientifica 2003), numerous nanotechnology-based products are already on the market, and U.S. government funding for research on nanotechnologies has grown from $116 million in fiscal year 1997 (Lloyd 2004) to $810 million in fiscal year 2005 (S.189 2003)—about twice that invested in the genome project. By 2015 to 2020, researchers project that global industrial output from nanotechnology may exceed $1 trillion and that the nano-industry will employ approximately 2 million people (Zhang and Karn 2005). Despite this extraordinary—even considered "revolutionary"—industrial growth, only recently has nanotech made it to the mainstream press.

Nanotechnology refers to the manipulation of molecules and atoms at a tiny scale—one billionth of a meter. Products considered nano, meaning "dwarf" in Greek, extend from one to one hundred nanometers. At the nano-scale, materials exhibit different or new properties. Changed properties include greater material strength, enhanced reactivity, better catalytic functioning, and higher conductivity. These and other properties offer many benefits for nearly all sectors; hence, the widespread draw to this technology.

With the current penetration of these materials into our every day lives (whether known or unknown by consumers), we can anticipate that nanomaterials will become even more mainstream in the near future. However, because we are still on the cusp of this technology, we must take care to ensure that, not only the benefits, but also the side effects of these technologies are considered at early stages. The need for concurrent research on the environmental and health impacts of nanotechnologies is becoming more pressing.

Recent studies have begun to evaluate potential toxicological risks from nanoparticles.[1] U.S. government funding for other risk analyses has been granted, however, it only represents one percent of the nearly $1 billion devoted to the National Nanotechnology Initiative (NNI) (Walsh 2005).[2] Further assessment of health and environmental risks is needed.

An industrial ecology perspective can aid in the understanding of the type and extent of environmental impacts from nanotechnology. Robert White, former president of the National Academy of Engineering, defined industrial ecology as "the study of the flows of materials and energy in industrial and consumer activities, of the effects of these flows on the environment, and of the influences of economic, political, regulatory, and social factors on the flow, use, and transformation of resources," (1994). Graedel and Allenby point out that industrial ecology considers "the metabolisms of technological organisms, their potential environmental impacts,

[1] Research performed by DuPont and published in *Toxicological Sciences* (the only nano-related risk study made publicly available by a company) found that nanotubes inhaled at high doses by rats blocked airways in the lungs, which led to the death of about 15 percent of the rats (Warheit et al. 2004). Another study found that concentrations of nanoparticles in the lungs and brains following inhalation exposure by rats (Oberdörster et al. 2004). Researchers also found that carbon nanotubes instilled in the lungs of mice resulted in inflammation that could have implications for occupational exposure (Lam et al. 2004). Exposure through water streams also may also present dangers. Largemouth bass experienced brain inflammation through exposure to fullerenes (Oberdörster 2004).

[2] The remaining 99 percent has been assigned to new product development.

and the ways in which their interactions with the natural world could be restructured to enable global sustainability," (2003). The term "technological organisms" appropriately applies to nanomaterials, which are formed at the atomic and molecular level and many of which mimic properties found in natural systems.

Industrial ecology stresses a "forward-looking analysis"—to properly design and manufacture products in a manner that prevents or reduces negative environmental impacts and interactions in nature. "It asks how things might be done differently…avoiding irreversible harms and damages that are expensive to remedy," (Lifset and Graedel 2002). Once products are developed and become commercially available, it takes far more effort to revamp technological production processes. Nanotechnology offers a prime opportunity for industrial ecologists to use their tools and assess this emerging technology in the nascent stages of product development.

This paper uses an industrial ecology perspective to evaluate life cycle impacts of nanotechnologies through a review of life cycle assessments performed for nano-based products. In the next section, literature calling for a more thorough assessment of nanotechnology is discussed; section 3 explains the methodology used for this research review; section 4 presents an overview of the market penetration of nanotechnologies; and section 5 presents and analyzes the life cycle assessment findings. The final section (6) offers conclusions and recommendations for further research.

2. Life Cycle Assessment Background

In evaluating nanotechnology's potential environmental impacts and interactions within nature, we must look across the life cycle of these emerging products. One of industrial ecology's central evaluation tools, life cycle assessment (LCA), offers that ability. Using this approach, the material and energy inputs and liquid, solid, and gaseous residues are evaluated during extraction, production, use, and end-of-life stages of the product life.

Many reports have already called for the necessity of LCA to address the impacts of nanotechnologies from cradle to grave. The UK Government commissioned the Royal Society and Royal Academy of Engineering in 2003 to perform a study on potential ethical, social, and health and safety issues associated with nanotechnology that regulations had not already covered (The Royal Society 2004). This study highlighted the importance of LCA as a tool for identifying risks; it recommended that "a series of lifecycle assessments be undertaken for the applications and product groups arising from existing and expected developments in nanotechnologies, to ensure that savings in resource consumption during the use of the product are not offset by increased consumption during manufacture and disposal," (The Royal Society 2004).

A European Commission meeting held in Brussels in March 2004, called for "risk assessment throughout the life cycle of a nanotechnology…not only at the macro, ecological level but also within the human body" in order to protect human health and consumers (EC 2004). In the National Science Foundation (NSF) publication, Societal Implications of Nanoscience and Nanotechnology, Lester Lave (Director of the Carnegie Mellon Green Design Initiative) stressed the need for life cycle analysis to address "undesired consequences" of nanotechnologies (2001).

He suggests that the advantages of particular products may be outweighed by recognized respiratory potential health and environmental consequences, once realized. For instance, increased cancer risks associated with asbestos exposure (outweighing its benefit as an insulator) led to its ban; similarly, the high ozone depleting potential of CFCs used as refrigerants led to their phaseout under the Montreal Protocol.

As cited in Hood 2004, Mihail Roco, the NSF Nanotechnology Senior Advisor, states: "This [responsible risk assessment] is no longer something you do after the fact, after you do the other research, but has to be done from the beginning, to be an integral part of the research." Other experts in the field also emphasize that the time is *now* to evaluate environmental and health risks from these technologies. David Rejeski, Director of the Foresight and Governance Project at the Woodrow Wilson International Center, writes: "the environmental community is facing its first opportunity to *shape* an emerging social and technological infrastructure in ways that could dramatically improve environmental conditions," (2004). Mark Wiesner and Vicki Colvin of Rice University seek "to ensure that nanotechnologies, and the materials that enable them, evolve as instruments of sustainability rather than as environmental liabilities," (2005). Research at Georgia Institute of Technology and Rice University is currently investigating the fate and transport of nanomaterial waste, specifically fullerenes, in the environment (2005).

The insurance community is also beginning to play a critical and much needed role in encouraging more rigorous review on both the opportunities and hazards of nanotechnology. A report by the Swiss Reinsurance Company acknowledges that "the insurance industry must…conduct a careful analysis of nanotechnology in order to identify where any problems might be," (Swiss Re 2004). The report even goes so far as to say that "the paucity of data in this field invites a host of fears and alarmist scenarios." The public generally fears that the rush to develop these nano-based products and bring them to market means the proper safety testing may go overlooked. A recent study of the public's perceptions of nanotechnology by the Woodrow Wilson International Center's Project on Emerging Nanotechnologies indicated that Americans feel uninformed by government and industry groups on the risks of nano-based products, even though they recognize that nanotechnology will offer major benefits (Macoubrie 2005).

One of the claims to fame of nanotechnology in the environmental realm is the minimization of material use. However, the tiny size of these products may conceal significant use of energy, water, or other materials needed for production. For instance, Williams et al. (2002) found that, when taking into account all inputs of fossil fuels, chemicals, water, and elemental gases, a 2-gram microchip mobilized 34,372 grams of resources. Purity required for the creation of microchips demanded a significant amount of energy, chemicals, and water. Life cycle approach helped to reveal the complete ecological footprint of this microchip product, and can do the same for many nano-based products. On the other hand, some nanotechnology methods ("bottom-up") may reduce reliance on substances with high purity and thereby avoid some of the environmental problems associated with producing high purity substances.

This paper attempts to inventory and evaluate life cycle assessments performed for nanotechnologies across sectors and products. I initially hypothesized that a number of (at least 10) life cycle assessments on nanotechnologies would have been performed to date and would provide clues to environmental benefits and impacts of nanotechnologies. For instance, because nanomaterials facilitate dematerialization, I expected the life cycle assessments to show certain environmental benefits (e.g., less energy consumption, less emissions from transportation, less material waste generated at end-of-life). I expected that energy use, although lower during use of a nano-based product, may be higher during production as compared to a conventional product. In addition, I anticipated that the existing life cycle assessments would evaluate a range of product types and address all life stages, but also reveal some gaps (e.g., toxicity of nanomaterials because so little toxicological research has been performed). The findings from this research may be useful for informing future life cycle assessments of nanotechnologies, particularly to better understand where gaps remain, which methods and data sources proved useful, and where we should direct future research efforts.

3. Methodology

To carryout this research, I first reviewed nanomaterial market penetration across product categories and sectors. I then performed a literature review of life cycle assessments on nanotechnologies. Using the internet, libraries, and articles submitted to the Journal of Industrial Ecology, I tried to identify existing LCAs on nano-based products. I also contacted various experts in the fields of nanotechnology, industrial ecology, and life cycle assessment for information.

4. Overview of Nanotechnology Market Penetration

Nanomaterials have already entered many product lines and industries. Because of this existing and the potential penetration of nanotechnologies into the marketplace, both the positive and negative impacts will be far-reaching. To quote Cientifica's projection in 2003: "nanotechnology will affect almost every market either directly or indirectly." The sectors with nano-scale products in use or in development include the following: automotive, chemical, construction, cosmetics, electronics, energy, engineering, environmental, food and drink, household, medicine, sports, textiles, and warfare (VDI 2004, Hood 2004). Products derived from nanotechnologies reside in everything from sunscreens to tennis rackets to solar panels to water decontamination devices. A book by Uldrich and Newberry 2003 suggests that the top ten industries (in terms of billions of dollars of investment) that will be revolutionalized by nanotechnology include healthcare, long-term care, electronics, telecom, packaging, chemical, plastics, apparel, pharmaceutical, and tobacco. Roco 2003 indicates annual nano-sales of $1 trillion in ten years including $340 billion for materials, $300 billion for electronics, $180 billion for pharmaceuticals, $100 billion for chemical catalysts and processing. Table 1 provides a list of some of the applications of nanotechnology.[3]

Materials produced at the nano-scale take various forms. The Royal Society categorizes nanomaterials by dimension as follows:

- One dimension: surface coatings and films;
- Two dimensions: nanowires, nanotubes, biopolymers;

[3] AZoNano.com, an online warehouse of nanotechnology information ("the A to Z of Nanotechnology") also provides a lengthy list of nano-based product applications (2005).

- Three dimensions: nanoparticles (metal oxides)—precipitates, colloids, and quantum dots, nanocrystalline materials, fullerenes or carbon 60 (i.e., buckyballs), dendrimers[4] (The Royal Society 2004).

Table 1: Nanotechnology Sector Applications

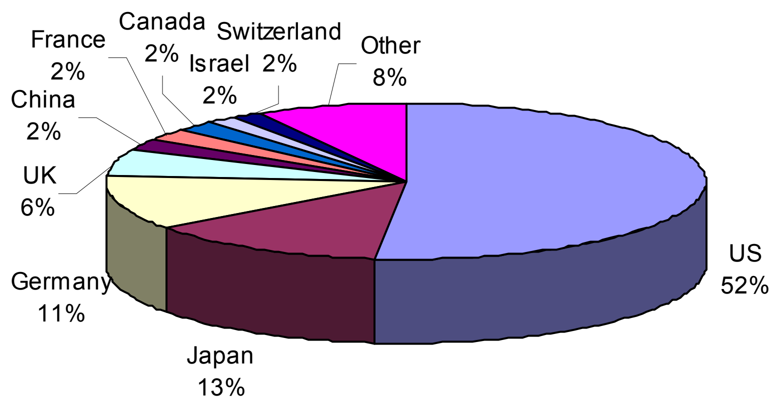
Sector/Application	
Automotive	**Chemical**
Lightweight construction; Catalysts, Painting; Tires; Sensors; Windshield and body coatings	Fillers for paints; Composite materials; Impregnation of papers; Adhesives; Magnetic fluids
Construction	**Cosmetics**
Materials; Insulation; Flame retardants; Surface coatings; Mortar	Sunscreen; Lipsticks; Skin creams; Toothpaste
Electronics	**Energy**
Displays; Data memory; Laser diodes; Fiber optics; Optical switches; Filters; Conductive, antistatic coatings	Lighting; Fuel cells; Solar cells; Batteries; Capacitors
Engineering	**Environmental**
Protective coatings for tools, machines; Lubricant-free bearings	Environmental monitoring; Soil and groundwater remediation; Toxic exposure sensors; Fuel changing catalysts; Green chemistry
Food and Drink	**Household**
Packaging; Storage life sensors; Additives; Juice clarifiers	Ceramic coatings for irons; Odor removers; Cleaners for glass, ceramics, metals
Medicine	**Sports**
Drug delivery systems; Contrast medium; Rapid testing systems; Prostheses and implants; Antimicrobial agents; In-body diagnostic systems	Ski wax; Tennis rackets; Golf clubs; Tennis balls; Antifouling coatings for boats; Antifogging coatings for glasses, goggles
Textiles	**Warfare**
Surface coatings; "Smart" clothes (anti-wrinkle, stain resistant, temperature controlled)	Neutralization materials for chemical weapons

Source: VDI 2004 and Hood 2004.

Cientifica identified 834 companies involved in nanotechnology worldwide in 2003. Among these, the majority (52 percent or 430 companies) are located in the United States, as shown in Figure 1. Japan and Germany contain the next highest numbers of nanomaterial producers with 110 and 94 companies, respectively. A large number of research institutions are also involved in nanotechnology. Cientifica estimates that there are 369 universities and research institutions active in the nanosector (2003). The United States accounts for 28 percent of global involvement in nano-research, Japan follows closely behind at 24 percent (See Figure 2).

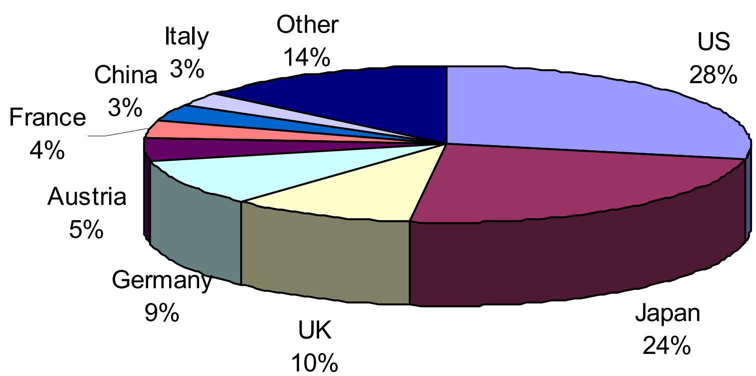
[4] Spherical polymeric molecules. Detailed information available at http://nano.med.umich.edu/Dendrimers.html.

Figure 1: Percentage of Companies Producing Nanomaterials by Country (as of June 2003)



Note: Other includes Australia, Netherlands, Taiwan, Austria, Sweden, Finland, Korea, Russia, Italy, and Spain.
Source: Cientifica 2003.

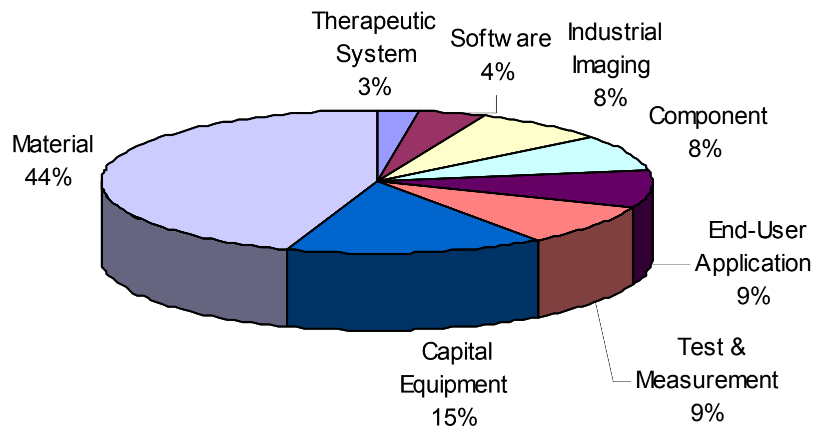
Figure 2: Percentage of Universities and Institutions Involved in Nano-Research by Country (as of June 2003)



Note: Other includes Australia, Spain, Sweden, Switzerland, Belgium, Netherlands, Israel, Poland, Russia, and Taiwan.
Source: Cientifica 2003.

According to a now annual survey by the *Small Times* trade magazine, there are 467 companies producing nanomaterials or the equipment to produce them, or making use of nanomaterials within products in the United States (2004). Of these industries, the majority are devoted to material development (44 percent), as shown in Figure 3 below. Capital equipment and test and measurement account for the next two largest nanotechnology industries (15 and 9 percent, respectively).

Figure 3: Categories of Nano-based Industries in the United States



Source: Small Times 2004.

A cover story in *Chemical & Engineering News* cited another estimate by Lux Research for the number of start-up companies involved in nanotech-related work worldwide. Lux suggests that this number is as high as 1,200, and that about half of these start-ups are located in the United States (Thayer 2005).

5. Life Cycle Assessment Findings

5.1 Overview

Thus far, only a handful of life cycle assessments (LCAs) on nanotechnologies have been completed. A summary of the LCAs identified through this project are provided in Table 2. For each LCA, the table lists the study year and location, the nanotech sector and product assessed, the focus of the study, and the specific approach used. The life cycle phases addressed during each study, the technological benefits of the nanomaterial, the environmental benefits and costs, and life stages with the greatest and least benefits compared to traditional products are also identified.

Although few LCAs have been completed, others are underway or in the early stages of development. Information on proposed or planned LCAs are presented in Table 3. Please note that although this project aimed to identify all completed and proposed LCAs on nanotechnologies, there may be some that were inadvertently missed through this research effort. If you are aware of additional LCAs, please contact the author. Various experts in this arena have also confirmed the lack of published LCAs on nanotechnologies. For instance, the following comments were received among the researchers contacted:

- David Shonnard[5] of Michigan Technological University says he is "not aware of any such studies other than the ones you cited,"(2005).
- Shannon Lloyd[6] of the Department of Civil and Environmental Engineering at the University of Pittsburgh indicates that "there have been only a few LCAs on nanotechnology products or processes published to date," (2005a).
- Suren Erkman[7] of the Institute for Communication and Analysis of Science and Technology with expertise in nanotechology from an industrial ecology perspective, states: "I am not aware of other LCA studies of nanotech other that the ones mentioned in your list," (2005).
- Roland Clift of the Center for Environmental Strategy at the University of Surrey, with expertise in both of the areas of LCA and nanoscience, explains: "I don't know of any other studies. Furthermore, I don't think the available studies have really addressed the main question," (2005a), where the main question may be "that the people who advocate roles for nanotechnology in energy systems have yet to show whether the benefits outweigh the energy used in production," (2005b).

The sections following the summary tables discuss the LCA results by sector, product, life stages assessed, and life cycle benefits and costs. Lessons learned from this review, such as LCA approach, data sources, and gaps are also highlighted in a follow-up discussion.

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[5] David Shonnard is an Associate Professor of Chemical Engineering and a life cycle analysis expert. He is scheduled to be a guest lecturer for the NSF Summer Institute on Nano Mechanics and Materials' short course on Nanotechnology, Biotechnology, and Green Manufacturing for Creating Sustainable Technologies, June 20-24, 2005.

[6] Shannon Lloyd completed her doctoral thesis entitled "Using Life Cycle Assessment to Inform Nanotechnology Research and Development" at the Carnegie Institute of Technology in September, 2004.

[7] Suren Erkman is the former Book Editor for the Journal of Industrial Ecology.

Table 2: Summary of Performed Life Cycle Assessments of Nanotechnologies

Reference	Year of Study, Location	Sector	Nanotech Product	Focus of Study	Approach	Life Cycle Phases Included	Tech Benefits	Environmental Benefits	Environmental & Other Costs	Life Stages with Greatest Benefit[a]	Life Stages with Least Benefit[a]
Lloyd and Lave 2003	Year not indicated United States	Auto-motive	clay-polypro-pylene nano-composite in light-duty vehicle body panels	economic and environ-mental impacts comparing nano-composite s to steel and aluminum	Economic Input-Output Life Cycle Assessment (EIO-LCA) model developed by Carnegie Melon	Extraction, Production, Use	weight reduction and improved fuel economy; enhanced platelet mechanical properties	overall reduced environmental impact; large energy savings; reduction in fuels, ores, and water use; reduction in GHGs and conventional pollutants; reduction in haz waste generated for the upper bound performance nanocomposite	higher manufacturing cost; increase in haz waste generated for the lower bound performance nanocomposite	Material Production and Use (fuel economy) compared to steel body panels	Petroleum Production compared to steel body panels
Lloyd et al. 2005	2005 and 2030 projected United States	Auto-motive	nano-scale platinum-group metal (PGM) particles in automotive catalysts	PGM that could be saved from nanotech and life cycle benefits from reducing PGM mining and refining	Economic Input-Output Life Cycle Assessment (EIO-LCA) model developed by Carnegie Melon and GaBi software system developed by the University of Stuttgart with PE Product Engineering GmbH	Production and Criteria Air Pollutant Emissions during Use	reduced platinum-group metal (PGM) loading levels by 95%, improved dispersion of metals in auto catalysts	overall reduced environmental impact; large energy savings; reduction in fuels used, reduction in GHGs and criteria air pollutants (2X less criteria air emissions during vehicle use) ; reduction in haz waste generated and toxic releases and transfers	None indicated in comparison to current technology	Production	Not indicated
Volz and Olson 2004 (submitted)	United States	Automoti ve	carbon nanofiber (CNF) reinforced polymers	evaluation of environme ntal impact of different polymer and CNF reinforced polymer alternative s	Ecobilan TEAM software Assessed impacts of global warming, stratospheric ozone depletion, acidification, eutrophication, and total energy consumption at each life stage used carbon black in place of CNF due to data constraints	Certain Processes during Extraction, Production, Use, End-of-Life	Reduced weight, increased structural strength, improved conductivity	NA (not compared to traditional carbon fibers)	Similar impacts among polymers.	Least impact: Extraction	End-of-Life: Global Warming Potential, Acidification, Eutrophication; Use: Ozone Depletion Potential, and Energy Use
Steinfeldt et al. 2004 - citing Harsch & Schuckert 1996	Year not indicated Germany	Paint	nano-varnishes	ecological efficiency	comparative ecological life-cycle assessment (nano-varnish	Extraction, Production of components and varnish, Pre-treatment	allows for application of a thinner coating layer with same functionality of	5X more resource efficient (far less varnish needed for same effectiveness); 65% lower VOC	Not indicated	Extraction, Production, Use (probably due to transportation advantages of	Application compared to other coatings

Reference	Year of Study, Location	Sector	Nanotech Product	Focus of Study	Approach	Life Cycle Phases Included	Tech Benefits	Environmental Benefits	Environmental & Other Costs	Life Stages with Greatest Benefit[a]	Life Stages with Least Benefit[a]
					compared to water-based, solvent-based, and powder varnishes)	of surface, Varnishing, Use, End-of-Life	other coatings	emissions; 30% lower GHG emissions; lower acidification potential		lightweight material) compared to other coatings	
Steinfeldt et al. 2004	Not indicated Germany	Chemical / Plastics	nanotube catalytic converter to produce styrene	process innovation	deduction using a "general outline of the technology"	Focus on Process; Used process energy data to estimate overall life cycle energy use	increased energy efficiency	50% lower energy use during styrol synthesis (325 MJ/kg using a nanotube catalytic converter vs. 636 MJ/kg with classic styrol synthesis); 8-9% lower energy use over the entire life cycle; reduction in heavy metal use and associated emissions	potential risks from the use of nanotubes (need to be assessed)	Production compared to an iron-oxide catalytic converter	Not indicated
Steinfeldt et al. 2004	Not indicated Germany (with use of U.S. study data)	Electronics/Display	OLEDs and CNT-FED flat displays compared to CRT, LCD, and plasma displays	nano-innovations and eco-efficiency	qualitative comparison and LCA estimates for CRT and LCD from Socolof et al. 2001	Pre-Production, Production, Use	increased energy efficiency, higher resolution and brightness, full color, lightweight, low cost	greater material and energy efficiency; lower production input for OLEDs; 2X greater energy efficiency in use phase compared to conventional LCDs; 20% lower energy use over entire life cycle compared to LCDs	significant risks not expected	Use	Pre-Production
Steinfeldt et al. 2004	Not indicated Germany	Lighting	white LEDs and quantum dots compared to conventional and energy saving light bulbs	nano-applications and eco-efficiency	Not indicated	Use	High energy intensity and broad visible array; multiple applications	white LEDs more energy efficient than the classical light bulb; white LEDs only more efficient than energy saving bulbs when they reach light efficiency of over 65 lm/W; energy efficiency expected with quantum dots in the future	white LEDs 3X less efficient than an energy saving light bulb	Use compared to classical light bulb	Use compared to energy saving light bulb

Notes: CF = Color Filter; CNT-FED = Carbon Nanotube Field Emitter Display; LCA = Life Cycle Analysis or Assessment; LCD = Liquid Crystal Display; LCI = Life Cycle Inventory; LED = Light Emitting Diode; OLED = Organic Light Emitter Display; PGM = Platinum-Group Metal; TFT = Thin Film Transistor.

[a] Compared to other technologies.

Table 3: Summary of Proposed or Underway Life Cycle Assessments of Nanotechnologies

Contact, Affiliation	Year of Study, Location	Nanotech Product	Focus of Study/ Approach	Reference
Earl Beaver, Bridges to Sustainability with Rice University	currently	Nanomaterials	Manufacture and use	Beaver 2004, Lloyd 2005a
J.M. Kenny, University of Perugia, Material Science and Technology Centre of the Department of Civil and Environmental Engineering	Year not indicated Italy	Nanocomposites	Development and application of Life Cycle Engineering and Life Cycle Analysis tools	Nanofire 2005.
European Union NAIMO (Nanoscale Integrated processing of Self-Organizing Multifunctional Organic Materials) research project -consulting group hired	Unknown	Organic electronics and nanostructured materials - solar cells and field effect transistors	assess the environmental impact of these technologies	Lloyd 2005a
Claudia Som EMPA, Technology and Society Lab with the Biocompatible Materials Lab	1/05 to 12/06 Switzerland	Carbon nanotubes (CNT)	"perform a foresight study on what potential problems may arise in the CNT life cycle, in order to be able to take precautionary measures right during the R&D process." For the life cycle approach, which will be done in 2006, EMPA "probably… will develop scenarios for specific applications and do expert interviews for all stages of the life cycle for this specific application." "Qs not much data are available, a traditional life cycle assessment does not seem to be useful," (Som 2005).	Som 2005, EMPA 2005
P.V. Kandachar, Department of Design Engineering, Delft University of Technology	01/03 to 12/07 Netherlands	Products designed in polymers	Life Cycle Engineering and Design: Engineering Design with New Materials	Delft University Website 2005
Jessica Lin, University of Michigan School of Natural Resources and Environment and Ross School of Business	2005-2006 United States	Carbon nanotubes	Hydrogen fuel cells in vehicles	Lin 2005
Mike Greenberg, under Mike Gorman, University of Virginia	currently, anticipated completion in 2007 United States	Carbon trimetaspheres	Develop upstream management framework for use in Earth Systems Engineering and Management "addressing such issues as how to integrate toxicology data, how to acquire otherwise proprietary information from Luna (the manufacturer/patent holder), what regulatory implications there might be, and which of the myriad planned applications should receive emphasis."	Greenberg 2005a, 2005b

5.2 Sectors/Products Assessed

LCAs have been performed for very few products and nanomaterials and across only a few sectors. Table 4 below presents some of the product and nanomaterial applications for each sector and also identifies where known LCAs on nanotechnologies have been performed and are lacking.

As shown in the table, the identified LCAs on nanotechnologies have been performed only in the automotive, chemical, electronic/display, and energy/lighting sectors. LCAs of product applications in the automotive and energy-related sectors are most common because these nano-applications are more frequently in the news and have the biggest impact in the use phase (Lloyd 2005b). Sectors that have not yet been assessed on a life cycle basis include the construction, cosmetics, engineering, environmental, food and drink, household, medicine, sports, textiles, and warfare industries.

Products assessed within these LCAs include (a) clay polypropylene nano-composite and (b) carbon nanofiber reinforced polymers applied as lightweight construction body panels in light-duty vehicle, (c) nano-scale platinum-group metal particles used in automotive catalysts, (d) nano-varnish, (e) semiconductor crystals and carbon nanotubes used in electronic displays, and (f) quantum dots and semiconductor crystals for lighting. All the LCAs, except for that performed by Volz and Olson 2004 submitted, performed the nano-based product LCAs in comparison to current product technologies.

The LCAs have focused mostly on carbon nanotubes, nanowires, semiconductor crystals, and quantum dots. Buckyballs (carbon 60), nanowires, metal oxides, and dendrimers are not known to have yet been analyzed with LCA.

Table 4: Nanotechnology Sector Applications and Identified LCAs

Sector/Application[a]	LCAs Performed
Automotive	
Lightweight construction	Lloyd and Lave 2003 - clay polypropylene nano-composite Volz and Olson 2004 (submitted) - carbon nanofiber reinforced polymers
Catalysts	Lloyd et al. 2005 - nano-scale platinum-group metal (PGM) particles
Painting; Tires; Sensors; Windshield and body coatings	
Chemical	
Fillers for paints	Steinfeldt et al. 2004 (citing Harsch & Schuckert 1996) - nano-varnish with sol-gel technology
Composite materials; Impregnation of papers; Adhesives; Magnetic fluids	
Construction	
Materials; Insulation; Flame retardants; Surface coatings; Mortar	
Cosmetics	
Sunscreen	

Lipsticks; Skin creams; Toothpaste	
Displays	Steinfeldt et al. 2004 - semiconductor crystals in Organic Light Emitter Displays[b] and carbon nanotubes
Data memory	
Laser diodes; Fiber optics; Optical switches; Filters; Conductive, antistatic coatings	
Energy	
Lighting	Steinfeldt et al. 2004 - quantum dots and semiconductor crystals in Light Emitting Diodes[b]
Fuel cells; Solar cells; Batteries; Capacitors	
Engineering	
Protective coatings for tools, machines; Lubricant-free bearings	
Environmental	
Environmental monitoring; Soil and groundwater remediation	
Toxic exposure sensors; Fuel changing catalysts; Green chemistry	
Food and Drink	
Packaging; Storage life sensors; Additives; Juice clarifiers	
Household	
Ceramic coatings for irons; Odor removers; Cleaners for glass, ceramics, metals	
Medicine	
Drug delivery systems; Contrast medium; Rapid testing systems; Prostheses and implants; Antimicrobial agents; In-body diagnostic systems	
Sports	
Ski wax; Tennis rackets; Golf clubs; Tennis balls; Antifouling coatings for boats; Antifogging coatings for glasses, goggles	
Textiles	
Surface coatings; “Smart” clothes (anti-wrinkle, stain resistant, temperature controlled)	
Warfare	
Neutralization materials for chemical weapons	

[a]Source: VDI 2004 and Hood 2004.
[b]Source: Azonano.com 2005.

5.3 Life Stages Assessed

The LCAs presented here have addressed some, but not all life stages. In Table 5, the life stages included for each study are denoted with an “X.” All of these studies addressed the use phase, and all, except the LCA on LEDs and quantum dots, assessed the production phase. Impacts during transportation and end-of-life (landfilling, recycling, reuse, composting, or incineration) were areas least addressed by the studies. Researchers left these and other life stages out of the scope of particular LCAs primarily due to a lack of data or because they deemed such life stages upfront to have minimal impact. For instance, Volz and Olson indicate: “other processes such as transportation, oil refining, reuse, maintenance, and incineration have been excluded from this LCA due to lack of data or inconsistency of data.” This was not surprising given that estimating uncertain transportation and end-of-life impacts would require a great deal of speculation. However, qualitative assessments would have added value to the studies.

Table 5: Life Stages Assessed in the Identified LCAs of Nanotechnologies

Reference, Product	Extraction	Production	Transportation	Use	End-of-Life
Lloyd and Lave 2003, clay-polypropylene nano-composite in light-duty vehicle body panels	X	X		X	
Lloyd et al. 2005, nano-scale platinum-group metal particles in automotive catalysts		X		X (criteria air pollutant emissions)	
Volz and Olson 2004 submitted, carbon nanofiber reinforced polymers	X (certain processes)	X		X	X
Steinfeldt et al. 2004 - citing Harsch & Schuckert 1996, nano-varnishes	X	X (components and varnish)		X	X
Steinfeldt et al. 2004, nanotube catalytic converter to produce styrol	X estimated based on production energy use	X	X estimated based on production energy use	X estimated based on production energy use	X estimated based on production energy use
Steinfeldt et al. 2004, OLEDs and CNT-FED flat displays	X	X		X	
Steinfeldt et al. 2004, white LEDs and quantum dots				X	

Note: X = addressed in the study. Blank cells = not addressed in the study.

5.4 Life Cycle Benefits and Costs

Most of the LCAs found a reduced overall environmental impact across the product life cycle compared to current technology. Specific benefits identified with the use of the nano-based material for the life stages inventoried included:

- *Increased energy efficiency* (for the nano-composite in light-duty vehicle body panels compared with steel or aluminum, nano-scale platinum-group metal particles in auto catalysts, nanotube catalytic converters, nano-based flat displays, white LEDs when compared to conventional light bulb)
- *Increased resource efficiency* (for nano-varnishes, nano-based flat displays).
- *Reduced fuel use* (for the nano-composite in light-duty vehicle body panels, nano-scale platinum-group metal particles in auto catalysts
- *Reduced water use* (for the nano-composite in light-duty vehicle body panels
- *Reduced heavy metal use* (for nanotube catalytic converters)
- *Lowered greenhouse gas emissions* (for the nano-composite in light-duty vehicle body panels, nano-scale platinum-group metal particles in auto catalysts, and nano-varnishes).

- *Lowered criteria air pollutants* (for the nano-composite in light-duty vehicle body panels, nano-scale platinum-group metal particles in auto catalysts, and nano-varnishes)
- *Reduced hazardous waste generated* (for the upper bound performance nanocomposite, nano-scale platinum-group metal particles in auto catalysts).

Many of the studies did not evaluate environmental impacts or risks. Steinfeldt et al. 2004 pointed out that potential risks from the use of nanotubes still remain to be assessed. For the studies that did consider costs or risks from the life cycle of nano-based products compared with that for current conventional products, the following were identified:

- *Higher manufacturing cost* (for nano-composite in light-duty vehicle body panels compared with steel or aluminum).
- *Increased generation of hazardous waste* (for the lower bound performance nanocomposite).
- *Lower energy efficiency* (for white LEDs compared with an energy saving light bulb).

5.5 Approach and Data Sources

The LCAs of nanotechnologies typically carried out the assessment in comparison to the corresponding current technology. For instance, the completed LCAs made the following comparisons:

- clay-polypropylene nano-composites were compared to steel and aluminum composites in light-duty vehicle body panels;
- nano-scale platinum-group metal (PGM) particles were compared to conventional PGM use in automotive catalysts;
- nano-varnishes were compared to water-based, solvent-based, and powder varnishes;
- a nanotube catalytic converter was compared to an iron-oxide catalytic converter in its production of styrol;
- OLEDs and CNT-FED flat displays were compared to CRT, LCD, and plasma displays;
- white LEDs and quantum dots were evaluated in comparison to conventional and energy saving light bulbs.

The specific approaches used for carrying out the LCAs varied. Steinfeldt et al. did not provide detail on the approaches employed, but indicated a comparative ecological LCA approach for the nano-varnish study; it appears that they used available LCA data and deduction for the other assessments. Lloyd made use of the Economic Input-Output Life Cycle Assessment (EIO-LCA) model[8] developed by Carnegie Melon and GaBi software system[9] developed by the University of Stuttgart with PE Product Engineering GmbH. Her first LCA on the vehicle composites used the EIO-LCA model alone (Lloyd and Lave 2003), while her study on PGM particles in catalysts used both models (Lloyd et al. 2005). She recommends the use of two models and multiple databases as a way to cross-check/perform a sensitivity analysis on the results (2005b).

The EIO-LCA model estimates both economic and environmental impacts (e.g., energy inputs, criteria air pollutant and greenhouse gas emissions, hazardous waste outputs, and toxic releases and transfers) "across the supply chain for purchases in any commodity sector of the U.S.

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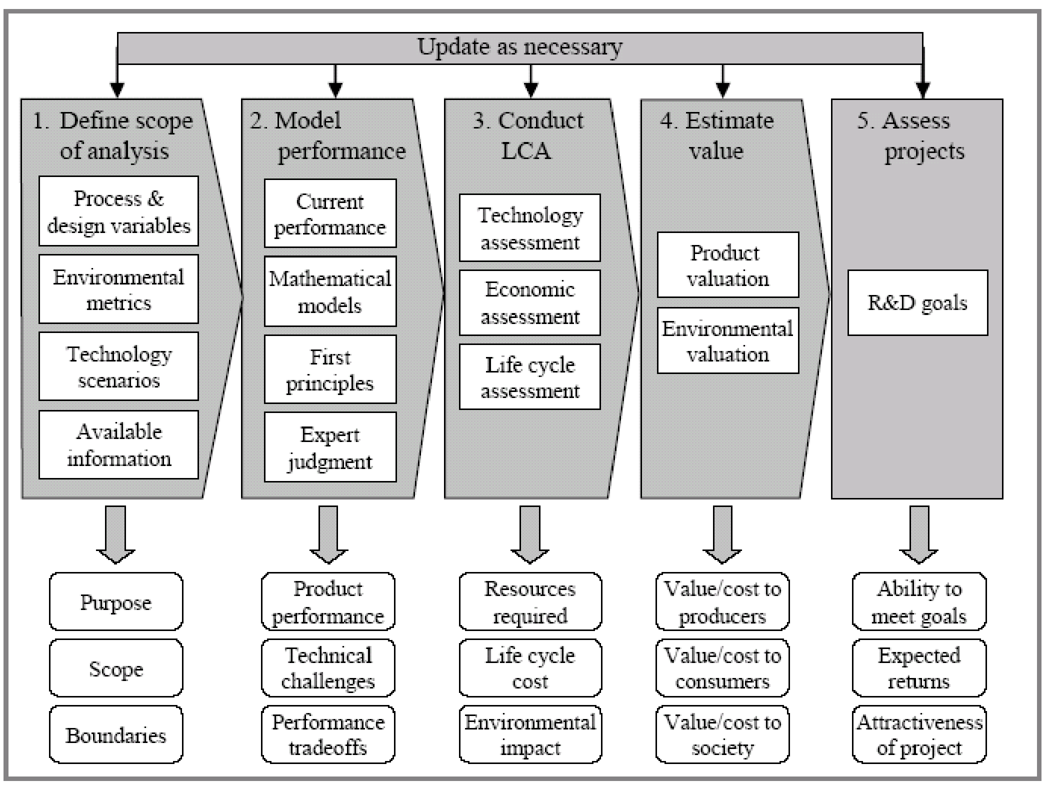
[8] http://www.eiolca.net/
[9] http://www.gabi-software.com

economy," using public data (Lloyd et al. 2005). The GaBi software, "a process-based, ISO/SETAC-style LCA model" uses metal data from "industry, technical and patent literature, and other sources" to inventory various inputs (e.g., renewable and non-renewable energy, water, inert rock, and precious metal ore) and outputs (e.g., air emissions, hazardous, consumer, and radioactive waste, and metals and hydrocarbons into water) across the life cycle (Lloyd et al. 2005).

Both models have their limitations. The EIO-LCA is specific to U.S. economic purchases and "does not distinguish between different grades or types of materials produced in the same sector. GaBi misses some "supply chain effects." Perhaps the most significant limitations of these models involve (a) their assumption of "a linear relationship between environmental effects and amount of PGM [or other material] purchased or produced" and (b) their use of data on current technology (Lloyd et al. 2005). These are significant because environmental impacts of nanomaterials may not be proportional to the amount produced, depending on how "amount" is measured (number, volume, etc.) as they may be for conventional materials. To better understand how nanomaterials behave in the environment, nanotechnology should be evaluated according to a separate standard that takes into account the risks and environmental impacts caused by the type and nature of material inputs and outputs, not simply quantity or size of materials. Such considerations could focus more on the size, shape, and surface coatings of nanomaterials (i.e., evaluating potential for release into the air during production and use).

To better evaluate and anticipate environmental effects of nano-based products in the early stages of research and development, Lloyd created the following LCA framework.

Figure 4: Framework for Using Life Cycle Assessment to Evaluate Expected Nanotechnology-based Products



Source: Lloyd 2004

Volz and Olson at the University of Toledo made use of the Ecobilan Tool for Environmental Analysis and Management (TEAM) software[10] for carrying out an LCA on carbon nanofibers. This tool uses a database called the Data for Environmental Analysis and Management (DEAM) and allowed for the assessment of impacts of global warming, stratospheric ozone depletion, acidification, eutrophication, and total energy consumption at each life stage. Volz and Olson's LCA also used other data sources, which may be relevant for future LCAs of nanomaterials. These included the Association of Plastics Manufacturers in Europe, the U.S. National Renewable Energy Lab's LCI Project, U.S. Patent Office input data, Oak Ridge National Laboratory reports, Rocky Mountain Institute data, and other published reports. The authors note that the DEAM database is limited because it refers mostly to European data sources and is somewhat dated (Volz and Olson 2004).

5.6 Gaps

Performing a LCA of a product is a laborious and potentially costly endeavor. One would not expect that each LCA would include all life stages and quantify all potential impacts. However, it is important to highlight gaps that could be filled in future research. The gaps identified through this review of the completed LCAs of nanotechnologies include the following:

- Evaluation of a variety of products across multiple sectors (Table 4 highlights the gaps).
- Assessment of the transportation or end-of-life phases.
- Inclusion of all material inputs, beyond energy use.
- Consideration of the nature of nanomaterials in comparison to conventional materials where impact is measured by size or quantity of material.
- Consideration of the destination (i.e., fate and exposure) of material outputs.
- Consideration and explicit evaluation of health and environmental risks.

6. Conclusions and Recommendations for Future Assessments

As indicated in this paper, the completed LCAs have focused on the automotive, electronic, chemical, and lighting sectors. Future assessments should consider nano-based products applied in other sectors and include a more significant consideration of additional material inputs, end-of-life phases, and potential risks across all life phases. I did not expect to find quite so many gaps in these analyses. It will be important that future LCAs also model nano-specific effects, which appear to be ignored in most of these LCAs. For instance, hazardous material outputs estimated in Lloyd et al. 2005 refer to conventional hazardous waste resulting from the sector supply chain, not waste considered "hazardous" because it contains nanomaterials.

For future studies, Lloyd recommends the integration of LCA with risk analysis (2005b). Textbook LCAs do in fact consider toxicity and exposure issues; however, in practice, most LCAs do not consider exposure and many do not quantify human health impacts. LCAs of nano-based products should evaluate health risks (e.g., where releases take place and their fate and transport) occurring during the process and use phases. One producer of carbon nanotubes

[10] http://www.ecobilan.com/uk_lcatool.php

indicated that welders dealing with chemical inputs with these nanomaterials face some of the greatest exposure and risk (Carnahan 2005).

Because of potential health risks associated with various nanomaterials—such as buckyballs with their durability and application in pharmaceutical products, and metal oxides used in sunscreens—LCAs, risk assessments, and substance flow analyses should further evaluate these nanotechnologies. It would also be interesting to assess carbon nanotube-based products in greater detail because they are making their way into so many applications. Cientifica affirms that "big markets, apart from materials, in which nanotubes may make an impact, include flat panel displays (near-term commercialization is promised here), lighting, fuel cells and electronics," (2004). As described in a recent *Environmental Health Perspectives* publication, carbon nanotubes are considered "one of the most widely used and researched engineered nanoparticles" (Hood 2004). Based on this analysis of LCAs, I evaluated the feasibility of performing a substance flow analysis on carbon nanotubes in a follow-up study.

The results of this LCA inventory paper indicate that, in the analysis of nanotechnology using a life cycle approach, more attention is needed. Few LCAs have been completed that are publicly available. The existing LCAs do not assess nano-specific impacts, such as those related to hazardous potential of nanoparticles. The performed LCAs also assess fewer products and life stages than expected since nanomaterials are being used in the development of so many products. Future LCAs and qualitative assessments should focus on evaluating specific human health and environmental impacts and risks associated with *nano*-based inputs and products during premanufacture activities, product manufacture, packaging and transport, use, and recycling and disposal. These efforts will help inform and improve safe development, management, and use of nanotechnology as this field moves forward.

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