Green Engineering & Life Cycle Assessment (LCA) at Virginia Tech

Oak Ridge National Lab
April 10, 2014

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Research Associate Professor – Materials Science & Engineering

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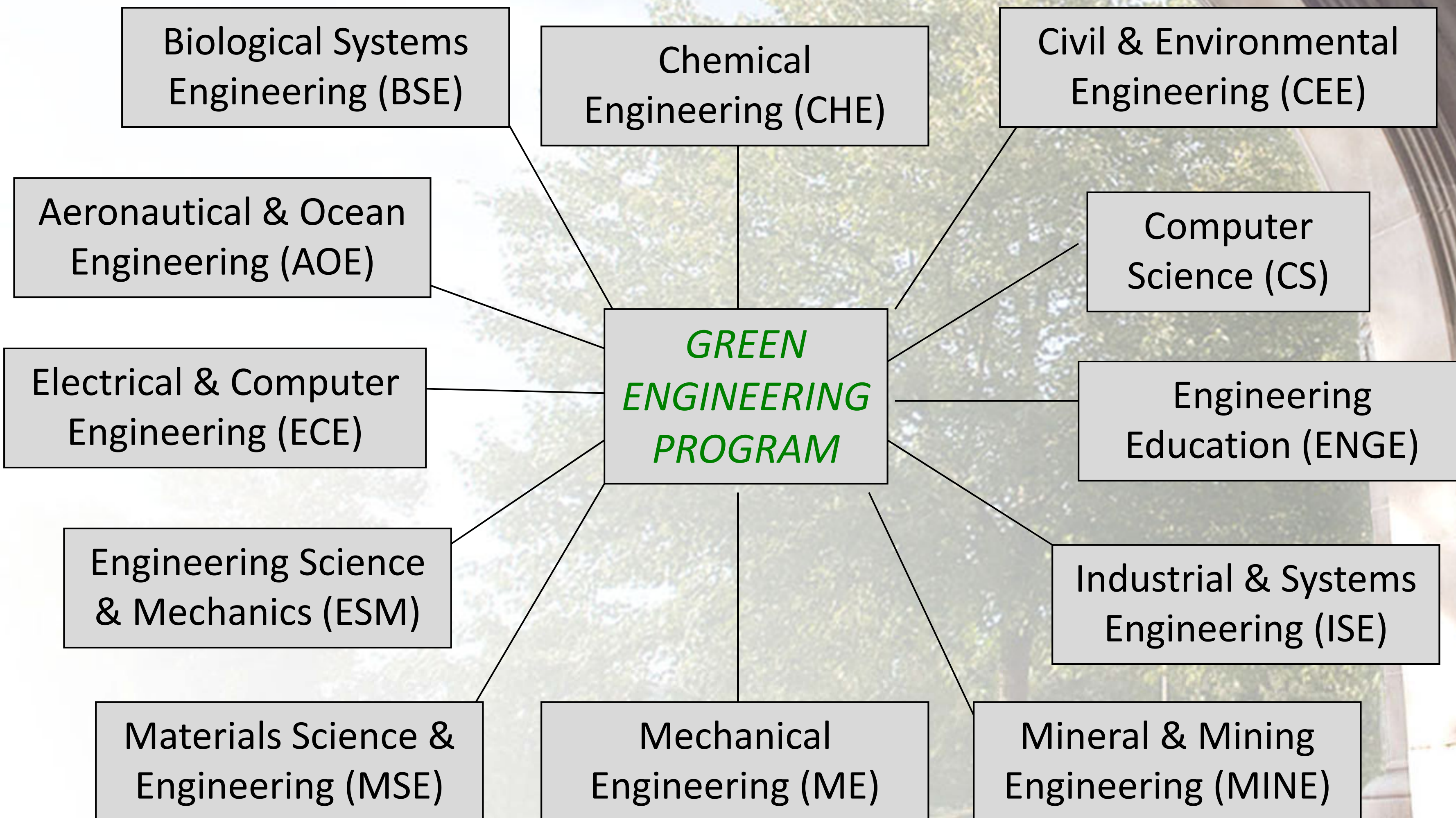
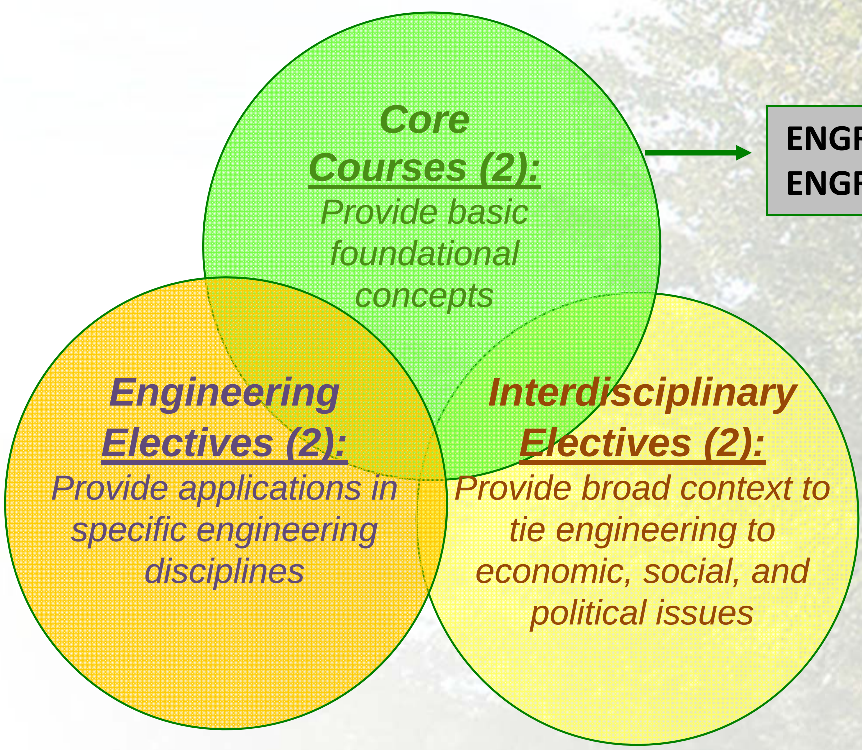


VT Green Engineering Curriculum

- **A Green Engineering Minor is available for students completing 18 credit hours (6 courses):**



ENGR 3124 – Intro to Green Engineering
ENGR 4134 – Environmental Life Cycle Assessment

Green Engineering Minor:
Engineering Electives

Aerospace Engineering

AOE 4064	Fluid Flows in Nature

Biological Science and Engineering

BSE 3324	Small Watershed Hydrology
BSE 3334	Nonpoint Source Pollution Assessment and Control
BSE 4304	Nonpoint Source Pollution Modeling & Management
BSE 4394	Water Supply & Sanitation in Developing Countries
BSE 4504	Bioprocess Engineering
BSE 4524	Biological Process Plant Design
BSE/CEE 5244	Advanced GIS in Hydrological Analysis
BSE 5354	Nonpoint Source Pollution Modeling

Chemical Engineering

CHE 3134	Separation Processes
CHE 3184	Chemical Reactor Analysis & Design

Civil and Environmental Engineering

CEE 3104	Introduction to Environmental Engineering
CEE 4064	Design for Hazard Control in Construction
CEE 4104	Water and Wastewater Treatment Design
CEE 4114	Fundamentals of Public Health Engineering
CEE 4134	Environmental Sustainability
CEE 4144	Air Resources Engineering
CEE 4154	Indoor Environmental Quality and Sustainable Facilities
CEE 4164	Environmental Microbiology
CEE 4174	Solid and Hazardous Waste Management
CEE 4264	Sustainable Land Development
CEE 4304	Hydrology
CEE 4344	Water Resources Planning
CEE 4354	Environmental Hydrology
CEE 4554	Natural Disaster Mitigation
CEE 4594	Soil and Groundwater Pollution

Electrical Engineering

ECE 4304	Design in Power Engineering
ECE 4364	Alternate Energy Systems (*online course*)
ECE 5364	Electric Energy & Environmental Systems

Engineering Science and Mechanics

ESM /ME 4194	Sustainable Energy Solutions for a Global Society

Industrial Systems Engineering

ISE 2204/2214	Manufacturing Processes and Laboratory
ISE 4644	Occupational Safety and Hazard Control
ISE 4304	Global Issues in Industrial Management

Materials Science and Engineering

MSE 2044	Elements of Materials Engineering
MSE 4055	Material Selection and Design

Mechanical Engineering

ME 4034	Bio-Inspired Technology
ME 4154	Industrial Energy Systems
ME 4164	Energy Systems for Buildings
ME 4204	Internal Combustion Engines
ME 4554	Advanced Technology for Motor Vehicles
ME 4724	Engineering Acoustics
ME 5254	Fuel Cell Systems
ME 5814	Energy Harvesting

Mineral and Mining Engineering

MINE 3544	Mineral Processing Laboratory
MINE 3554	Resource Recovery
MINE 4544	Mine Reclamation and Environmental Management

Nuclear Science and Engineering

NSEG 3145	Fundamentals of Nuclear Engineering
NSEG 3146	Fundamentals of Nuclear Engineering
NSEG 3604	Radiation Detection, Protection, and Shielding
NSEG 5204	Nuclear Fuel Cycle

- Senior capstone design projects with a focus on the environmental *impact* of engineering also count as engineering electives.

Green Engineering Minor:
Interdisciplinary Electives

Agriculture and Applied Economics

AAEC 3314	Environmental Law
AAEC 4304	Environmental & Sustainable Development Economics
AAEC 4314	Environmental Economic Analysis and Management
AAEC 4344	Sustainable Development Economics

Apparel, Housing, and Resource Management

AHRM 4604	Housing, Energy, and the Environment

Architecture

ARCH 4055	Environment and Building Systems
ARCH 4056	Environment and Building Systems

Biology

BIOL 2804	Ecology
BIOL 4004	Freshwater Ecology
BIOL 4014	Environmental Toxicology
BIOL 4044	Biogeography

Chemistry

CHEM 4984	Green Chemistry

Crop and Soil Environmental Sciences

CSES 3644	Plant Materials for Environmental Restoration
CSES 4644	Land-Based Systems for Waste Treatment
CSES 4734	Environmental Soil Chemistry

Economics

ECON 4014	Environmental Economics

Environmental Science

ENSC/CSES 3604	Fundamentals of Environmental Science
ENSC 3634	Physics of Pollution
ENSC/CSES 4774	Reclamation of Drastically Disturbed Lands
ENSC/CSES 4854	Wetland Soils and Mitigation

Entomology

ENT 2004	Insects and Human Society
ENT 4264	Pesticide Usage

Fisheries and Wildlife

FIW 4614	Fish Ecology

Forestry

FOR 2554	Nature and American Values

Geography

GEOG 3104	Environmental Problems, Population, & Development
GEOG 4204	Geography of Resources
GEOG 5234	Human Impacts on the Environment

Geosciences

GEOS 2104	Elements of Geology
GEOS 3014	Environmental Geosciences
GEOS 3034	Oceanography
GEOS 4634	Environmental Geochemistry

History

HIST 3144	American Environmental History

Philosophy

PHIL 2304	Global Ethics

Political Science

PSCI 3344	Global Environmental Issues

Sustainable Biomaterials

SBIO/FOR 2784	World Forests and Forest Products
SBIO 3004	Sustainable Nature-Based Enterprise
SBIO 3324	Green Building Systems
SBIO 3434	Chemistry and Conversion of Sustainable Biomaterials
SBIO 3444	Sustainable Biomaterials and Bioenergy
SBIO 3454	Society, Sustainability Biomaterials and Energy

Urban Affairs and Planning

UAP 3354	Introduction to Environmental Policy and Planning
UAP 4264	Environmental Ethics and Policy
UAP 4374	Land Use & the Environment: Planning and Policy
UAP 4394	Community Renewable Energy Systems

***Area 2 core curriculum courses**
***Area 7 core curriculum courses**

Sustainability?

- Sustainability is the process of deciding what to do in order to maintain a defined quality of life.

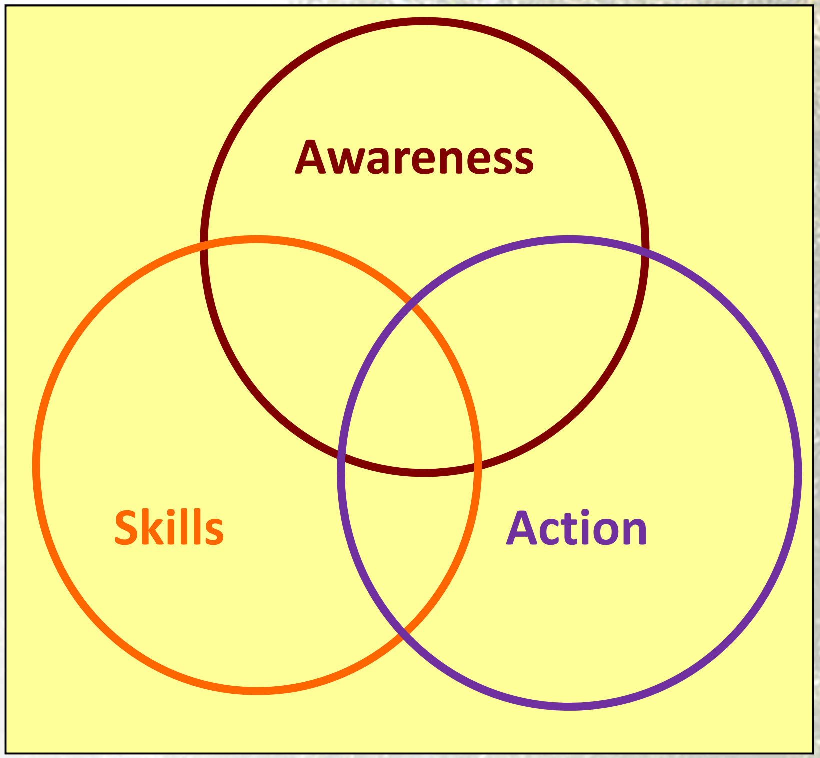
Source: Andy Lau – Penn State March 2007

Everything is connected

Design circular materials loops

Solar energy powers life

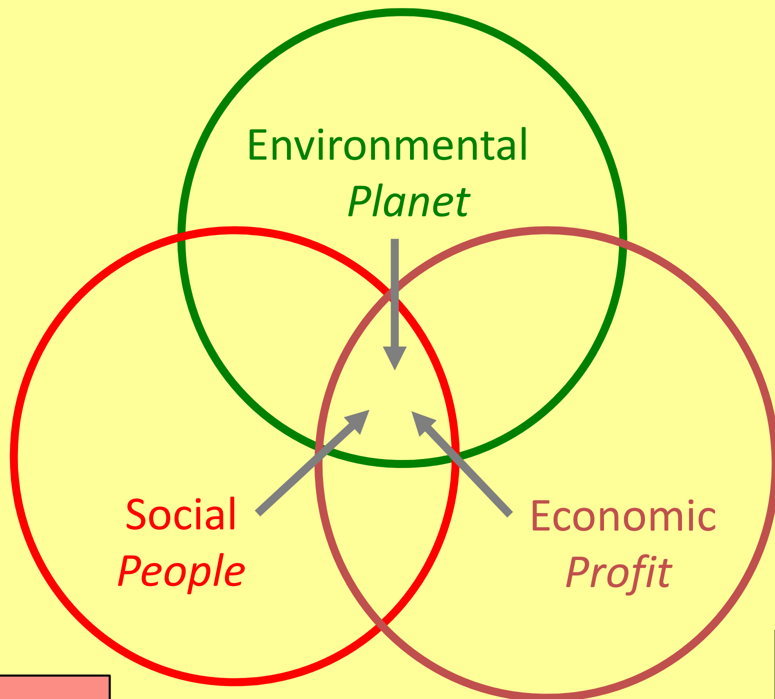
Implementing Sustainability Is Multi-Faceted



- All of these are needed to move toward sustainable solutions. Green Engineering teaches awareness and skills, but Action is required to get benefits.

Sustainability, The Triple Bottom Line, and LCA

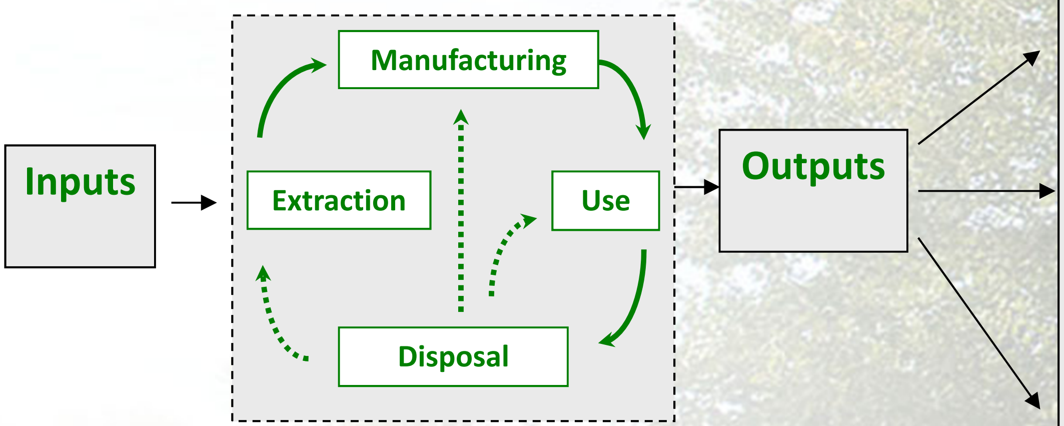
Environmental Impact Statement (EIS)
Risk Assessment
Life Cycle Assessment

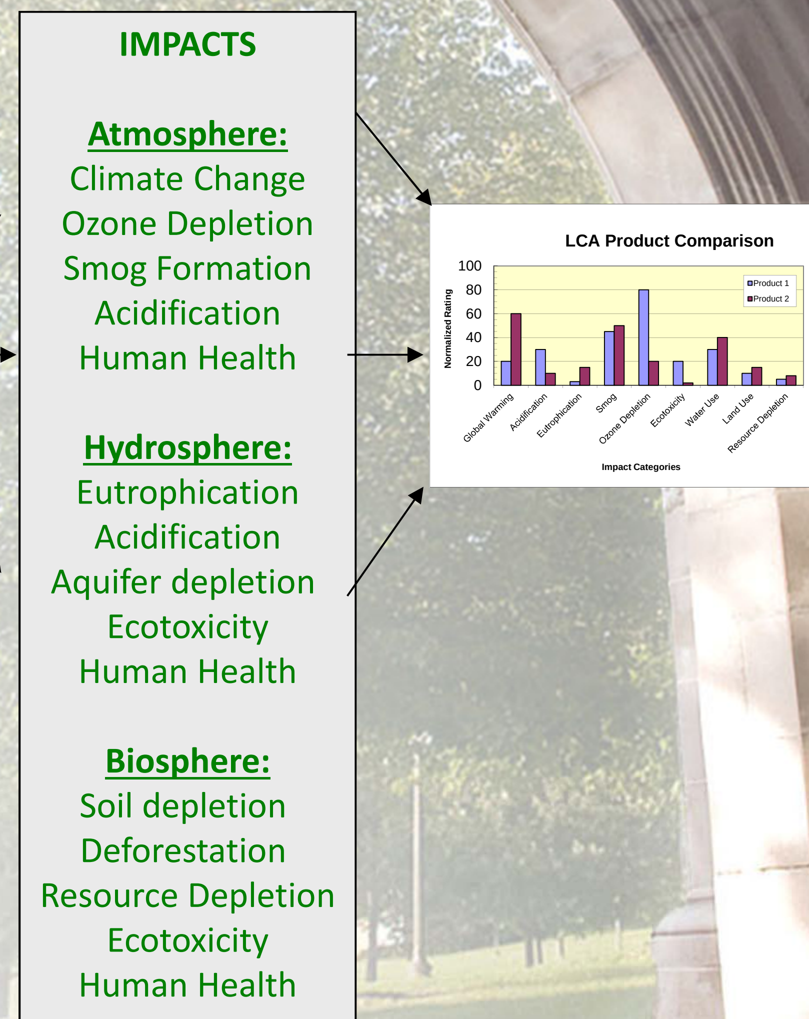


Quality of Life Index
Happiness Index
Human Development Index

Net Present Value (NPV)
Return on Investment (ROI)
Cost – Benefit Analysis
Life Cycle Accounting

Life Cycle Assessment (LCA) Is A Quantitative Decision-Making Tool





- LCA quantifies environmental impacts across all the entire life cycle on the product/process
- Impacts must be weighted for decisions (subjective)

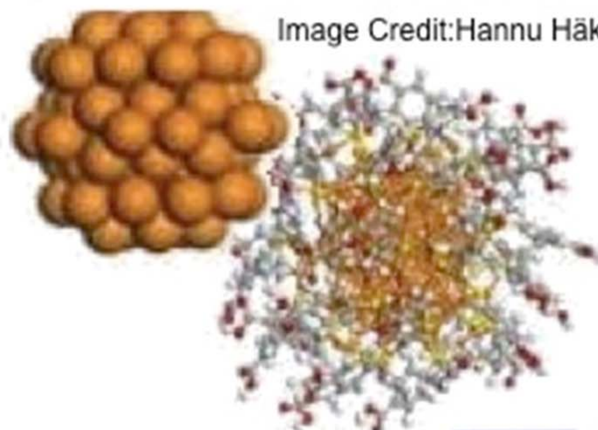
LCA Limitations

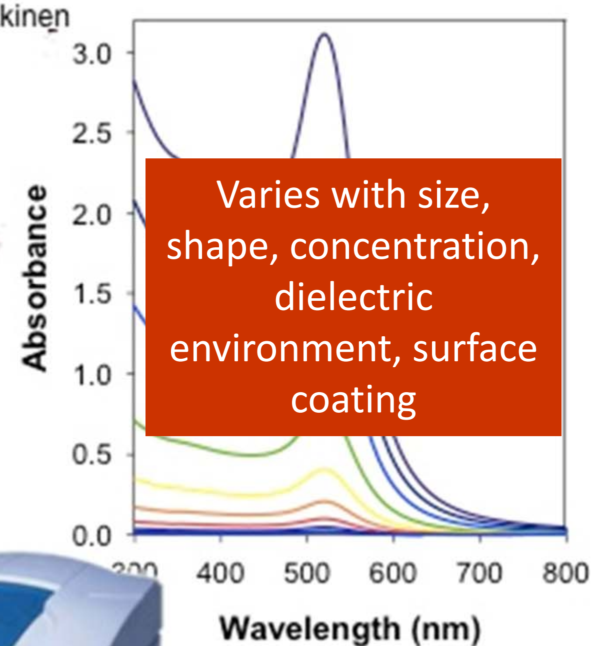
- LCA analysis typically occurs at one point in time
- All analyses are incomplete to some degree
  - *System boundary choices create critical differences*
- Environmental impacts are extrapolated into the future
  - *Exposures often have different time scales for different mechanisms (air, water, health)*
- Characterization factors are unknown for many chemicals and there is not consensus for some of the impact categories
- Spatial issues
  - *Impacts can be local, regional, or global*
- Data quality varies and may have been collected over various time scales
- Weighting is subjective and therefore often controversial

VT LCA Example Applications

Gold Nanoparticles

- **Applications**
  - Pharmaceuticals
  - Biosensors
  - Catalysis
- **Advantages**
  - Ease of synthesis
  - Size control
  - Characterization
  - Surface functionalization
  - Plasmonics



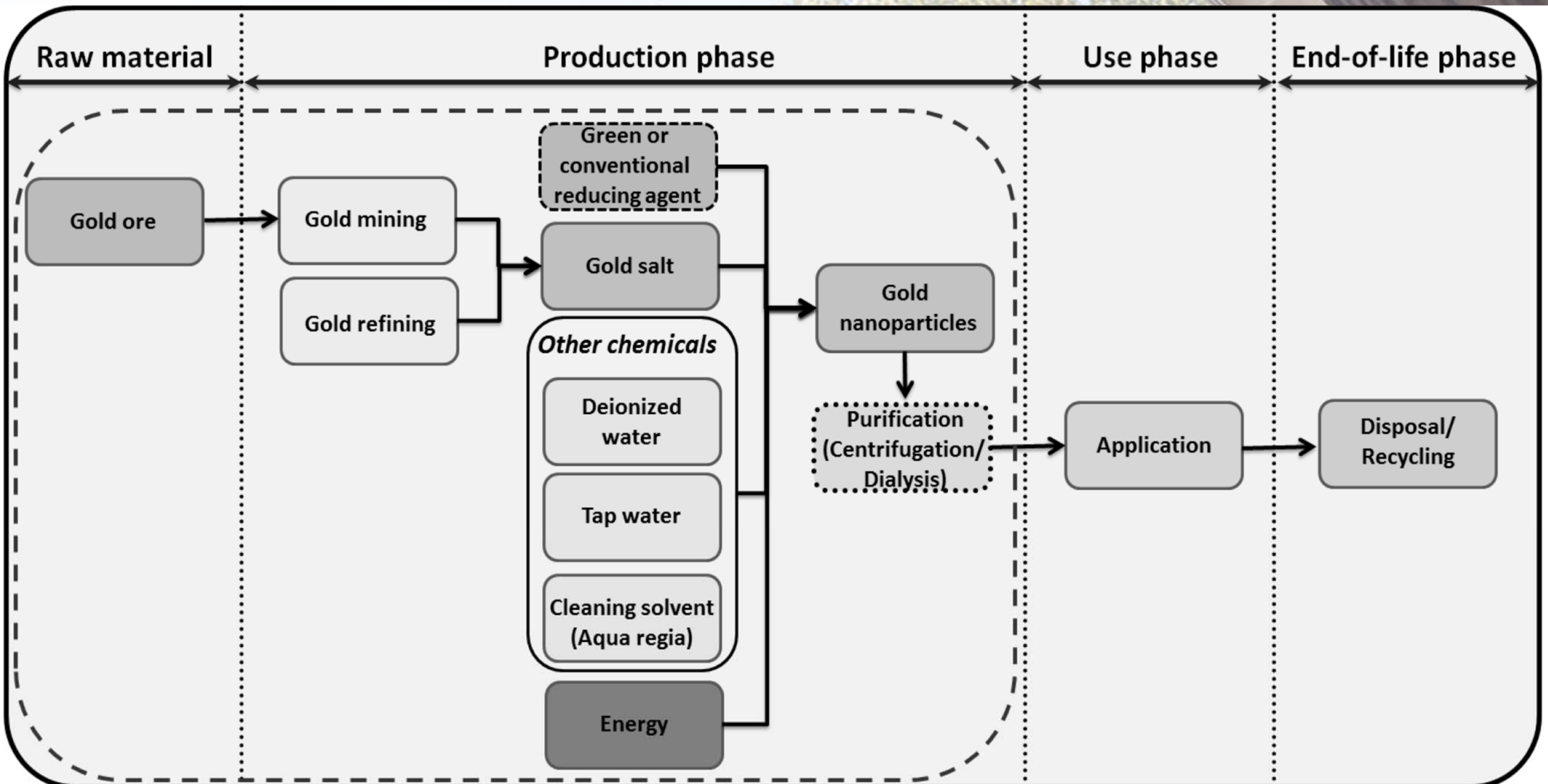


Varies with size, shape, concentration, dielectric environment, surface coating

Novel optical behavior from interaction of electromagnetic energy with surface e^- of small metallic spheres; induced dipole oscillates in phase with electric field of incoming light—

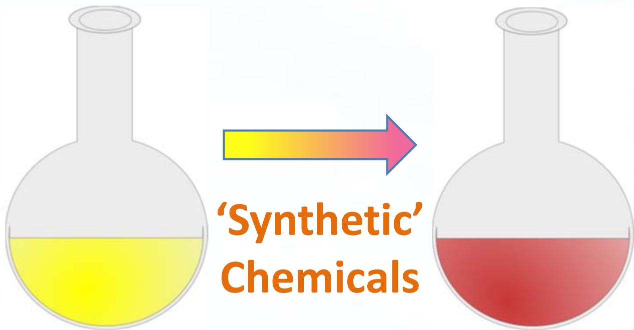
unique nanoscale phenomenon

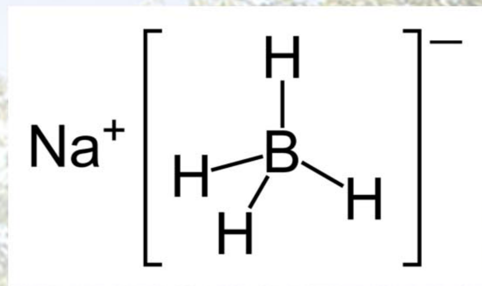
Gold nanoparticles

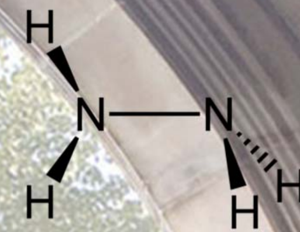


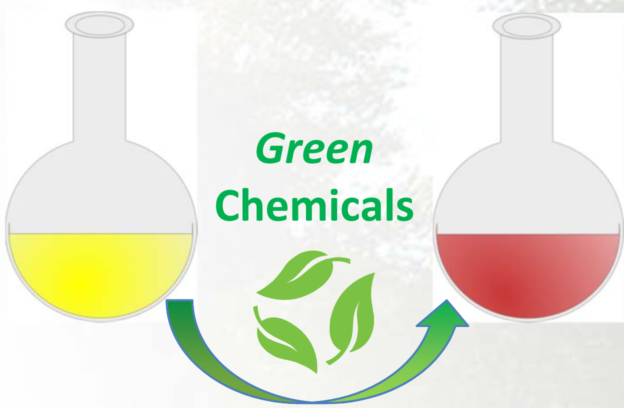
- VT initial research for the LCA of gold nanoparticles is cradle-to-gate meaning this would be the starting point for specific applications.

Green Synthesis?




sodium borohydride


hydrazine



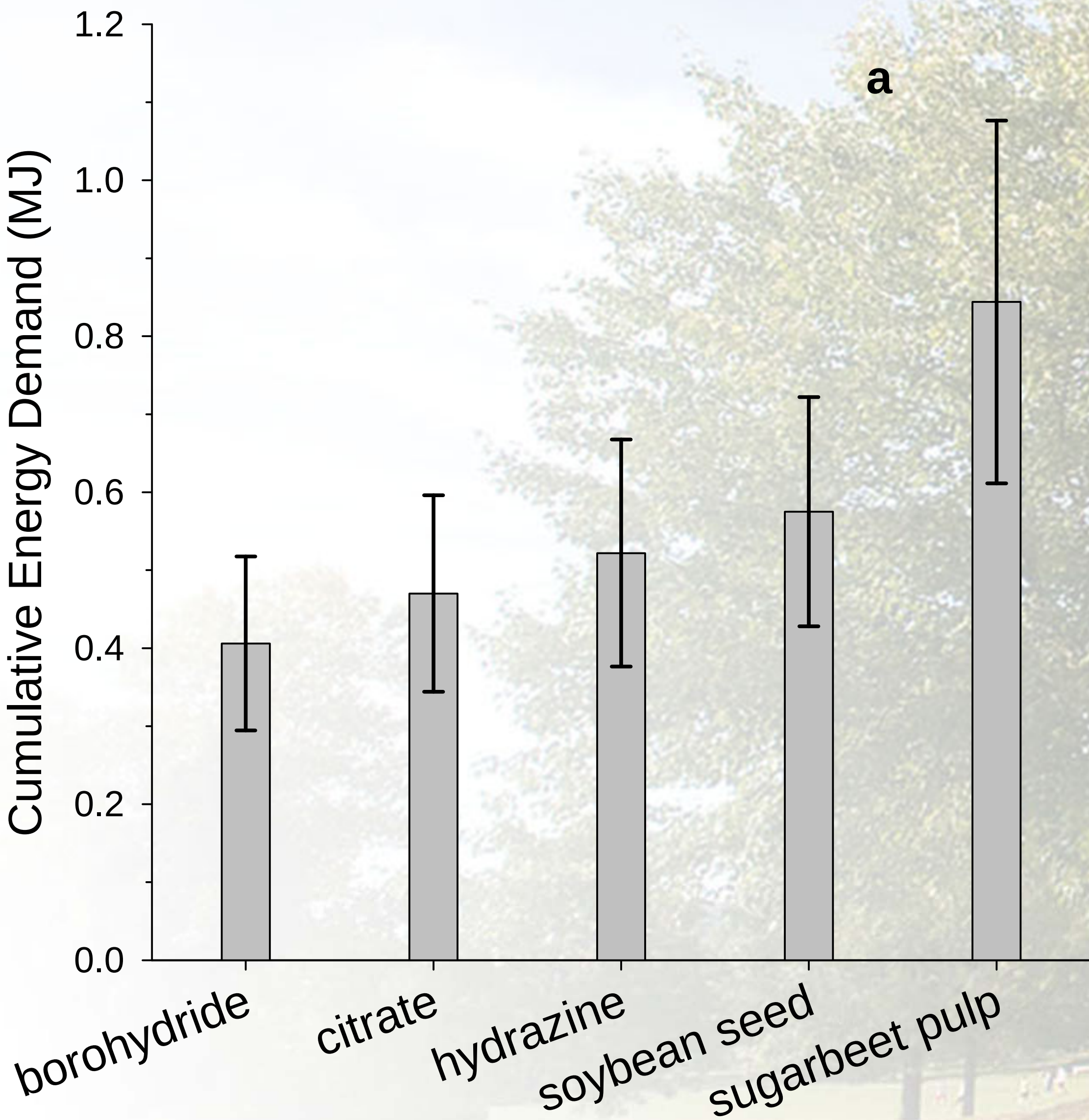

grape pomace


cypress leaves


coriander leaves

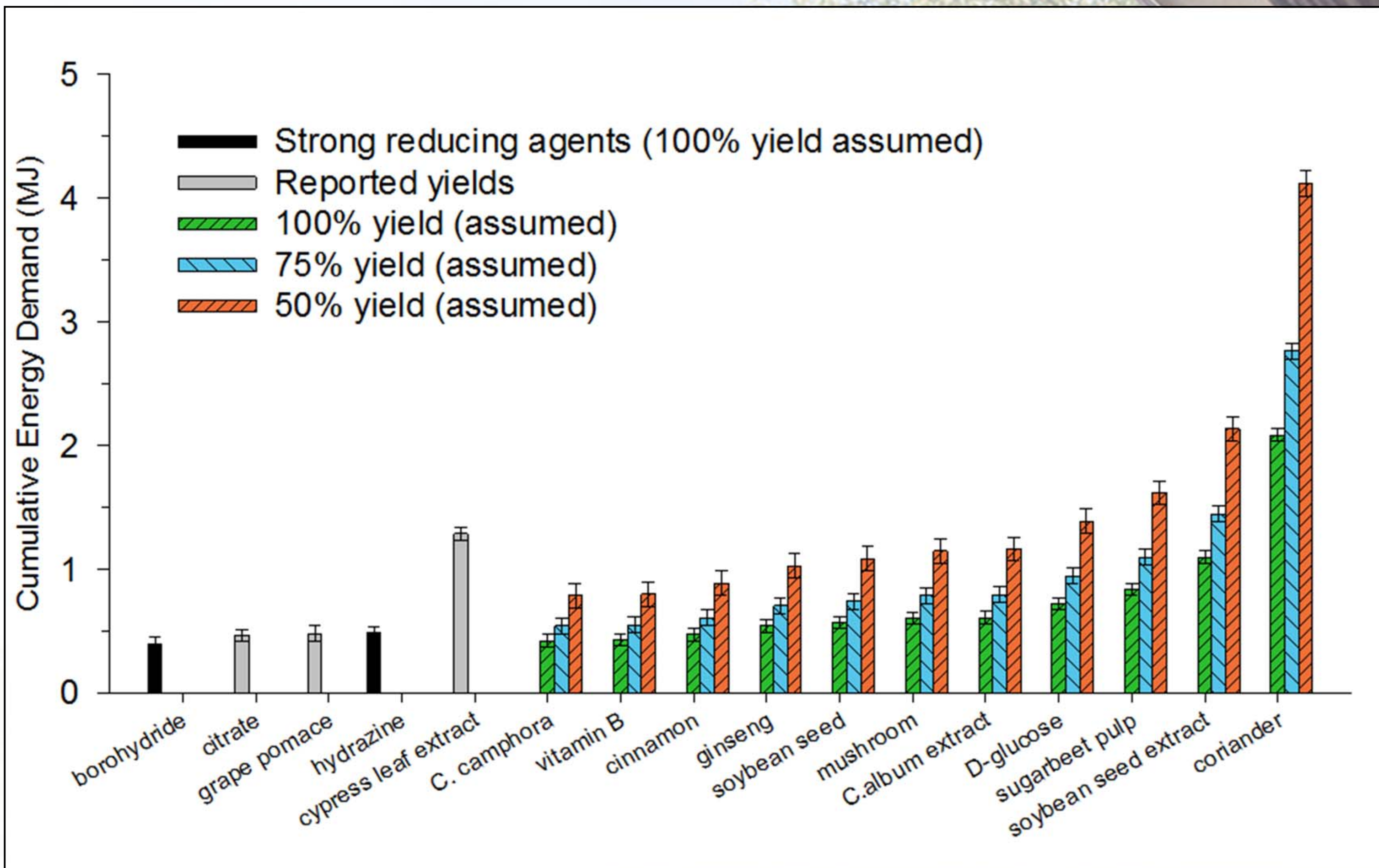

soybeans

Nanogold Reducing Agents (CED)



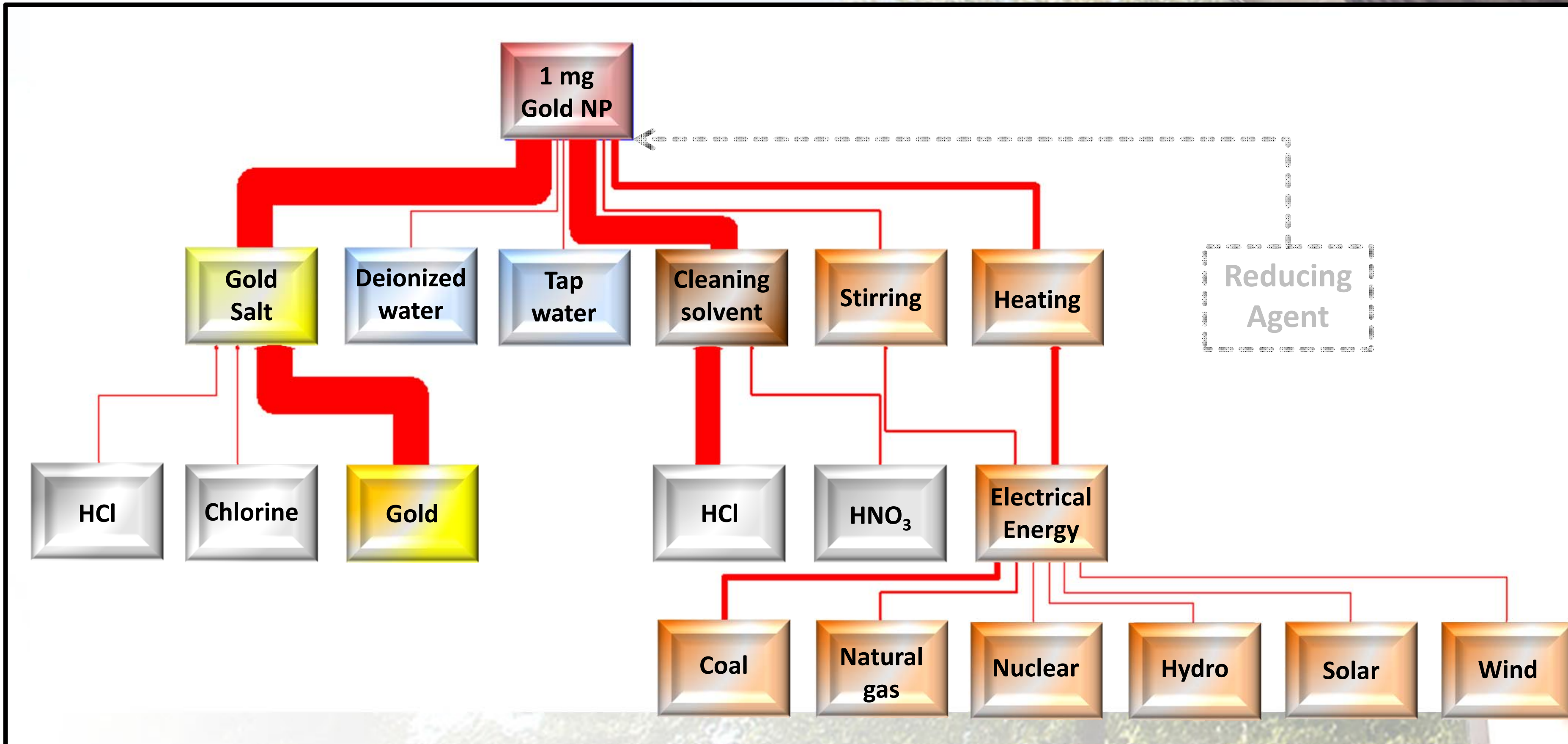
- Reducing agents derived from natural plants can have higher overall cumulative energy demand (CED) compared to more industrial chemicals.

Nanogold Process/Yield Effects (CED)



- Yields for chemical reactions are required for accurate LCA inputs/outputs and especially important for rare materials (gold). In this case, yield had to be assumed lacking information from the articles in the literature

Upstream Extraction & Manufacturing



- All of the reducing agents had very low environmental impact compared to the extraction and manufacturing of the gold precursor which dominated. The cleaning solvents also had much higher impacts than expected and should be optimized.

Nanogold Source Gold Effects (CED)

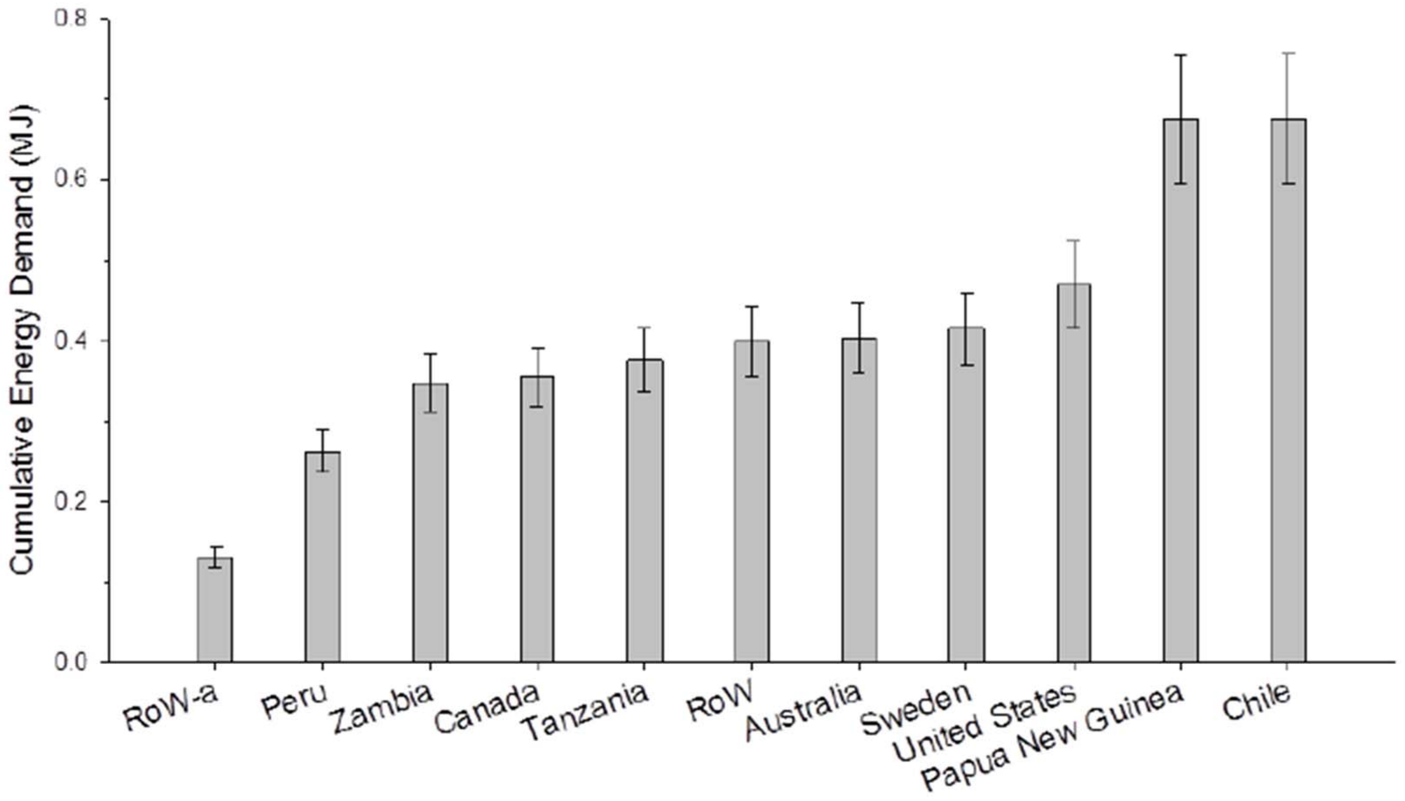
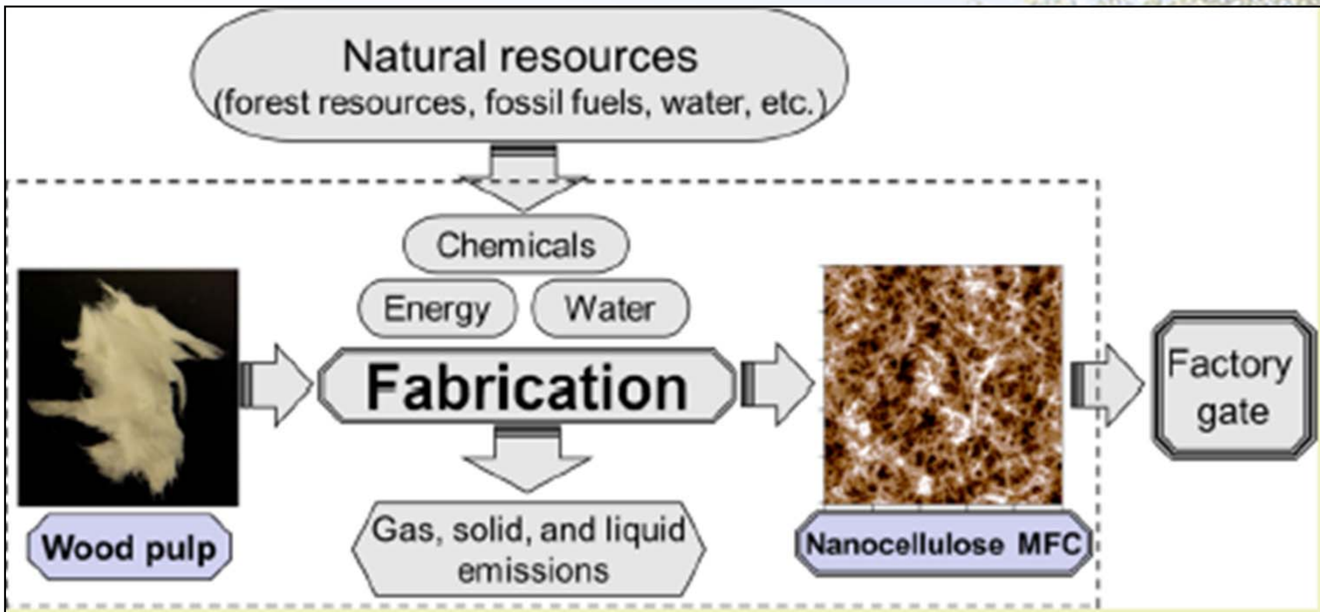


Figure S1 The effect of different gold sources on the cumulative energy demand for citrate-reduced AuNPs. (RoW: Rest of the world. RoW-a: Rest of the world (precious metals from electronic scrap.)

- The results are also quite sensitive to the source of the gold. This may seem out of control for the researcher, but suppliers should be questioned to raise awareness.

Nanocellulose LCA

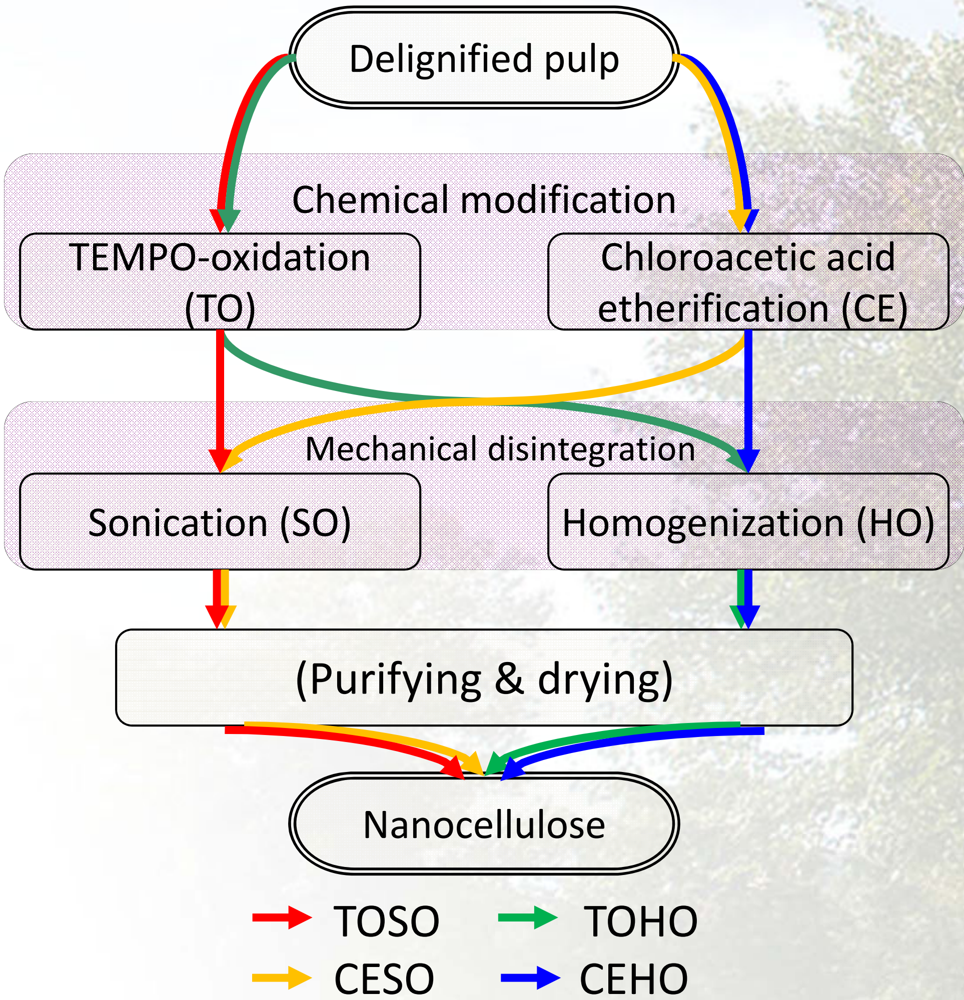


Li, Q., McGinnis, S., Sydnor, C., Wong, A., & Renneckar, S. (2013). Nanocellulose life cycle assessment. *ACS Sustainable Chemistry & Engineering*, *1*(8), 919-928.

- The manufacturing process for nanocellulose fibers was also studied using LCA to understand impacts of the bench-scale process options.

Build life cycle inventory
Assess 4 fabrication routes
Identify heavy environmental burden steps
Evaluate relative impact of nanocellulose

Nanocellulose LCA Process Diagram



- 4 different processing routes were analyzed consisting of combinations of chemical and mechanical treatment.

TEMPO = (2,2,6,6-Tetramethylpiperidin-1-yl)oxy

Nanocellulose LCA Impact Assessment

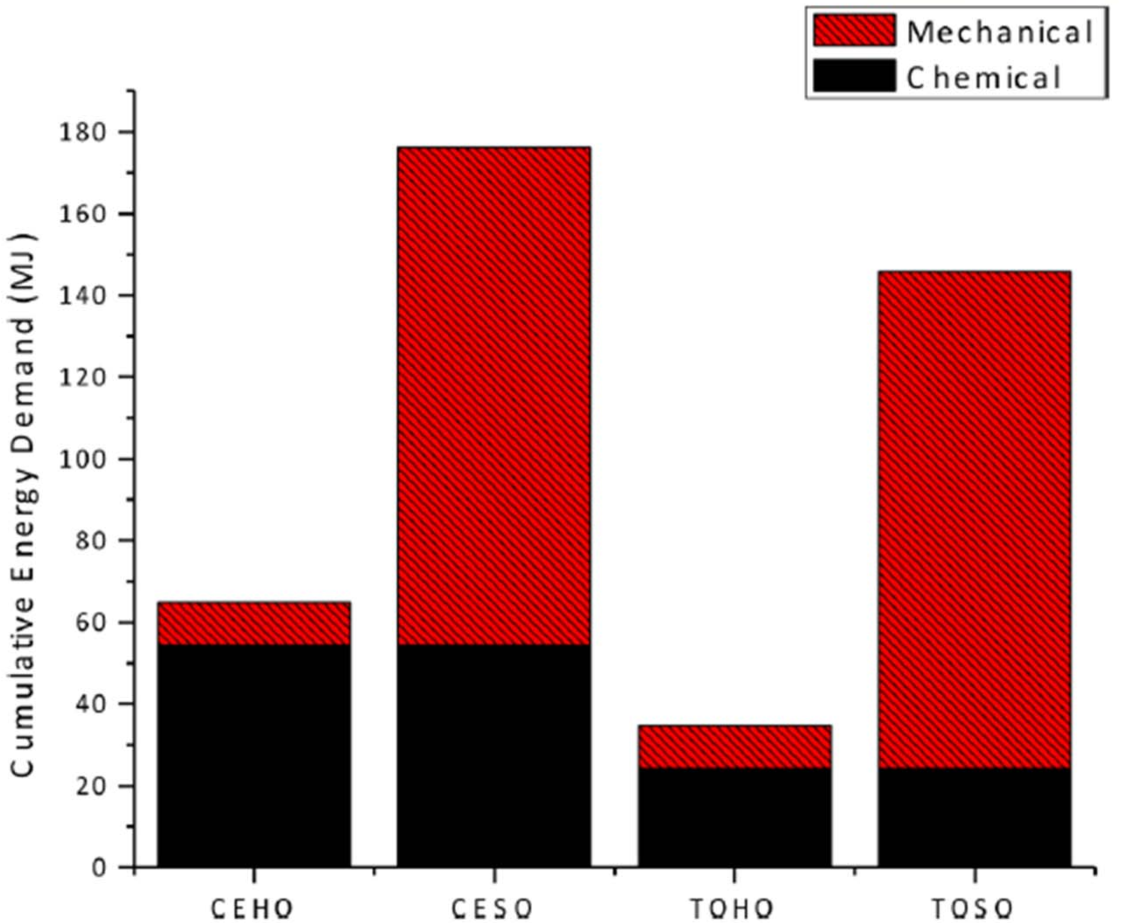


Figure 4. CED values for nanocellulose production routes separated into mechanical and chemical processes.

- Results help to see differences between mechanical and chemical processes.
- Even though done at the lab scale, this data is useful when considering options for scale-up.

Nanocellulose LCA Impact Assessment

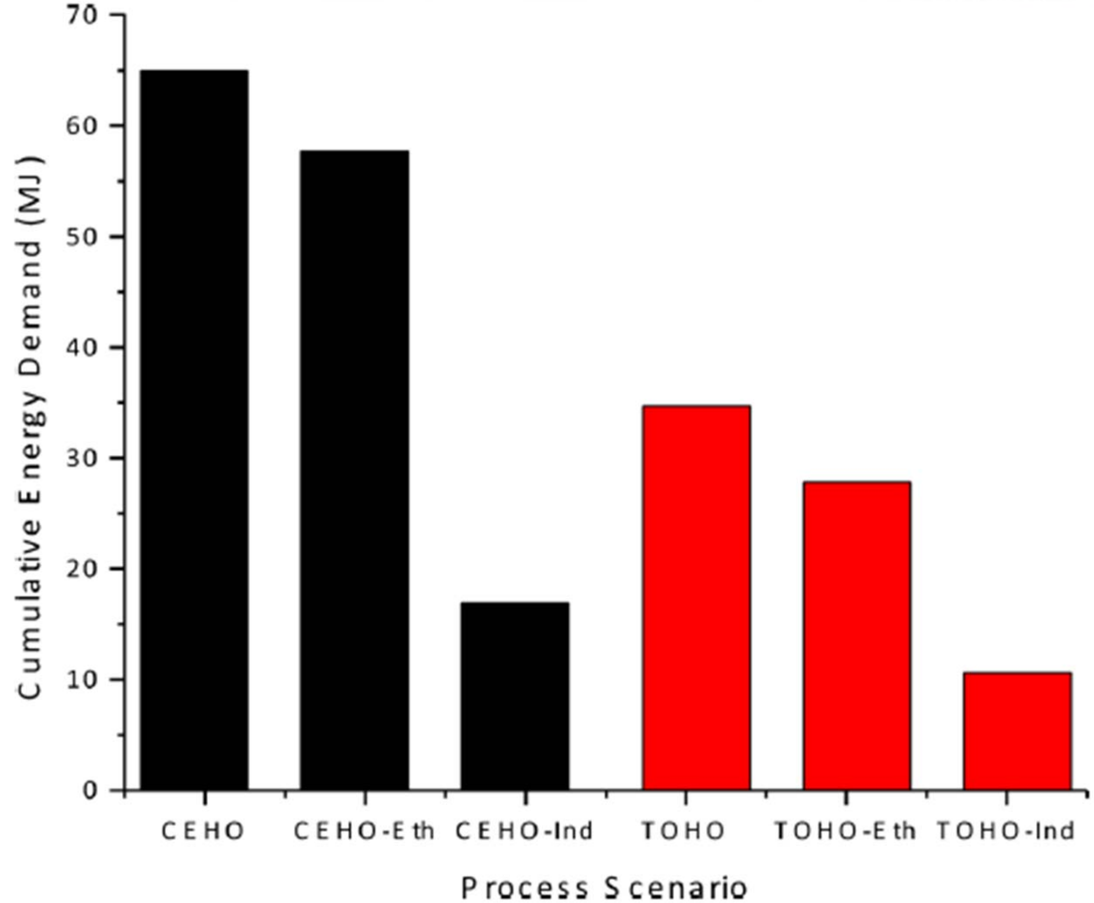


Figure 6. CED for nanocellulose baseline, ethylene-based ethanol, and estimated industrial scenarios.

- The solvent ethanol is used in both processes and has a impact.
- The baseline is corn-based ethanol which is more energy-intensive.
- Ethanol from ethylene and estimated for more efficient large-scale industrial processing are lower.

Nanocellulose Ethanol Solvent Impacts

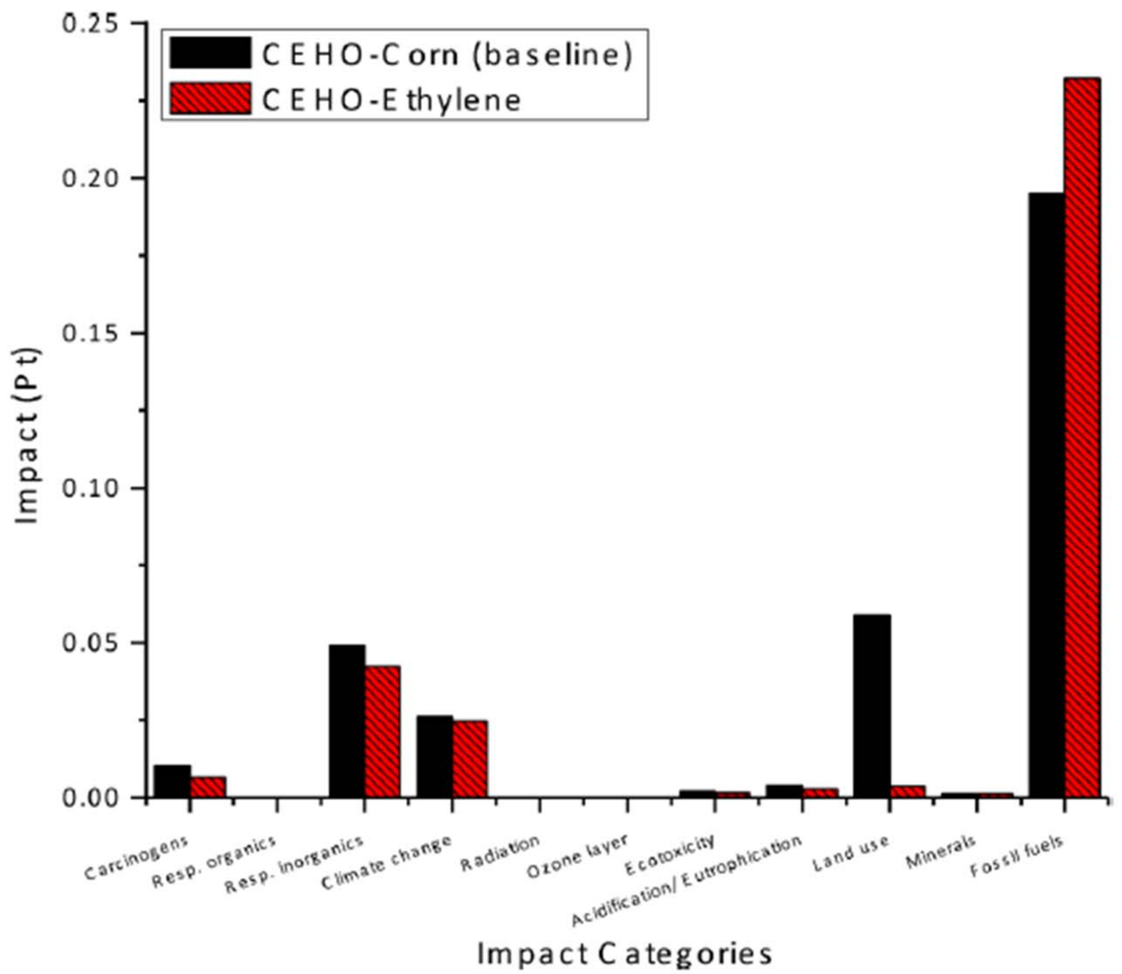


Figure 7. Baseline EI99 graph for baseline CEHO method with corn-based and ethanol-based ethanol scenario.

- Corn shows more land impacts but characterization factors for land are controversial and more difficult to measure.

Discussion – what are LCA issues and important research areas for biofuels?

Environmental Science & Technology

FEATURE

pubs.acs.org/est

Grand Challenges for Life-Cycle Assessment of Biofuels

T. E. McKone,[*,†,‡,§] W. W. Nazaroff,[†,§] P. Berck,[†,§] M. Auffhammer,[†,§] T. Lipman,[†,§] M. S. Torn,[†,‡,§] E. Masanet,[†,§] A. Lobscheid,[‡,§] N. Santero,[†,§] U. Mishra,[†,§] A. Barrett,[†,§] M. Bomberg,[†,§] K. Fingerman,[†,§] C. Scown,[†,§] B. Strogen,[†,§] and A. Horvath[†,§]

[†]University of California, Berkeley, California, United States

[‡]Lawrence Berkeley National Laboratory, Berkeley, California, United States

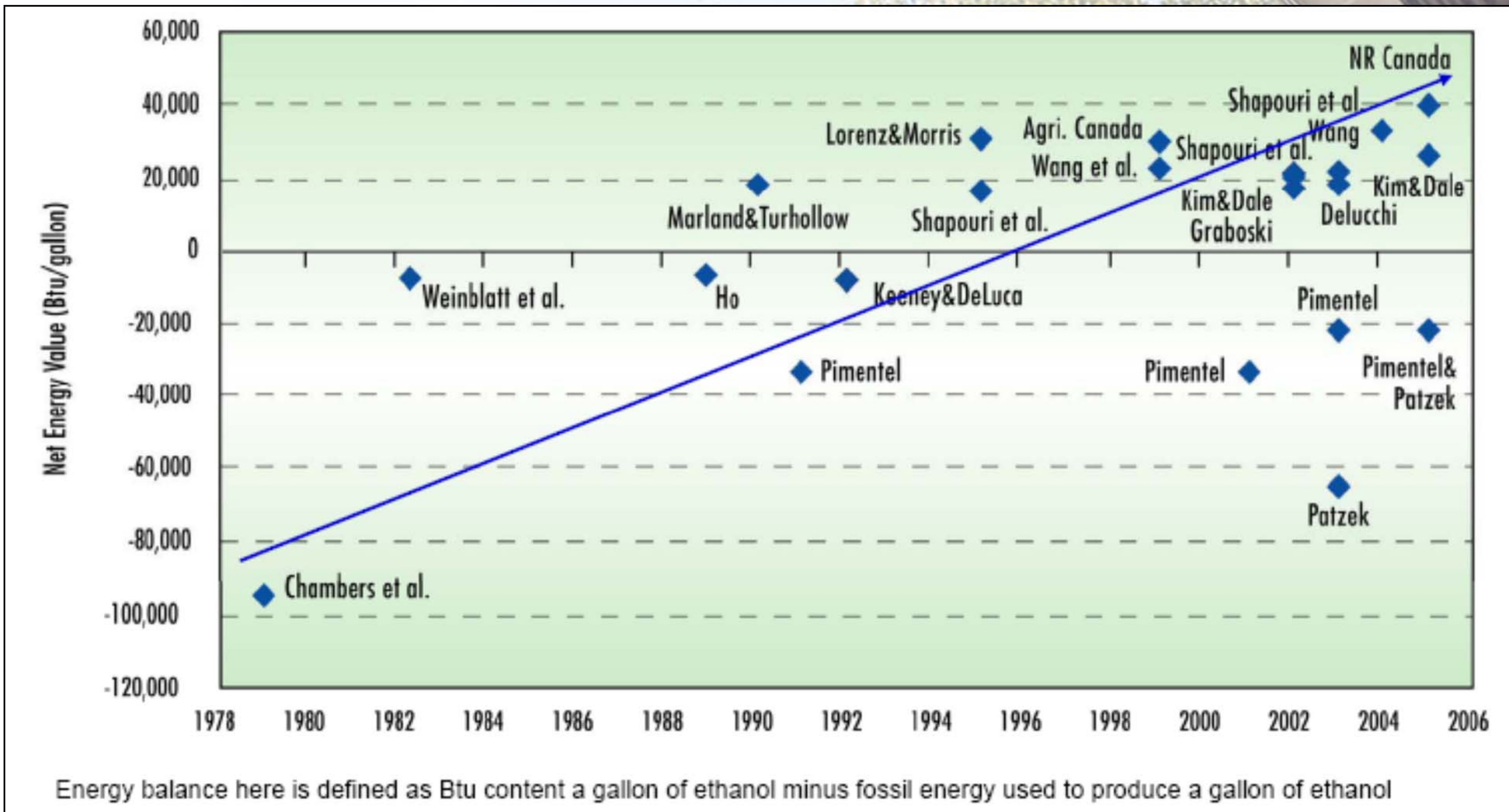
[§]Energy Biosciences Institute, Berkeley, California, United States

Grand Challenges for Applying Life-Cycle Assessment to Biofuels

- These grand challenges are discussed well and apply more broadly to many LCA applications other than biofuels.

  1. *Understanding farmers, feedstock options, and land use*
  2. *Predicting biofuel production technologies and practices*
  3. *Characterizing tailpipe emissions and their health consequences*
  4. *Incorporating spatial heterogeneity in inventories and assessments*
  5. *Accounting for time in impact assessments*
  6. *Assessing transitions as well as end states*
  7. *Confronting uncertainty and variability*

Net Energy for Ethanol



M. Wang, Energy Systems Division Seminar, Argonne National Lab, August 3, 2005.

- LCA meta-comparisons are very difficult due to different scope boundaries for most studies. LCA results depend critically on boundary definitions.

LCA-based regulations need strict definitions for scope boundaries

Section 526 of the Energy Independence and Security Act of 2007 (EISA)

– "No Federal agency shall enter into a contract for procurement of an alternative or synthetic fuel, including a fuel produced from nonconventional petroleum sources, for any mobility-related use, other than for research or testing, unless the contract specifies that the lifecycle greenhouse gas emissions associated with the production and combustion of the fuel supplied under the contract must, on an ongoing basis, be less than or equal to such emissions from the equivalent conventional fuel produced from conventional petroleum sources."

- Extraction boundaries for biofuels and conventional fuels need to be very well defined for a fair comparison of life cycle GHG emissions. Moreover, should such policy LCAs be attributional or consequential?

Consequential vs. Attributional LCAs for Biofuels

Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissio

Timothy Searching
Jacinto Fabiosa,[4]

Most prior studies
gases because biof
have failed to coun
prices and convert
diverted to biofuels
land-use change, w
doubles greenhous
Biofuels from switc
result raises concer
waste products.

29 FEBRUARY 200

Land Clearing and the Biofuel Carbon Debt

Joseph Fargione,[1] Jason Hill,[2,3] David Tilman,[2]* Stephen Polasky,[2,3] Peter Hawthorne[2]

Increasing energy use, climate change, and carbon dioxide (CO_2) emissions from fossil fuels make switching to low-carbon fuels a high priority. Biofuels are a potential low-carbon energy source, but whether biofuels offer carbon savings depends on how they are produced. Converting rainforests, peatlands, savannas, or grasslands to produce food crop–based biofuels in Brazil, Southeast Asia, and the United States creates a "biofuel carbon debt" by releasing 17 to 420 times more CO_2 than the annual greenhouse gas (GHG) reductions that these biofuels would provide by displacing fossil fuels. In contrast, biofuels made from waste biomass or from biomass grown on degraded and abandoned agricultural lands planted with perennials incur little or no carbon debt and can offer immediate and sustained GHG advantages.

www.sciencemag.org SCIENCE VOL 319 29 FEBRUARY 2008

LCAs for Bio-based Materials

Table 1: Biobased LCAs. The analyses listed below either included chemicals that typically contribute to the following categories or included a separate impact assessment for the following impact catergories: GW=global warming, FF=fossil fuel use, EH=eutrophication, HH=human health (including air quality, carcinogenicity, human toxics, and smog), H_2O=water use, EQ=ecosystem quality (including acidification and soil health), LU=land use

LCA reference	Bio-product	Environmental impacts included						
		GW	FF	EH	HH	H_2O	EQ	LU
Akiyama (2003)	Polyhydroxyalkanoate	X	X					X
Dornburg (2003)	Polymers	X	X					X
Fu (2003)	Ethanol	X	X	X	X		X	
Gerngross (2000)	Polyhydroxyalkanoate, polylactic acid	X	X					
Jungmeier (2001)	Bioenergy	X	X					X
Kadam (2002)	Ethanol	X	X	X	X		X	
Kim (2005 a)	Ethanol	X	X					
Kim (2005 b)	Polyhydroxyalkanoate	X	X	X	X		X	
Kurdikar (2000)	Polyhydroxyalkanoate	X						
Lynd (1996)	Ethanol	X	X		X*			
Lynd (2003)	Polyhydroxyalkanoate, ethanol		X					
McManus (2003)	Biolubricant	X	X	X	X		X	
Patel (1999)	Biofuels & Surfactants	X	X					
Shapouri (2002)	Ethanol		X					
Sheehan (1998)	Biodiesel	X	X		X	X	X	
Sheehan (2002)	Ethanol	X	X		X		X	
Sheehan (2003)	Ethanol	X	X		X		X	X
Slater (2002)	Polyhydroxyalkanoate, polylactic acid	X	X					
van den Broek (2001)	Bioenergy	X	X	X	X		X	
Vink (2003)	Polylactic acid	X	X			X		

*Reference: Landis, A.E. and T.L. Theis, *Response to 'Comments on Workshop Report on the Economic and Environmental Impacts of Biobased Production'.* International Journal of Life Cycle Assessment, 2005. **11**(3): p. 213-214.

- Global warming and fossil fuels impacts are studies in nearly all bio-based materials LCAs while eutrophication, water use, land use, and others are often not studied.

LCA and Biofuel Key Points from Grand Challenges Article

- *Barriers to LCA arise because many stakeholders want a final answer, to be "cleared for take off, with no call-backs". These stakeholders see LCA as a final exam; pass it and you are done being concerned with impacts and can proceed to technology deployment.*

- *At its best, LCA contributes to an ongoing process that organizes both information and the process of prioritizing information needs. We do not see these grand challenges as hurdles to be cleared, but rather as opportunities for the practitioner to focus attention and effort on making LCA more useful to decision makers.*

- *Decision makers who work in real time and often cannot wait for precise results must recognize that LCA can provide valuable insight but it is not necessarily a "truth-generating machine". Effective LCA can guide and inform decisions, but it cannot replace the wisdom, balance, and responsibility exhibited by effective decision-makers.*

Questions?

Contact Information:

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Institute for Critical Technology and Applied Science