

Presentation in mini-workshop at SusTec 2014, Jul 26th 2014

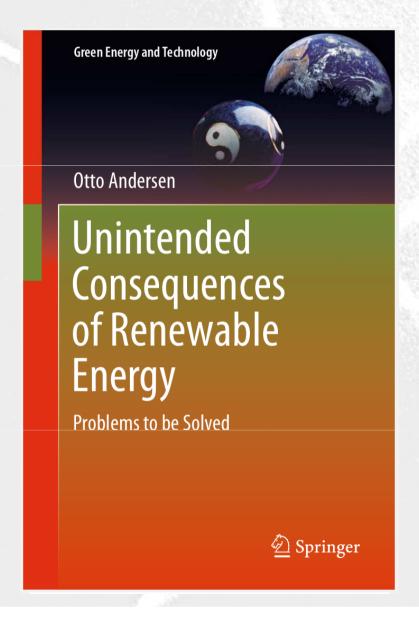
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### Overview

- Background
- Introduction: What are Unintended Consequences of Renewable Energy?
- Rebound Effects
- Consequential Life Cycle Environmental Impact Assessment
- Implementation of Hydrogen Gas as a Transport Fuel
- Biodiesel and its Blending into Fossil Diesel
- Towards the Use of Electric Cars
- Solar Cell Production
- Final Discussion and Conclusions

### Basis: The book



### Basis: The inspiration and the ideas

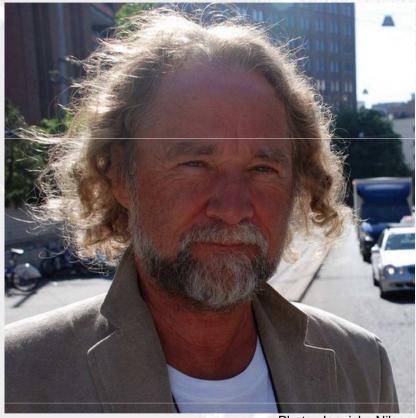


Photo: Jannicke Nilsen

Karl Georg Høyer

1946 - 2012

### Basis: The catalyst for the book



#### Renewable and Sustainable Energy Reviews

Volume 16, Issue 4, May 2012, Pages 2102-2110

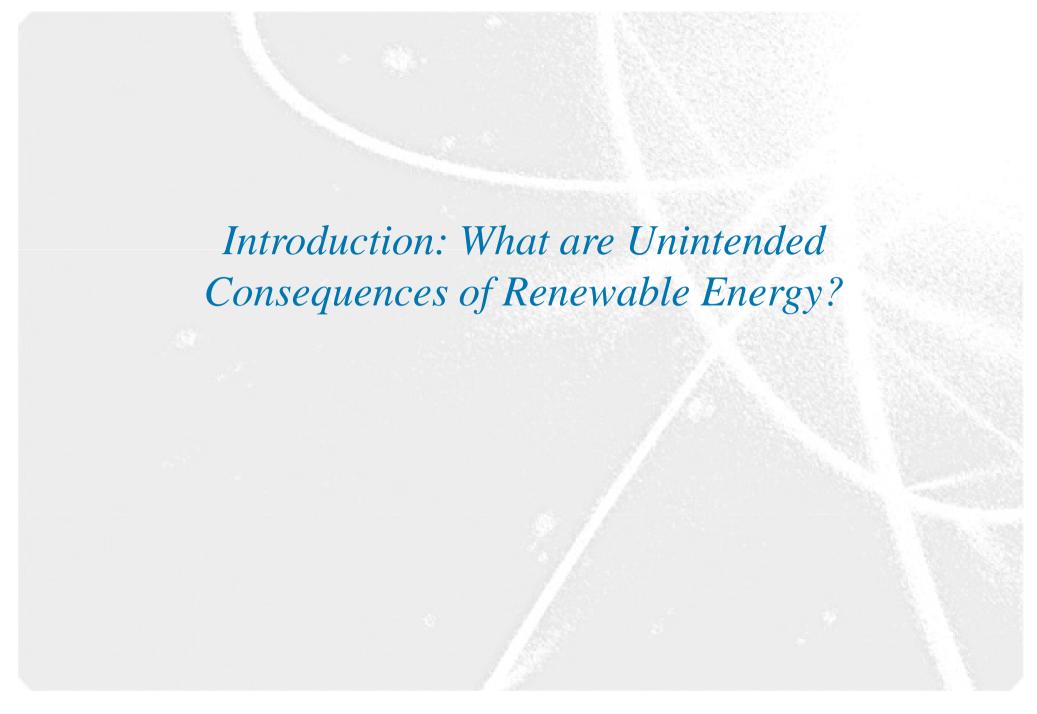


### Toxicological aspects of nanomaterials used in energy harvesting consumer electronics \*

Sergio Manzetti <sup>a, b</sup> , Otto Andersen <sup>a,</sup> ♣ , ☑ ,		
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#### **Abstract**

Sustainable energy harvesting, such as solar energy, depends increasingly on nanotechnology components. This article will look briefly at the principles of photovoltaic units and elucidate the toxicological aspects of its principal components, namely fullerenes and carbon nanotubes. Through this approach, we address the rebound effect related to health adverse and environmental aspects which is a key issue to be solved when innovating in energy harvesting. The understanding of sustainability in this context is that the technology provides lasting improvement by bringing environmental compatibility along with technological agility, providing major reductions in both material and energy resource use and avoid negative impacts on our environment and health. With the *rebound effect* we understand the unintended emergence of negative environmental impacts resulting from intentions of improving environmental issues.



#### The first use of the concept unintended consequences

People are occasionally so eager to realize the immediate benefits of an act, that they give no consideration whatsoever to its longer-term consequences.

In a similar way, consequences can be overlooked when a person's fundamental values requires her/him to pursue change.

The resulting **unintended consequences** of the actions may change these original values over time.

Merton RK (1936): The Unintended Consequences of Purposive Action. American Sociological Review.

#### Unintended consequences in relation to green technologies

Distinct unanticipated consequences that can partially or fully offset intended environmental benefits.

Zehner O (2011): Unintended Consequences of Green Technologies. In: Robbins et al. Green Technology. Sage.

## Unintended consequences as inherent risks of modern technology?

- Benefits of a technology must also be considered through an examination of the
   negative impacts of that technology
- Within this *reflexive modernization*, it is questioned whether certain applications of technology ought to have been developed, given the uncertainty of their safety

Beck U (1992): Risk Society: Towards a New Modernity. Sage.

## Murphy's law as a reminder of the need for technological improvements to avoid unintended consequences

- "If there is more than one way to do a job and one of those ways will end up in disaster, then somebody will do it that way" or "If anything can go wrong, it will"
- Murphy worked at Edwards Air Force Base when the old record of 31 times the force of gravity was exceeded, but nobody could tell by how much, due to failing gauges
- Murphy found out that a technician had installed them backward
- A direct implication for engineering was the redesigning of sensors so they could only be attached one way—the correct way.

Tenner E (1997): Why Things Bite Back: Technology and the Revenge of Unintended Consequences. Vintage.

### Unintended consequences occur in the context of interactions between energy and climate policies

- Highlighting of the *overlapping drivers and rationales* for the deployment of renewable energy, as well as *overlapping laws and regulations* (local, national, international)
- The overlaps can lead to substantial *interplay among policies*, and in turn lead to unintended consequences
- Crucial with an understanding of the *interplay among policies* and the *cumulative* effects of multiple policies
- Call for a multi- and interdisciplinary approach in the study of unintended consequences, in order to address the complex and diverse issues around decarbonization

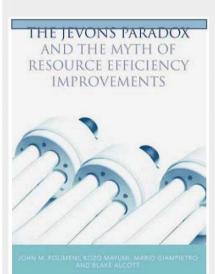
Intergovernmental Panel on Climate Change (2012): Renewable energy sources and climate change mitigation. Special Report. Cambridge University Press.



### What are rebound effects? (1)

- Behavioral or systemic response to the implementation of a new technology
- Can also be applied to other measures to reduce energy use and emissions in relation to climate change
- In principle, it can be used in reference to any natural resource or environmental problem
  - In energy economics: *Jevons paradox*:

The introduction of a new efficient steam engine **initially decreased coal consumption**, which led to a drop in the price of coal. This meant that more people could afford coal, making coal economically viable for new uses, which led to an **increase in coal consumption** (Jevons 1865)



Jevons W (1865): The coal question. Macmillan & Co, London.

### What are rebound effects? (2)

- Can be traced back to the late 1960s—early 1970s discourse on *environmental and ecological system dynamics* (Commoner 1972; Ehrich & Holdren 1971; Meadows et al. 1972; Odum 1969: Odum 1971)
  - Feedback mechanisms (positive and negative)
  - Results of manipulations with, or isolation of parts of the system, and can lead to chains of effects emerging in other parts of the system.
  - Thus, rebound effects can be understood as unpredictable backfires against anthropogenic encroachments in nature

Commoner B (1972) The environmental cost of economic growth. In: Population, resources, and the environment. Government Printing Office, Washington, DC, p 339–363

Ehrlich PR, Holdren JP (1971) Impact of population growth. Science 171(3977):1212-1217

Meadows D, Meadows D, Randers J, Behrens III W (1972) The Limits to Growth. Universe Books, New York

Odum E (1969) The strategy of ecosystem development. Science 164:262–270

Odum H (1971) Environment, Power, and Society. Wiley-Interscience, New York

### What are rebound effects? (3)

- The use of the concept rebound effects:
  - Most commonly within mainstream economics theory and analysis
  - Other, significant contributions from de-growth economists (Schneider 2008)
    - Rebound effects are diverse
    - Interdisciplinary approach is required for full understanding, including:
      - Fundamental research on social and technological structures and relations
- Improving the understanding of the concept through inclusion of other perspectives such as **industrial ecology**, in addition to economist and engineering views (Hertwich 2005; Madlener & Alcott 2009)

Schneider F (2008) Macroscopic rebound effect as argument for economic degrowth. Paper presented at the First international conference on Economic De-growth for Ecological Sustainability and Social Equity, Paris, April 18–19th 2008. Paris.

Hertwich EG (2005) Consumption and the rebound effect: an industrial ecology perspective. J Ind Ecol 9(1–2):85–98

Madlener R, Alcott B (2009) Energy rebound and economic growth:a review of the main issues and research needs. Energy 34:370–37

# Rebound effects in connection with energy efficiency measures

- The **magnitude** of the rebound effect is hihly disputed (Herring 2006)
  - If small (i.e., the increase of fuel consuming activities is < than 100 % of the improvement in efficiency) then energy efficiency improvements will lead to lower energy consumption
  - If large (i.e., the increase of fuel consuming activities is > than 100 % of the improvement in efficiency) then energy consumption will be higher.
- A key problem in resolving the **two positions** is that it **is not possible to run** '**control' experiments** to see whether energy use is higher or lower than if there had been no efficiency improvements.
- Even so, there is mounting evidence that at the national level it is not uncommon for total resource consumption to grow even while efficiency improves, suggesting that improvements in efficiency are not sufficient for curtailing energy consumption

Herring H (2006) Jevons paradox. Encyclopedia of Earth. Washington, D.C: Environmental Information Coalition, National Council for Science and the Environment.

# Rebound effects in connection with measures to reduce the emission of climate gases (1)

- When energy consumers believe their energy is derived from renewable sources, they may be less concerned about conserving it
  - In hybrid cars, where electricity replaces part of the fossil fuel consumption, the cars can contribute to the reduction in climate gas emissions, depending on how the electricity is produced.
  - If these cars are used more due to this, there is a potential rebound effect
  - In an empirical survey in Japan showed that a year after purchasing what they considered to be an 'environmentally friendly' car (e.g., a hybrid car), drivers who bought such cars were driving 1.6 times as far as they had done with their previous vehicle (Ohta & Fujii 2011)

Ohta H, Fujii S (2011) Does purchasing an 'Eco-car' promote increase in car-driving distance? Tokyo Institute of Technology, Tokyo

# Rebound effects in connection with measures to reduce the emission of climate gases (2)

- The biofuels policy of blending biodiesel with fossil diesel has a potential 'rebound" with the emergence of new type of toxic exhaust emissions (Andersen 2013)
- Several LCAs have revealed that the production phase of biofuels emits large amounts of climate gases (Reinhard & Zah 2009; Schmidt 2010)
  - The rebound effect is that the policy of biofuel implementation actually is working counter to the intended effect of the policy.

Andersen O (2013) Biodiesel and its Blending into Fossil Diesel. In: Unintended Consequences of Renewable Energy. Problems to be Solved. Springer London, London, pp 55–70 Schmidt J (2010) Comparative life cycle assessment of rapeseed oil and palm oil. Int J Life Cycle Assess 15(2):183–197

# Rebound effects in connection with measures to reduce other environmental pollutants

- Catalytic converters reduce vehicle emissions of NOx, NMVOC, and others
  - However, the catalytic converters are made from scarce metals, such as platinum and palladium
  - These metals are only found in very small concentrations in the Earth's crust.
     Ores of platinum in as low a concentration as 7 parts per million (ppm) are currently being mined
  - About 20 million tons of mineral ore are refined to produce 140 tons purified platinum metal (Frosch & Gallopoulos 1989).
  - Massive mining operations are necessary to excavate the metals resulting in the movement of massive volumes of earth, and leaves behind polluted tailings and ground water.

Frosch R, Gallopoulos N (1989) Strategies for manufacturing. Sci Am:94–102



### Direct rebound effects

- Direct or "comfort" rebound effect occurs when improvements in energy-efficiency encourages greater use of the products and services
  - E.g. When consumers purchases a new car, which is more fuel-efficient than the old, they might drive more because it becomes cheaper for them to drive (Owen 2010)
- Direct rebound effects are sufficiently large to cause a "backfire"— that is they lead to overall increase in energy consumption
- First noted in the 19th century in relation to the steam engine, where raised productivity and energy efficiency, but increased society's total energy demand (Sorrell 2010)
- First brought to the attention of energy economists through the **Khazzoom-Brookes** postulate:

With fixed real energy price, energy efficiency gains will increase energy consumption above where it would be without the gains (Khazzoom 1980)

Owen D (2010) The efficiency dilemma. If our machines use less energy, will we just use them more? (December 20). The New Yorker

Sorrell S (2010) Energy, economic growth and environmental sustainability: five propositions. Sustainability 2:1784–1809

Khazzoom J (1980) Economic implications of mandated efficiency in standards for household appliances. Energy J 1(4):21–40

### Indirect rebound effects

- Money saved on reduced fuel consumption are being spent on other energy-intensive goods and services, such as:
  - airconditioners
  - a second (or third) car in a household
- When energy-efficiency technologies (e.g., thermal insulation) needs considerable energy in the production phase of their life cycle
  - E.g. in some processes for production of thermal insulation there is substantial emission of the compound 1,1,1,3,3-pentafluorobutane (HFC-365mcf) with the chemical formula CF<sub>3</sub>CH<sub>2</sub>CF<sub>2</sub>CH<sub>3</sub> (Mersiowsky & Krähling 2002). This compound is a very strong greenhouse gas, actually 890 times stronger than CO<sub>2</sub>

Mersiowsky I, Krähling H (2002) Life cycle assessment of high-performance thermal insulation systems for domestic buildings. Paper presented at the InLCA-LCM 2002. American Center for Life Cycle Assessment

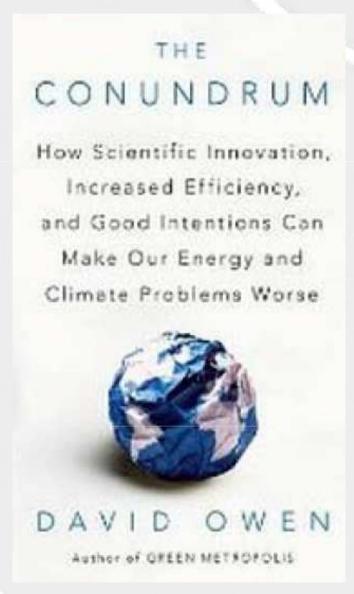
### Society-wide rebound effects

- The sum of the **direct** and **indirect** rebound effects from energy efficiency improvements is often called the **society-wide**, **economy-wide**, or **overall** rebound effect
- It is commonly expressed as a percentage of the expected saved from a specific measure to improve energy efficiency
- Economic models estimate that the overall rebound effect is highly variable, and ranges from 5 % to 60 % (Gillingham et al. 2013; Nässén & Holmberg 2009)
- Estimated to be about 50% for the years 2010-2030 (Barker et al. 2009)

Gillingham K, Kotchen M, Rapson D, Wagner G (2013) The rebound effect is overplayed. Nature 493:475–476 Nässén J, Holmberg J (2009) Quantifying the rebound effects of energy efficiency improvements and energy conserving behaviour in Sweden. Energy Efficiency 2:221–231

Barker T, Dagoumas A, Rubin J (2009) The macroeconomic rebound effect and the world economy. Energy Efficiency 2:411–427

### Critique of the concept rebound effect



- 1. It is only at the micro end of the economics spectrum that the number of mathematical variables can be kept manageable. But looking for rebound only in individual consumer goods, or in closely cropped economic snapshots, is as futile and misleading as trying to analyze the global climate with a single thermometer
- 2. Miles per gallon is the wrong way to assess environmental impact of cars. Far more relevant is to consider the productivity of driving
- 3. Promoting energy efficiency without doing anything to constrain overall energy consumption will not cause overall energy consumption to fall

### Rebound effects and renewable energy

- General for all renewable energy technologies that displace fossil fuel technologies
  - The case of bioenergy:
    - If increased production of solid, liquid, and gaseous biofuels leads to lower demand for fossil fuels, this in turn could lead to lower fossil fuel prices and increased fossil fuel consumption (Rajagopal et al. 2011; Stoft 2010; Zehner 2011)
- Moving down the ladder of specific energy content
  - The transition from fossil sources of energy to renewable sources often implies using an energy form with less specific energy content.
  - The energy rich carbon atoms are densely packed in fossil fuels, but a renewable source such as biodiesel is more loosely packed, with significant amounts of oxygen (approx 10 % in biodiesel) present. Fossil fuels thus contain more carbon than biofuels do.

Rajagopal D, Hochman G, Zilberman D (2011) Indirect fuel use change (IFUC) and the life cycle environmental impact of biofuel policies. Energy Policy 39:228–233

Stoft S (2010) Renewable fuel and the global rebound effect. Global Energy Policy Center Research paper No. 10–06.

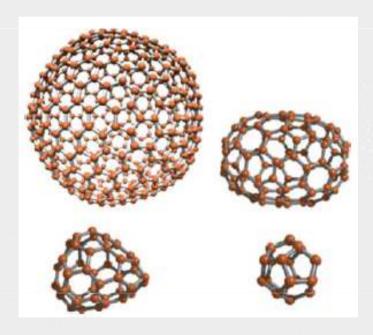
Zehner O (2011) Unintended consequences of green technologies. In: Robbins et al (eds) Green technology. Sage, London 427–432

### Bioenegy and rebound effects

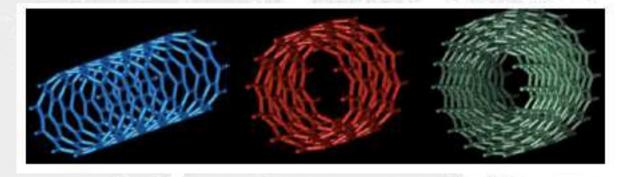
- When the whole energy chain is taken into consideration, there is much input of fossil energy to the renewable energy chains, in particular during production (e.g., growing of energy crops) and distribution
- Moving from fossil to a renewable fuel is not an energy-efficiency measure (rather a climate change remediation or energy security measure)
- The concept of rebound effects is mainly used in connection with energy— efficiency improvements, not the opposite. Thus, it is difficult to envision its use in relation to renewable energy, when bioenergy is the case

### Toxicological rebound effects

- Assessed for nanomaterials used in devices for the harvesting of renewable energy (Manzetti & Andersen 2012)
- New types of PV solar cells contain various forms of nanomaterials as principle components to achieve the fast charge transfers required in organic PV solar cells:



Models of fullerenes, from top left to bottom right: C<sub>500</sub> C<sub>96</sub> C<sub>46</sub> C<sub>20</sub>



Models of three main types of carbon nanotubes (CNTs): single walled CNT (left), double walled CNT (middle), and multi-walled CNT (right)

Manzetti S, Andersen O (2012) Toxicological aspects of nanomaterials used in energy harvesting consumer electronics. Renew Sustain Energy Rev 16(1):2102–2110

### Toxicological rebound effects (2)

- Fullerenes have electronic properties that give them the ability to potentially function as a "vehicle" for toxic compounds in penetration through membranes into lung cells (Manzetti et al. 2013)
- This can occur because their ability to undergo potent reactions with different biochemical compounds and by their ability to generate nanoparticles
- Fullerenes exert damage to bacteria, plankton, cells, and multicellular organisms (Fortner et al. 2005; Qiao et al. 2007)
- CNTs have unique toxicological properties, resembling those of asbestos, making the compounds potentially dangerous to public health and the environment during manufacture, use, and waste handling/disposal (Manzetti & Andersen 2013)

Manzetti S, Behzadi H, Andersen O, van der Spool D (2013) Fullerenes toxicity and electronic properties. Environ Chem Lett 11(2):105–118

Fortner J, Lyon D, Sayes C, Boyd A, Falkner J, Hotze E (2005) C60 in water: nanocrystal formation and microbial response. Environ Sci Technol 39:4307–4316

Qiao R, Roberts A, Mount A, Klaine S, Ke P (2007) Translocation of C60 and its derivatives across a lipid bilayer. Nano Lett 7:614–619

Manzetti S, Andersen O (2013) Carbon nanotubes in electronics: background and discussion for waste-handling strategies. Challenges 4(1):75–85

### Toxicological rebound effects (3)

- The toxicity of fullerenes is not well known, and more knowledge is necessary to fully understand the correlation between toxicological properties of fullerenes and their chemical properties, size, composition, and interaction with different types of organs and tissues in the body
- CNTs are accumulating in the environment at an increasing rate, and due to their small size, they become integrated into the nutritional and reproductive environment of humans and animals (Velzeboer et al. 2011)
- CNTs, in the form of aerosol particles, have been shown to interfere with living organisms, and thus pose health risks through cellular damage and even mortality (Kwok et al. 2010; Lam et al. 2006; Shvedova et al. 20005; Teeguarden et al. 2011)

Velzeboer I, Kupryianchyk D, Peeters E, Koelmans A (2011) Community effects of carbon nanotubes in aquatic sediments. Environ Int 37:1126–1130

Kwok K, Leung K, Flahaut E, Cheng J, Cheng S (2010) Chronic toxicity of double-walled carbon nanotubes to three marine organisms: influence of different dispersion methods. Nanomedicine 5(6):951–961

Lam C-W, James J, McCluskey R, Arepalli S, Hunter R (2006) A review of carbon nanotube toxicity and assessment of potential occupational and environmental health risks. Crit Rev Toxicol 36(3):189–217

Shvedova A, et al. (2005) Unusual inflammatory and fibrogenic pulmonary responses to single-walled carbon nanotubes in mice. Am J Physiol Lung Cell Mol Physiol 289:698–708

Teeguarden J, et. Al. (2011) Comparative proteomics and pulmonary toxicity of instilled single-walled carbon nanotubes, crocidolite asbestos, and ultrafine carbon black in mice. Toxicol Sci 120(1):123–135∆

### Toxicological rebound effects (4)

- Fullerenes and CNTs are examples where rebound effects can emerge from technologies that were intended to reduce environmental impacts
- To conclude, it is a significant, though under-communicated fact, that rebound effects have not traditionally been considered in life cycle assessments and when comparing the environmental impacts of various products (Guinee et al. 2011; Thiesen et al. 2008)
- As a result, policies and practices for renewable energy have been put in place with counterproductive results, resulting in unintended consequences

Guinee J, Heijungs R, Huppes G, Zamagni A, Masoni P, Buonamici R, Ekvall T, Rydberg T (2011) Life cycle assessment: past, present, and future. Environ Sci Technol 45(1):90–96

Thiesen J, Christensen T, Kristensen T, Andersen R, Brunoe B, Gregersen T, Thrane M, Weidema B (2008) Rebound effects of price differences. Int J Life Cycle Assess 13(2):104–114



### The Life Cycle Approach to Energy Analysis

- LCA is:
  - The compilation and evaluation of the inputs, outputs, and environmental impacts of a product (or energy) system throughout its life cycle (Nieuwlaar 2004)
- LCA of an energy form thus takes into consideration:
  - The whole life cycle of the energy;
    - from extraction/production
    - through to refining
    - distribution/transmission
    - and to its final use
  - These different segments in the life cycle of the energy type are also known as parts of the "energy chain"

Nieuwlaar E (2004) Life cycle assessment and energy systems. Encyclopedia of energy. Elvevier, pp 647–654

### LCA of energy

- The methodology is guided by the principles, framework, and requirements in the ISO 14040:2006 and 14044:2006 standards
- Guidelines for conducting LCA are also provided in the international reference life cycle data system (ILCD) handbook (Wolf et al. 2012)

Wolf M, Pant R, Chomkhamsri K, Sala S, Pennington D (2012) The International Reference Life Cycle Data System (ILCD) Handbook. Towards more sustainable production and consumption for a resource-efficient Europe. European Commission, Ispra. Joint Research Centre. Institute for Environment and Sustainability

### LCA of energy systems

- A good introduction to the LCA of energy systems is provided by Kummel et al. (1997)
  - A discussion of the methodology for performing system-wide life cycle analysis in the energy field
  - Three future energy system scenarios in Denmark was studied, and compared to the current energy system
  - A first national evaluation of the Danish energy system, and took into considerations specific Danish emission data, dispersion conditions, population densities, and the specifics of the heating and electricity system
  - These aspects were not well included in previous studies, for example those by the European Commission (EC 1994; 1995)

Kuemmel B, Krüger Nielsen S, Sørensen B (1997) Life-cycle analysis of energy systems. Roskilde University Press, Roskilde

European Commission (1994) Biofuels. Report EUR 15647 EN. Brussels: DG XII

European Commission (1995) ExternE: Externalities of Energy. Prepared by ETSU and IER for DGXII: Science, Research & Development, Study EUR 16520-5 EN, Luxembourg

### A much used life cycle inventory data base

- A useful resource worth consideration is the LCA database Ecoinvent, developed by the Swiss Center for Life Cycle Inventories
- The database contains about 4,000 datasets for products, services and processes often used in LCA case studies (Althaus et al. 2007; 2010; Weidema 2009)

Althaus H, Bauer C, Doka G, Dones R, Frischknecht R, Hellweg S, Humbert S, Jungbluth N, Köllner T, Loerincik Y, Margni M and Nemecek T (2010) Implementation of life cycle impact assessment methods. Dübendorf, CH: Swiss Centre for Life Cycle Inventories

Althaus H, Doka G, Dones R, Hischier R, Hellweg S, Nemecek T, Rebitzer G and Spielmann M (2007) Overview and methodology. Dübendorf, CH: Swiss Centre for Life Cycle Inventories

Weidema B, Hischier R, Althaus H, Bauer C, Doka G, Dones R, Frischknecht R, Jungbluth N, Nemecek T, Primas A, Wernet G (2009) Code of practice. Swiss Centre for Life Cycle Inventories, Dübendorf

## Weakness in the current use of LCA for energy systems

- Rebound effects are not considered when comparing various products or systems (Guinee et al. 2011; Theisen et al. 2008)
- Inclusion of rebound effects may significantly influence the conclusions of LCAs (Reisdorph 2011; Theisen et al. 2008)

Guinee J, Heijungs R, Huppes G, Zamagni A, Masoni P, Buonamici R, Ekvall T, Rydberg T (2011) Life cycle assessment: past, present, and future. Environ Sci Technol 45(1):90–96

Thiesen J, Christensen T, Kristensen T, Andersen R, Brunoe B, Gregersen T, Thrane M, Weidema B (2008) Rebound effects of price differences. Int J Life Cycle Assess13(2):104–114

Reisdorph D (2011) Rebound effects & monetizing environmental impacts. Paper presented at the Life Cycle Assessment (LCA) XI, October 4. Power Point. Chicago, IL

#### Attributional vs. Consequential LCA

- LCAs are commonly conducted as either attributional LCA or as consequential LCA
- Attributional LCAs (aLCAs) are also referred to as:
  - descriptive
  - accounting
  - retrospective
- Consequential LCAs (cLCAs) are also know as:
  - change-oriented
  - prospective
- In the aLCA of an energy system, all the environmental impacts created in the life cycle of the energy form are detailed and summarized
- The focus of an aLCA is on describing the *environmentally relevant physical flows* to and from the life cycle stages and their subsystems
- The cLCA goes further, setting out to describe how environmentally relevant flows will change, in response to possible future decisions (e.g., energy policy implementations)
- The use of scenarios in cLCAs can be useful

#### Attributional vs. Consequential LCA (2)

- aLCAs are limited in their capacity to highlight the environmental impacts of a product or energy system
- aLCAs are a convenient means to identify and communicate improvement opportunities for existing products
- On the other hand, cLCAs can highlight the indirectly induced consequences of decision making, in addition to the direct ones

#### Attributional vs. Consequential LCA (3)

- The main characteristic of a cLCA is that it provides information on the enviromental consequences of a new action, or technology shift
  - It does this by integrating economic models to include *market information*
- The cLCA thus represents a convergence of LCA and economic modelling approaches (Earles & Halog 2011)
- In contrast, the aLCA tends to look backwards at effects that have occurred, while the cLCA usually is forward-looking.

Earles J, Halog A (2011) Consequential life cycle assessment: a review. Int J Life Cycle Assess 16(5):114–453

#### The accuracy problem in consequential LCA

- There is, however, an accuracy problem in that the models generated in a cLCA include aspects that are not always effects of changes (Ekvall 2002)
  - For example, cLCAs are typically based on the assumption that when the demand for a material increases in the life cycle investigated, the production of that material is increased by the same amount
  - But materials are typically bought on a market with other suppliers and purchasers
  - When more material is used in the system studied, less material of that type might be used in other product systems
  - As a result, the increase in total production can be much smaller than a cLCA indicates Ekvall 1999)

Ekvall T (2002) Cleaner production tools: LCA and beyond. J Cleaner Prod 10:403–406 Ekvall T (1999) System expansion and allocation in life cycle assessment—with implications for wastepaper management. PhD Thesis, Gothenburg, Sweden, Chalmers University of Technology

## The potential of cLCA to predict unintended consequences of renewable energy

- In a cLCA the system is expanded to include activities both within and outside the life cycle, that are affected by changes within the life cycle of the energy form (Ekvall & Weidema 2004; Rehl et al. 2012; Reinhard & Zah 2009)
- With regards to renewable energy technologies, cLCA can be used as a modeling tool for predicting future environmental consequences of a shift from fossil energy to renewable energy

Ekvall T, Weidema B (2004) System boundaries and input data in consequential life cycle inventory analysis. Int J Life Cycle Assess 9(3):161–171

Rehl T, Lansche J, Muller J (2012) Life cycle assessment of energy generation from biogas—attributional versus consequential approach. Renew Sustain Energy Rev 16(6):3766–3775

Reinhard J, Zah R (2009) Global environmental consequences of increased biodiesel consumption in Switzerland: consequential life cycle assessment. J Cleaner Prod 17(Suppl 1):46–56

#### Environmental Impact Assessment

- Environmental impact assessment (EIA) is another tool, in addition to LCA, for assessing the possible positive or negative impacts a proposed project or technology may have on the environment (Finnveden et al. 2009)
- LCA is location-independent, while EIA is a procedural tool for the evaluation of local environmental impacts (Jeswani et al. 2010)
- Besides assessing quantifiable aspects, EIA also provides qualitative assessment of landscape, archaeological and cultural assets, as well as concerns of potentially affected people
- EIA also requires involvement/participation of the public and other stakeholders in the process

Finnveden G, Hauschild M, Ekvall T, Guinee J, Heijungs R, Hellweg S, Koehler A, Pennington D, Suh S (2009) Recent developments in life cycle assessment. J Environ Manage 91(1):1–21

Jeswani H, Azapagic A, Schepelmann P, Ritthoff M (2010) Options for broadening and deepening the LCA approaches. J Cleaner Prod 18(2):120–127

#### Environmental Impact Assessment (2)

- There are several methods for conducting an EIA, including the assessment and management of risks (Morris & Therivel 2009)
- The risk aspect is of particular relevance in connection with unintended environmental consequences, as it provides knowledge of what can go wrong; how likely is it; and what are the consequences? (Brookes 2009)
- The European Commission defines EIA as "a procedure that ensures that the environmental implications are taken into account before the decisions are made" (EC 2013)
- The relevance of EIA to renewable energy is clear:

An EIA can be undertaken for projects, such as construction of facilities for utilizing renewable energy, on the basis of Directive 2011/92/EU - the Environmental Assessment Directive (EC 2013)

Morris P and Therivel R (eds) (2009) Methods of environmental impact assessment (Second). SPON PRESS, London. Taylor & Francis Group

Brookes A (2009) Environmental risk assessment and risk management (second.). In: Morris P, Therivel R (eds) Methods of environmental impact assessment. SPON PRESS, London. Taylor & Francis Group, pp 351–364

European Commission (2013) Environmental assessment. European Commission, Brussels.

#### Strategic Environmental Assessment

- When the object of the assessment is at a "higher" level of decision-making (i.e. for strategies, policies, public plans, or programs), a Strategic Environmental Assessment (SEA) can be done (Jeswani et al. 2010)
- SEA is guided by the Directive 2001/42/EU the "Strategic Environmental Assessment Directive"
- Common for both directives 2011/92/EU and 2001/42/EU is that they aim to ensure that plans, programs, and projects that are likely to have significant effects on the environment are environmentally assessed before they are approved or authorized.

Jeswani H, Azapagic A, Schepelmann P, Ritthoff M (2010) Options for broadening and deepening the LCA approaches. J Cleaner Prod 18(2):120–127

#### Strategic Environmental Assessment (2)

- The SEA is normally conducted at an early stage, and performed in conditions involving less information and higher uncertainties
- Comparative analysis of SEA practice in Britain, The Netherlands and Germany has revealed that use of SEA is widespread, but far from systematic (Fischer 2002)
- Furthermore, that there are advantages to be gained from adopting a systematic application of SEA in its entirety
- This is in contrast to current use, characterized by many different, and often deficient, approaches

Fischer TB (2002) Strategic environmental assessment in transport and land use planning. Earthscan Publications, London

### Environmental Impact Assessments - concluding remarks

- EIAs have been applied to renewable projects such as hydroelectric power plants (Sovacool & Bulan 2013):
  - The EIAs sought to predict the negative influence on water quality, such as
    - changes in the concentration of dissolved oxygen
    - nutrient loads
    - suspended sediments
    - tidal encroachment, bank erosion
- However, also EIAs have been criticised for underestimating real impacts by not include rebound effects (Reisdorph 2011)
- The role of an impact assessment is to categorize and quantify potential environmental effects.
  - Once this is done, deciding whether one impact is worse than another is necessarily a subjective process in which the perceptions of the decision maker are descisive factors (Curran 2008)

Sovacool B, Bulan L (2013) They'll be dammed: the sustainability implications of the Sarawak Corridor of Renewable Energy (SCORE) in Malaysia. Sustain Sci 8:121–133

Reisdorph D (2011) Rebound effects & monetizing environmental impacts. Paper presented at the Life Cycle Assessment (LCA) XI, October 4. Power Point. Chicago, IL

Curran M (2008) Life-cycle assessment. Human Ecology. Elsevier, pp 2168–2174

## Environmental Impact Assessments - concluding remarks (2)

- The methodologies and underlying assumptions for assessing environmental and socioeconomic effects are not yet standardized or uniformly applied
  - The conclusions reached by the EIA studies are thus inconsistent (Kim et al. 2009)
    - A particular challenge is that the system boundaries of the EIAs are difficult to quantify and that there are numerous interrelated factors, many of which are poorly understood or unknown (IPCC 2012)

IPCC (2012) Renewable energy sources and climate change mitigation. Special Report of the Intergovernmental Panel on Climate Change. Cambridge University Press

Kim H, Kim S, Dale B (2009) Biofuels, land use change and greenhouse gas emissions: some unexplored variables. Environ Sci Technol 43(3):961–967



#### Hydrogen Energy

- LCA has revealed some unintended consequences in connection with the use of hydrogen fuel in road transport
  - The quite influential WTW study conducted by the association of European oil companies, Concawe, concluded that using hydrogen as a road transport fuel would increase Europe's greenhouse gas emissions rather than cut them, at least in the shorter time frame (Edwards et al. 2008)
  - However, this study has been criticised for applying a mixture of attributional and consequential approach, which in addition to the short time frame has resulted in what is called "somewhat misleading" interpretations (Sanden & Karlstroem 2007)

Edwards R, Griesemann J-C, Larivé J-F and Mahieu V (2008) Well-to-wheels analysis of future automotive fuels and powertrains in the European context. CONCAWE, EUCAR and JRC

Sanden B, Karlstroem M (2007) Positive and negative feedback in consequential life-cycle assessment. J Cleaner Prod 15(15):1469–1481

#### The Palm Oil Controversy

- There has been a shift in the global supply of vegetable oil, away from soy, rape seed (canola), and sunflower, to larger use of palm oil
  - Many LCAs on rape seed oil have been conducted, and the results are being used as decision support for bioenergy policies
  - However, the assessments did not any longer reflect the real situation regarding what type of oils are actually being used (Schmidt & Weidema 2008)
  - It was shown that palm oil cultivation on peatland increases the contribution to global warming significantly, actually by a factor of 4–5 compared to cultivation on mixed soil types (Schmidt 2010)

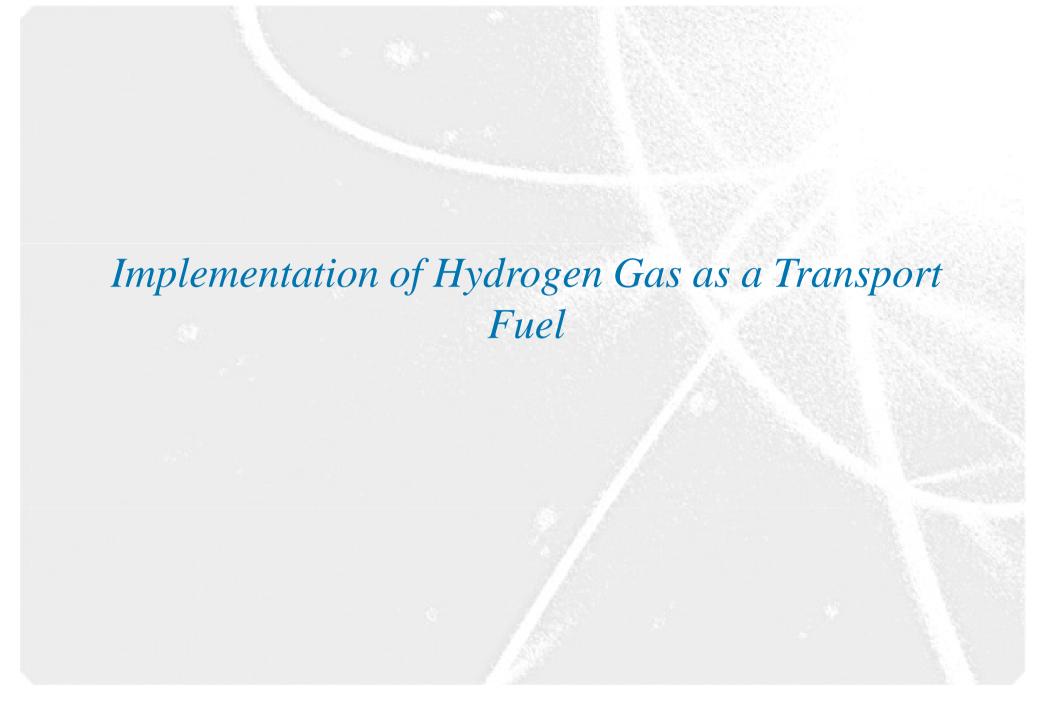
Schmidt J, Weidema B (2008) Shift in the marginal supply of vegetable oil. Int J Life Cycle Assess 13(3):235–239

Schmidt J (2010) Comparative life cycle assessment of rapeseed oil and palm oil. Int J Life Cycle Assess 15(2):183–197

#### **Biorefineries**

- That second-generation biofuel are not necessarily better for the environment, is also shown in a South African study (Melamu & Blottnitz 2011)
- Scenarios were made for a sugar mill to start selling its bagasse, currently used to provide process heat, to an advanced biofuels producer
- The sugar mill would have to buy an equivalent amount of coal to compensate for the process heat requirement
- Seven scenarios, ranging from status quo, where no bagasse is diverted, to 100 % bagasse diversion, also include one scenario with energy efficiency improvements in the sugar mill
- A cLCA was applied to the seven scenarios, covering GWP, non-renewable energy use, aquatic eutrophication and terrestrial acidification
- A basic financial analysis of the proposed scenarios showed that they are realistic, with potentially lucrative returns
- However, cLCA results showed that diverting bagasse without efficiency improvements from its current use to an ethanol biorefinery would backfire for all environmental impact categories studied
- The base case outperformed all the other scenarios, with the 100 % bagasse diversion scenario emerging the worst
- Thus, diverting cellulosic residues into biofuel production is not advised, unless accompanied by major energy efficiency improvements

Melamu R, Blottnitz H (2011) 2nd Generation biofuels a sure bet? A life cycle assessment of how things could go wrong. J Cleaner Prod 19(2–3):138–144

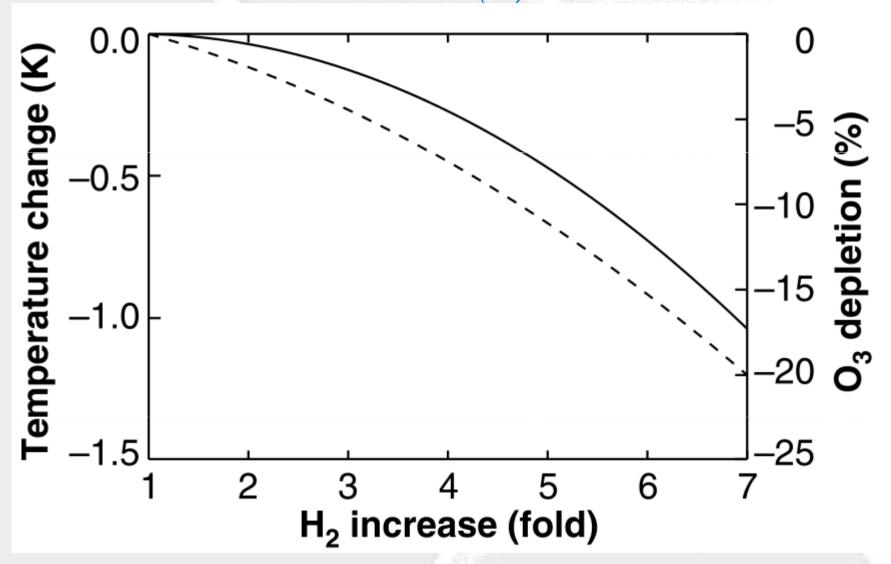


## Implementation of Hydrogen Gas as a Transport Fuel (1)

#### Potential Environmental Impact of a Hydrogen Economy on the Stratosphere

- Stratospheric Ozone-depletion
- Unintended emission of molecular hydrogen (H<sub>2</sub>) from future widespread use of hydrogen as fuel
- Leakage of H<sub>2</sub> from infrastructure and operations connected to the production, distribution, and use of the hydrogen fuel
- Increase the abundance of water vapor in the stratosphere. The water increase, plausibly as much as 1 part per million (ppm), would cause stratospheric cooling, enhancement of the heterogeneous chemistry that destroys ozone

### Implementation of Hydrogen Gas as a Transport Fuel (2)



Tromp T, Shia R-L, Allen M, et al. (2003) Potential environmental impact of a hydrogen economy on the stratosphere. Science 300(5626):1740–1742.



#### The basis





Supported by a grant from Iceland, Liechtenstein and Norway through the EEA Financial Mechanism and the Norwegian Financial Mechanism

Research Project No PL0261 - BIODEG

## OF BIO-COMPONENTS CONTENT IN FUEL ON EMISSION OF DIESEL ENGINES AND ENGINE OIL DETERIORATION

Period: 06.2008 - 03.2011 Budget: 888 790 Euro Agreement no.: E022/P01/2008/02/85

#### Partners:

OIL AND GAS INSTITUTE, Cracow, Poland http://www.inig.pl

INGENIEURSCHULE BIEL - Laboratory for exhaust emission control, Biel, Switzerland http://labs.hti.bfh.ch/index.php?id=abgaslabor&L=2

WESTERN NORWAY RESEARCH INSTITUTE, Sogndal, Norway http://www.vestforsk.no/en

#### The basis (2)



VF-rapport nr. 18/1998

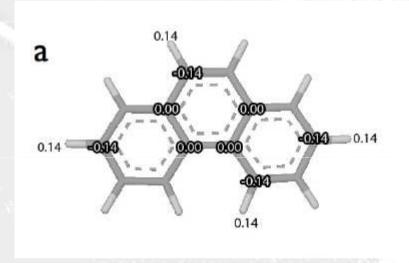
### "Biodiesel in heavy-duty vehicles in Norway

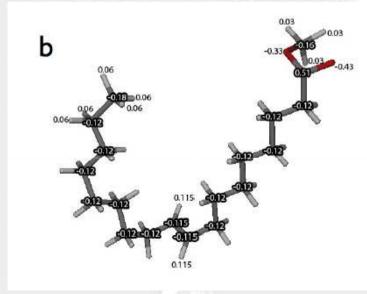
Strategic plan and vehicle fleet experiments"

Final report from European Commission ALTENER-project XVII/4.1030/Z/209/96/NOR

By Otto Andersen, Hans Einar Lundli, Eivind Brendehaug and Morten Simonsen

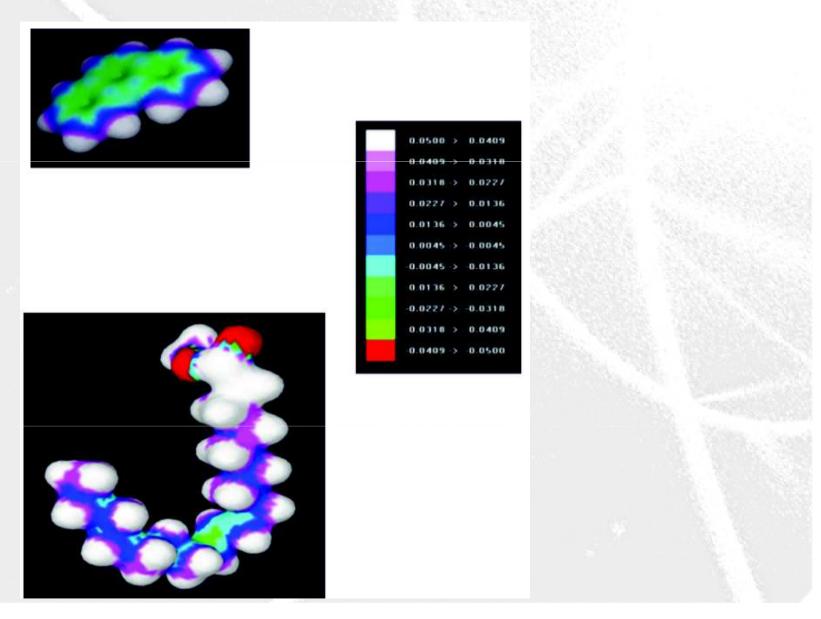
#### The two compound groups



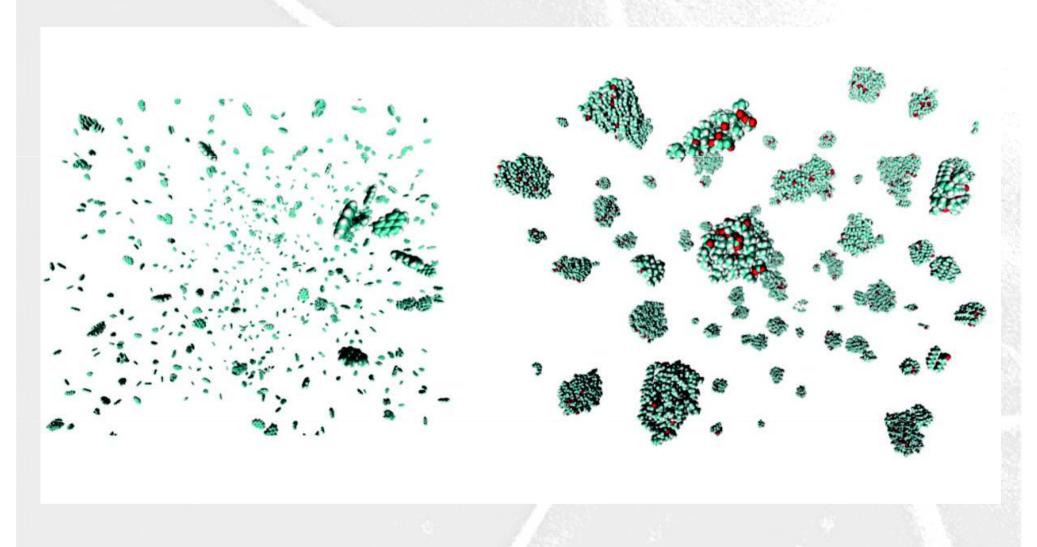


a Phenanthrene, b OME

#### The two compound groups (electron density)

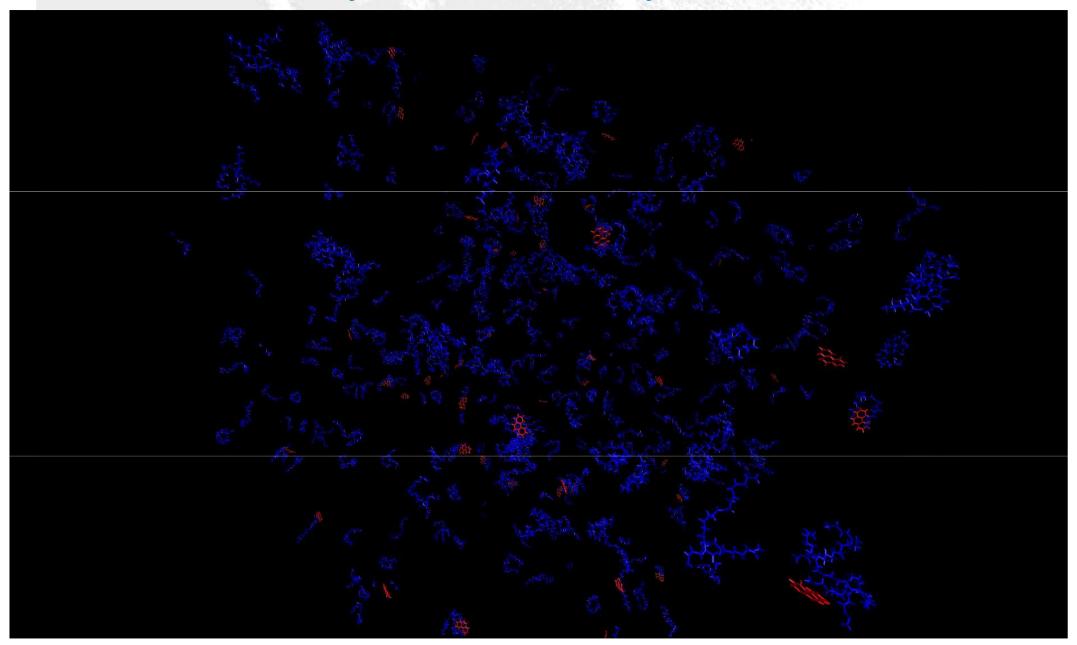


#### Biodiesel and its Blending into Fossil Diesel (11)

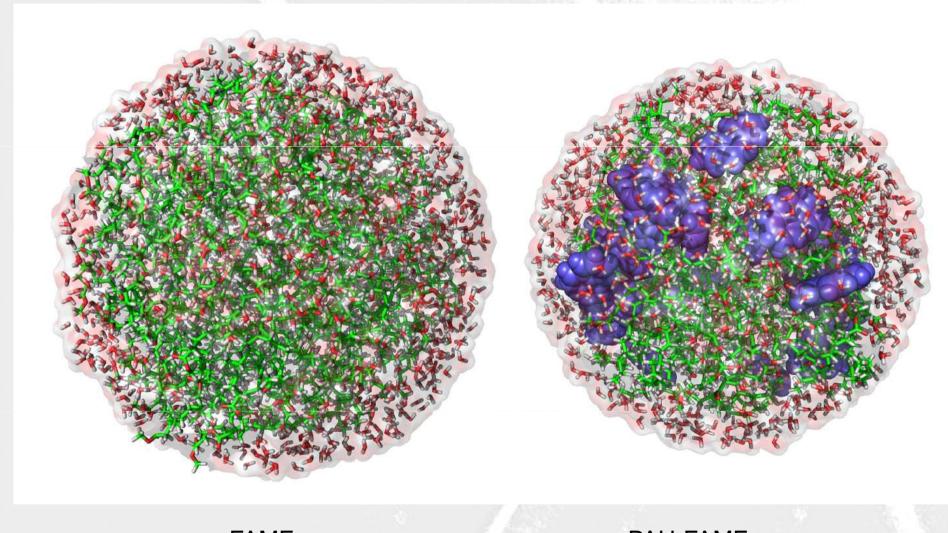


PAH FAME

### MDS of PAH-FAME NP formation

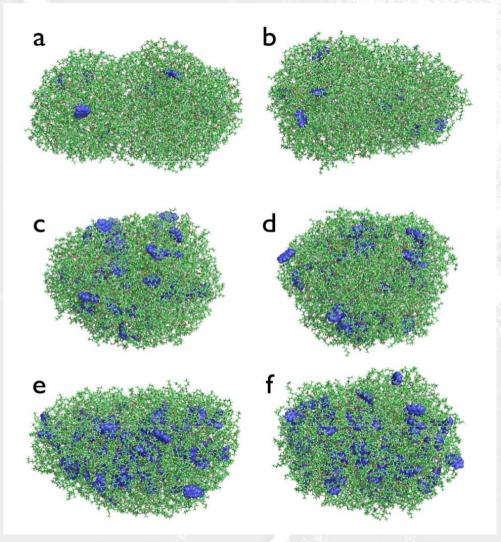


#### Simulated models of the nanoparticles in moisture



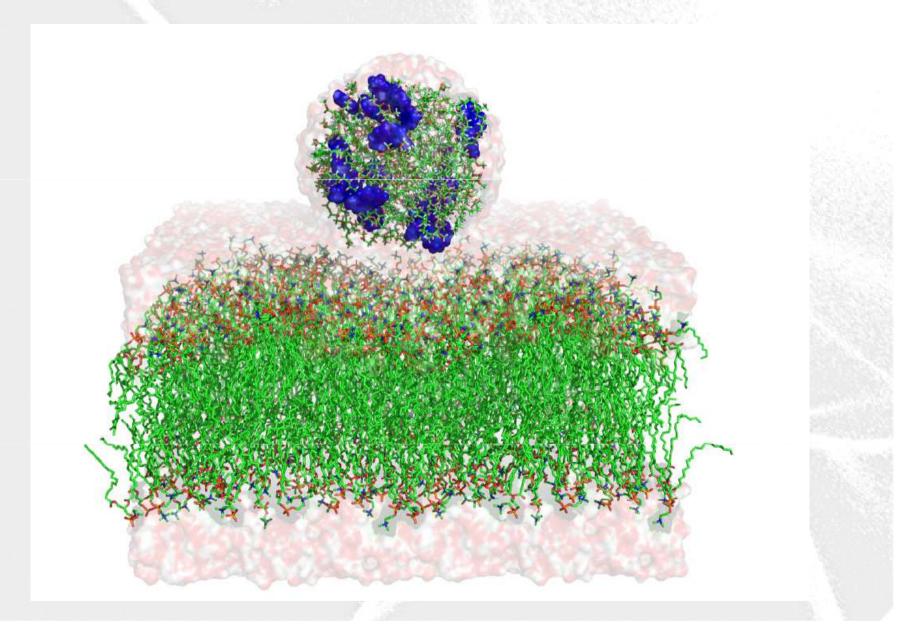
FAME PAH-FAME

### Simulated nanoparticles in vacuum

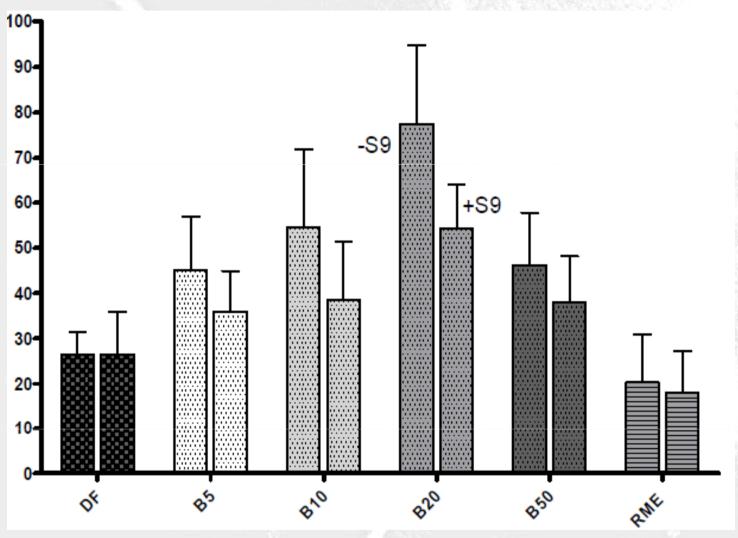


PAH-FAME NPs consisting of 512 OME molecules plus 10 (a, b), 50 (c, d), and 100 (e, f) Phe molecules

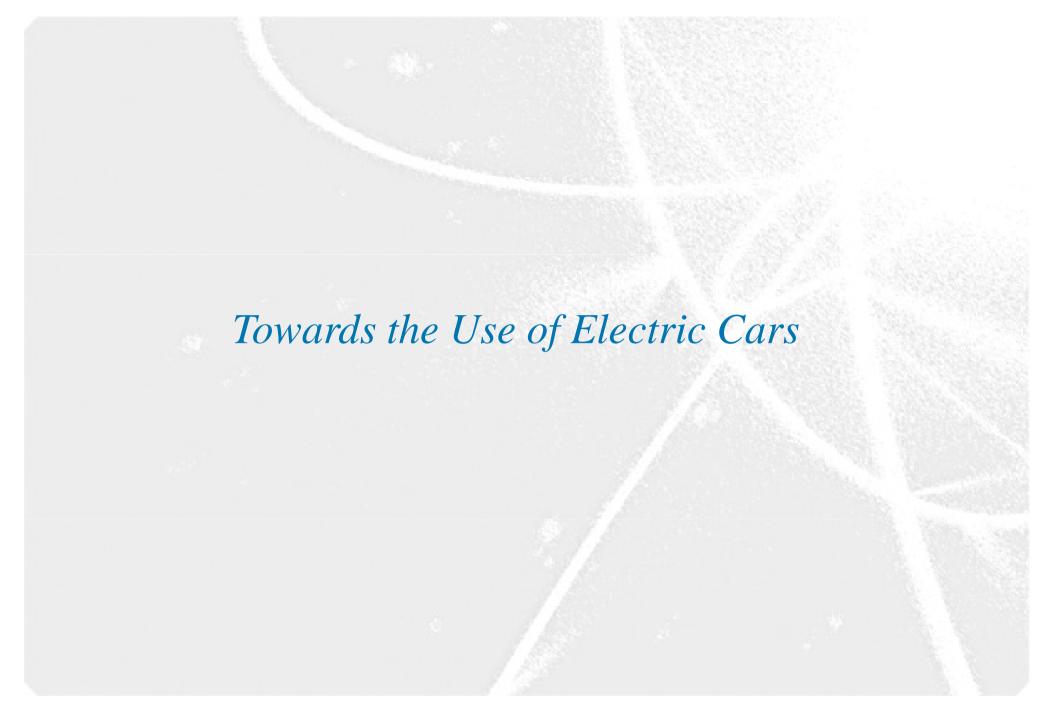
#### PAH-FAME interaction with cellular membrane



#### PAH-FAME theory can explain previous results



Munack A, Krahl J, Bünger J, Ruschel Y, Scröder O (2008) Exhaust gas emissions and mutagenic effects of modern diesel fuels, GTL, biodiesel, and biodiesel blends. Paper presented at the IGR — International conference of agricultural engineering XXXVII Congresso Brasileiro de Engenharia Agrícola Brazil, Aug 31 to Sept 4, 2008.



#### An example of a LCA of Electric Cars

### Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles

Troy R. Hawkins, Bhawna Singh, Guillaume Majeau-Bettez, and Anders Hammer Strømman

#### Keywords:

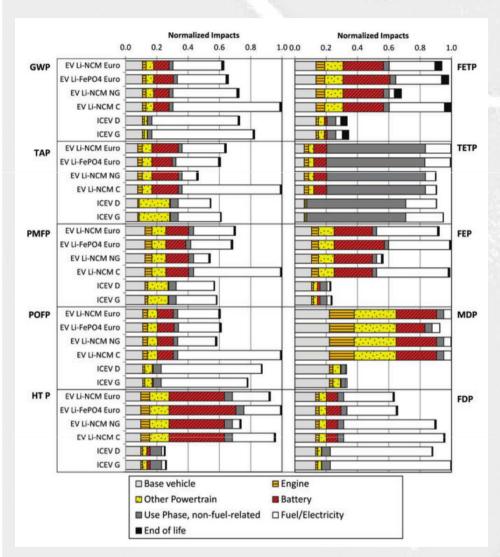
batteries electricity mix global warming industrial ecology life cycle inventory (LCI) transportation

Supporting information is available on the JIE Web site

#### Summary

Electric vehicles (EVs) coupled with low-carbon electricity sources offer the potential for reducing greenhouse gas emissions and exposure to tailpipe emissions from personal transportation. In considering these benefits, it is important to address concerns of problemshifting. In addition, while many studies have focused on the use phase in comparing transportation options, vehicle production is also significant when comparing conventional and EVs. We develop and provide a transparent life cycle inventory of conventional and electric vehicles and apply our inventory to assess conventional and EVs over a range of impact categories. We find that EVs powered by the present European electricity mix offer a 10% to 24% decrease in global warming potential (GWP) relative to conventional diesel or gasoline vehicles assuming lifetimes of 150,000 km. However, EVs exhibit the potential for significant increases in human toxicity, freshwater eco-toxicity, freshwater eutrophication, and metal depletion impacts, largely emanating from the vehicle supply chain. Results are sensitive to assumptions regarding electricity source, use phase energy consumption, vehicle lifetime, and battery replacement schedules. Because production impacts are more significant for EVs than conventional vehicles, assuming a vehicle lifetime of 200,000 km exaggerates the GWP benefits of EVs to 27% to 29% relative to gasoline vehicles or 17% to 20% relative to diesel. An assumption of 100,000 km decreases the benefit of EVs to 9% to 14% with respect to gasoline vehicles and results in impacts indistinguishable from those of a diesel vehicle. Improving the environmental profile of EVs requires engagement around reducing vehicle production supply chain impacts and promoting clean electricity sources in decision making regarding electricity infrastructure.

#### Normalized Impacts of Vehicle Production



Results for each impact category have been normalized to the largest total impact.

#### Impact categories:

GWP Global Warming Potential

TAP Terrestrial Acidification Potential

PMFP Particulate Matter Formation Potential

POFP Photochemical Oxidation Formation Potential

HTP Human Toxicity Potential

FETP Freshwater Eco-Toxicity Potential
TETP Terrestrial Eco-Toxicity Potential
FEP Freshwater Eutrophication Potential

MDP Mineral Depletion Potential FDP Fossil Depletion Potential

#### **Batteries:**

LiNCM Lithium Nickel Cobalt Manganese

LiFePO, Lithium Iron Phosphate

#### **Electricity sources:**

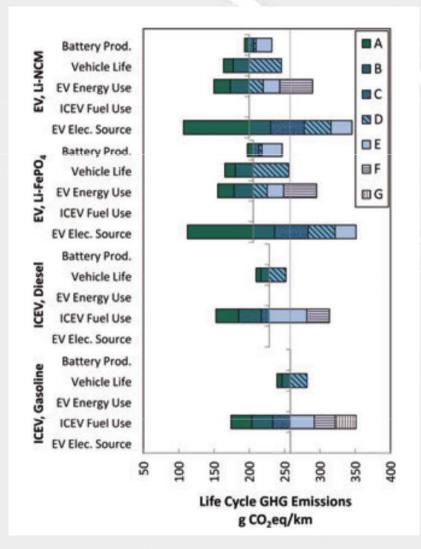
C Coal

NG Natural Gas

Euro European Electricity Mix

Hawkins T, Singh B, Majeau-Bettez B, Strømman A (2013) Comparative Environmental Life Cycle Assessment of Conventional and Electrical Vehicles. Int J Ind Ecol 17(1):53–64.

## Sensitivity of total life cycle greenhouse gas emissions to key parameters



Battery Prod (mass of battery required, normalized to base case):

0.8 (A), 1.0 (B), 1.2 (C), 1.3 (D), 2 (E)

Vehicle Life (km):

250 000 (A), 200 000 (B), 150 000 (C), 100 000 (D)

EV Energy Use (MJ/km):

0.3 (A), 0.45 (B), 0.6 (C), 0.75 (D), 0.9 (E), 1.2 (F)

ICEV Fuel (diesel) Use (L/km):

0.03 (A), 0.04 (B), 0.05 (C), 0.06 (D), 0.07 (E), 0.08 (F)

ICEV Fuel (gasoline) Use (L/km):

0.04 (A), 0.05 (B), 0.06 (C), 0.07 (D), 0.08 (E), 0.09 (F), 0.1 (G)

EV Elec. Source:

wind (A), natural gas (B), oil (C), coal (D), lignite (E)

LiFePO<sub>4</sub> Lithium Iron Phosphate

LiNCM Lithium Nickel Cobalt Manganese

Hawkins T, Singh B, Majeau-Bettez B, Strømman A (2013) Comparative Environmental Life Cycle Assessment of Conventional and Electrical Vehicles. Int J Ind Ecol 17(1):53–64.

#### Towards the Use of Electric Cars(4)

- Electric vehicles have **only marginally lower life-cycle GWPs** than gasoline and diesel vehicles (10-24% with present European electricity mix)
- It is counterproductive to promote EVs in regions where electricity is produced from oil, coal, and lignite combustion
- With a massive increase to be expected in the future number of electric vehicles, there is potential for serious unexpected consequences in terms of significant **increased**:
- human toxicity (180-290%), freshwater eco-toxicity, freshwater eutrophication
- metal depletion (200-300%
- In particular, the production of electronic equipment necessary for an electrical vehicle requires a variety of **metals**, which poses a **challenge for recycling** and raises **toxicity** concerns
- This stems, to a large degree, from the **high use of copper wires** in electrical vehicles, and the use of **nickel** in cars with lithium-nickel cobalt-manganese batteries
- Problem shifting:
- from GWP to toxicity and mineral resource depletion
- moving emissions away from the road rather than reducing them globally
- Hawkins T, Singh B, Majeau-Bettez B, Strømman A (2013) Comparative Environmental Life Cycle Assessment of Conventional and Electrical Vehicles. Int J Ind Ecol 17(1):53–64.
- Johnson J, Harper E, Lifset R, Graedel T (2007) Dining at the periodic table: metals concentrations as they relate to recycling. Environ Sci Technol 41(5):1759–1765
- Gaines L, Nelson P (2009) Lithium-ion batteries: possible materials issues. Argonne National Laboratory, Argonne
- Gaines L, Nelson P (2010) Lithium-ion batteries: examining material demand and recycling issues. Argonne National Laboratory, Argonne

### Towards the Use of Electric Cars(5)



Kennecott Copper Mine in Bingham Valley, Utah

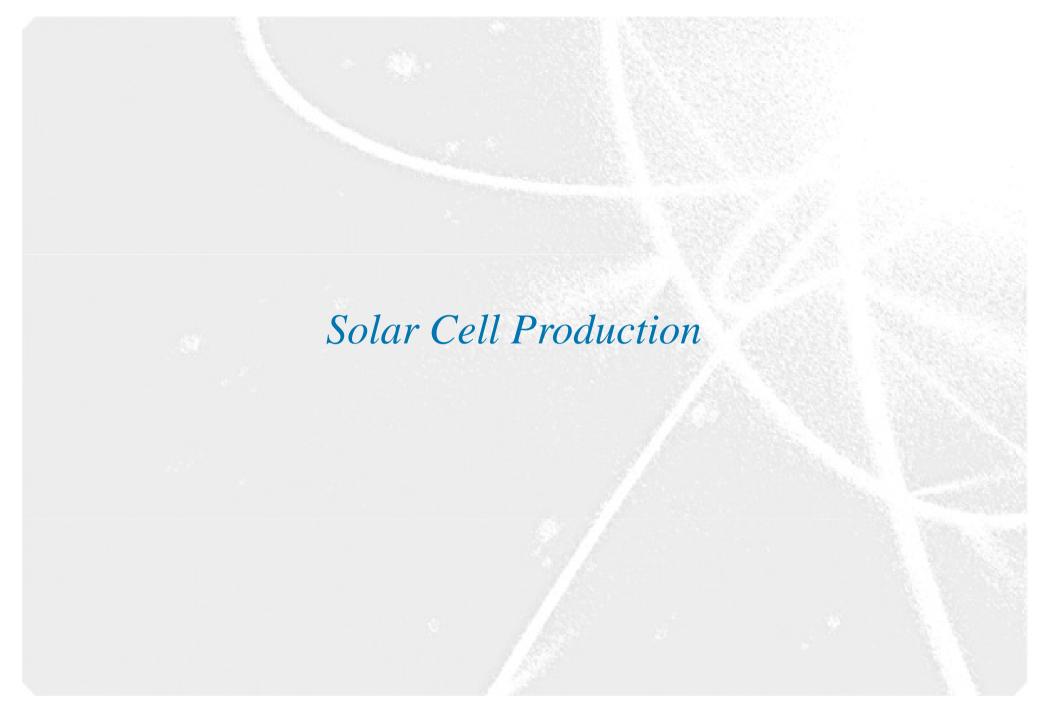


Anaconda copper Mine in Butte, Montana



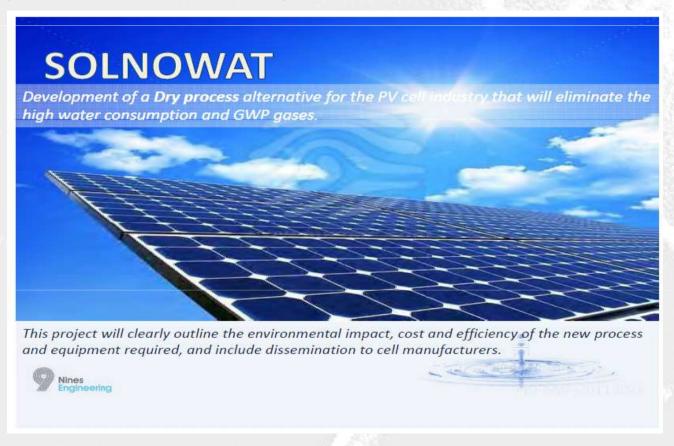
Nickel runoff, Sudbury, Ontario

Source: Sociological Images (2014), W.W. Norton Company Inc.



#### Solar Cell Production (1)

- Wet chemical **etching** of crystalline silicon photovoltaic wafers
- High water consumption from rinsing between successive chemical baths
- Emission of high-GWP gases
- New etching process needed (dry etching)

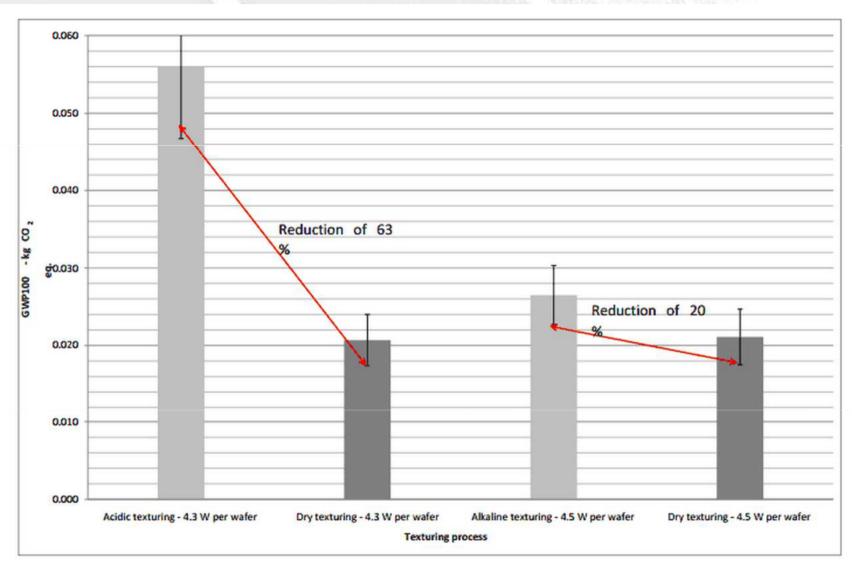


#### Solar Cell Production (2)

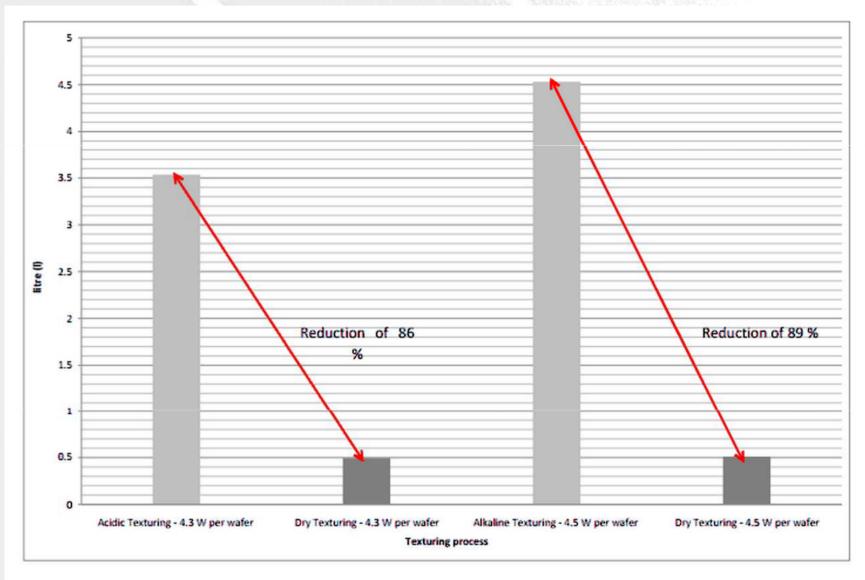
#### → CONSORTIUM:

Type of participant	Participant organisation name	Contact name	Country
SMEP	Ultra High Vacuum Solutions Itd T/A Nines Engineering	Laurent Clochard Edward Duffy	Ireland
SMEP	Alyxan	Michel Heninger	France
SMEP	Solartech S.R.O.	Ales Poruba	Czech Rep
SMEP	Zimmermann & Schilp Handhabungstechnik GmbH	Michael Schilp	Germany
RTD	Fraunhofer ISE and IWS	ISE: Johannes Seiffe IWS : Gerrit Madder	Germany
RTD	Vestlandsforsking	Otto Anderson	Norway

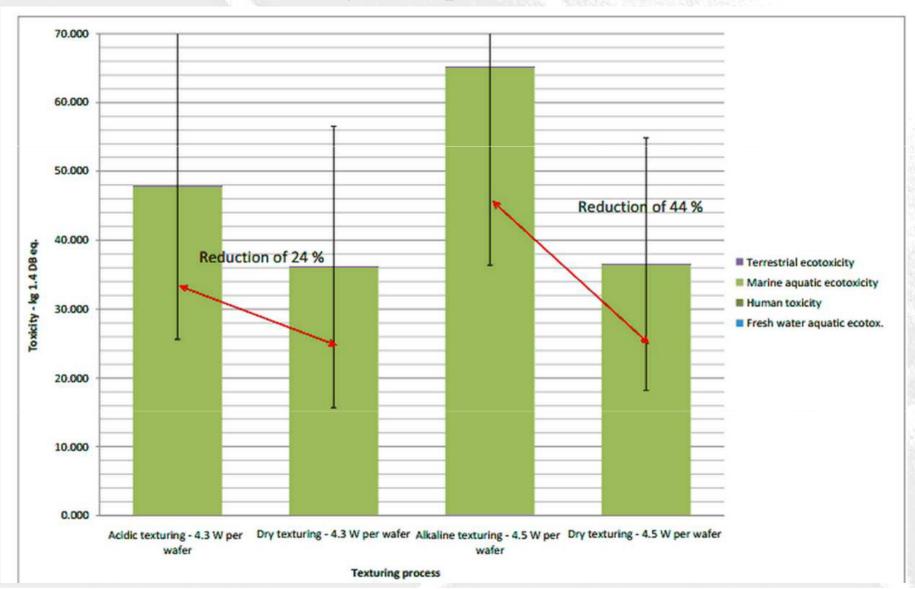
### Solar Cell Production (3) GWP comparison



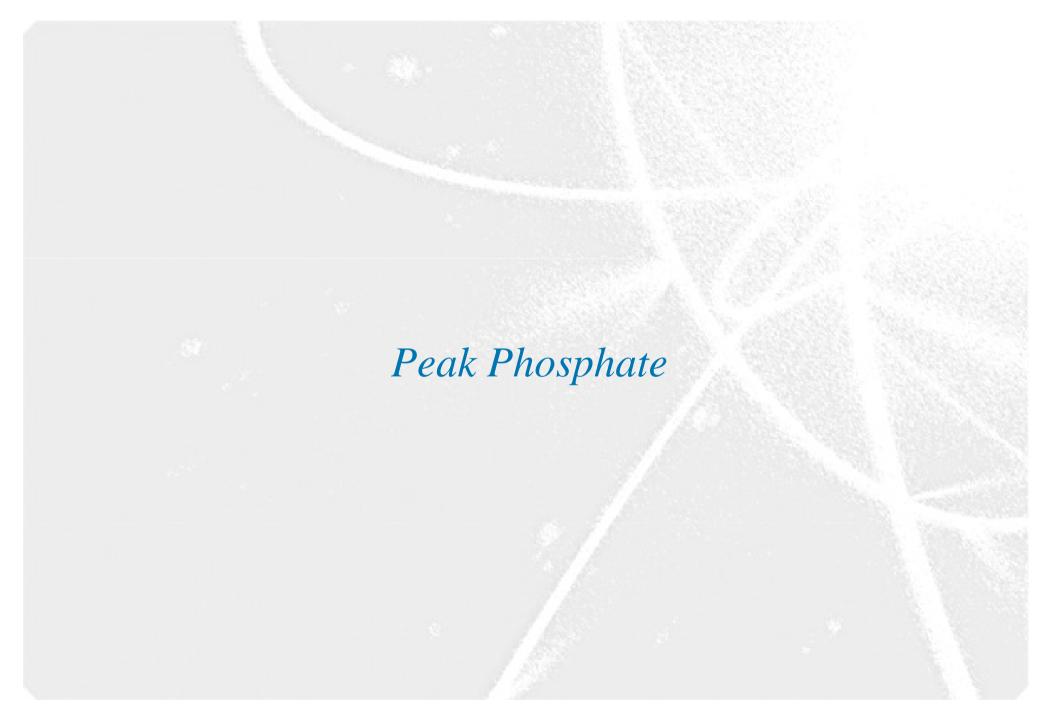
## Solar Cell Production (4) Water consumption comparison



## Solar Cell Production (5) Toxicity comparison







#### Peak Phosphate (1)

- Phosphate is used by plants to form the cell walls and membranes through phospholipids
- Phosphate is key parts of DNA
- There is no substitute for phosphorus in food production
- It is estimated that by 2025-2030 the world will reach **peak phosphate**, with a flattening out of fertilizer production
- 85 % of the global reserves of high grade phosphate is in Western Sahara
- Western Sahara has been occupied by Morocco since the Spanish colonialists left in 1976
- Many neighboring states reject the Moroccan administration of Western Sahara, and several states have established diplomatic relations to the "Sahrawi Arab Democratic Republic" represented by the Polisario Front. This movement is operating in exile in Algeria, and UN recognizes it as the rightful representative of the territory. It is believed that the phosphate deposits were the major reason that Morocco took an interest in the Western Sahara.
- The Polisario Front would like to have it back

### Peak Phosphate (2)



The Bou Craa mine in the Western Sahara sends phosphate down a 150-kilometer-long conveyor belt to the port of El Ayoun

Pearce F (2011) Phosphate: A Critical Resource Misused and Now Running Low. Yale University, New Haven, CT

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