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Life Cycle Assessment as a Component of Material Science & Engineering for a Sustainable World

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Outlines

- Materials Science Engineering (MSE) should contribute to a sustainable world;
  - But, environmental assessment is missing in MSE research and education in general.
- Life Cycle Assessment (LCA) for MSE;
  - LCA: “best framework for environmental assessment”;
  - Political and market-based driving forces for LCA;
- LCA R&D for MSE in China;
  - Development of LCA database (CLCD) and software (eBalance);
  - Development of methodology;
  - Case studies of materials and product;
- Conclusions and suggestions;

MSE and Sustainable Development

Obvious links between

- **Material Sci. & Eng.** research has been shaping production & consumption.
- **Materials Tech.** deliver functions/services during use stage,
- but also cause **resource/ energy/environmental impacts** along production, use and disposal stages (so-called life cycle of materials).

Simple truth

- MSE research <u>in the past</u> is held responsible, at least partly, for resource and energy depletion as well as environmental impacts.
- MSE research is needed <u>now and forever</u> to continuously reduce those impacts along the life cycle of every material.

Ecomaterials (EM) – response of MSE

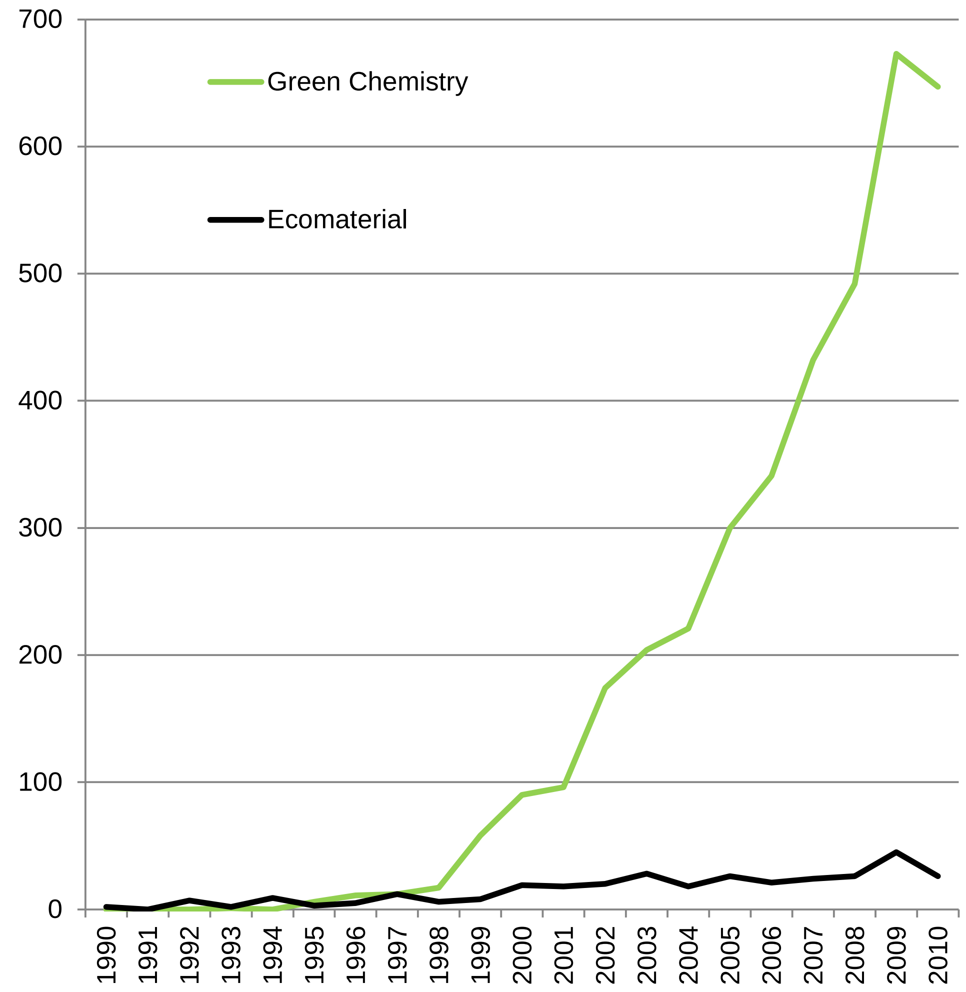
- Ecomaterials = Environmentally Conscious Materials;
  - Proposed in early 1990's by K. Halada & R. Yamamoto;
  - Similar terms, e.g. Environmentally friendly materials, Environmentally benign materials;
  - Regarded as challenges and opportunities in MSE and for material scientists;
- Activities in EM;
  - Research projects, publications and textbooks, educational programs;
  - International Conference on Ecomaterials (ICEM), every two years since 1993, and others;
  - Ecomaterial research society in Japan and China;
- **Observation:**
  - However, EM is falling much behind, compared to Green Chemistry (GC) !

EM vs GC: Fraternal twins

- Sharing many in common fundamentally, e.g.
  - Both are fundamental disciplines underpinning industrial systems.
  - Both are related to enormous resource and energy use as well as emissions.
  - Same concepts stressing environmental consciousness in conventional research work.
- but recognized very differently, e.g.
  - Peer-review journal on "Green Chemistry", none dedicated to EM
  - Awards to GC: e.g.
    - Presidential Green Chemistry Challenge, USA
    - Australia's Green Chemistry Challenge Awards
    - Canadian Green Chemistry Medal
    - The Nobel Prize Committee recognized the importance of GC: When awarded the metathesis method in organic synthesis in 2005, it said "the method represents a great step forward for 'green chemistry'".
  - Numbers of SCI papers on EM and GC ……

Number of SCI papers

- 3775 papers on Green Chemistry
- 325 papers on Ecomaterials (Keywords also: Environmentally friendly materials & Environmentally benign materials)
- The term of "ecomaterials" is seldom used except by Japanese and Chinese material scientists. It's even can not found in Wikipedia.



But why they are so different?

$1^{\#}$ Ambiguous definition and scope of EMs

- Misleading perception of EM
  - "EMs are materials for environmental protection" is misleading, in which EMs are just a small group of materials involved.
  - But in fact, ALL MATERIALS and PROCESSES have environmental impacts along their life cycle that are to be reduced.
- Definition and scope of GC
  - "Green chemistry is the design of chemical products and processes that reduce or eliminate the use and generation of hazardous substances", in which ALL CHEMICALS and PROCESSES are involved. *(P. Anastas, Acc. Chem. Res. , 2002)*
  - GC has much broader scope, including
    - use of greener synthetic pathways: e.g. greener feedstocks, reagents or catalysts, natural processes or atom-economical
    - use of greener reaction conditions: e.g. greener solvents, energy efficiency
    - design of greener chemicals

(Focus Areas of US Presidential Green Chemistry Challenge)

$2^{\#}$ Controversial examples of EMs

Lesson learned:

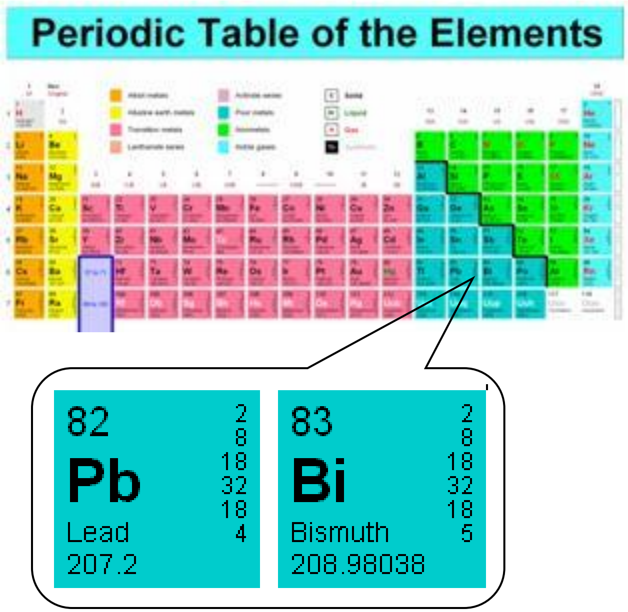
- It's so often and so easy to find drawbacks of "ecomaterials"
- It's not easy to tell which material or option is better from environmental perspectives.

- Silicon Solar Cell
  - "Green" during operation, but it takes 3-5 years to reclaim the energy consumed during its manufacture.

- Electric Automobile and Fuel Cell
  - "Green" during driving, but where the electricity and hydrogen comes from?
  - In China, ~80% electricity from coal-fired power.

Pb-free "ecomaterials" with Bi inside

- Bi: a "neighbour" of Pb, but less toxic
- Being widely tested in Pb-free
  - *solder, electric ceramics, paints, dye, glass, water pipe, battery , bullets…*
- But hidden environmental problems
  - Nearly 1/3 of Bi co-exists with Pb
  - Both depleted resources: Pb ~25 yr, Bi ~30 yr
  - Big difference in global yields: Bi ~5000 t/yr, Pb ~6 million t/yr, 1200 times!



A risk to the environment & a risk to material scientists !

Lesson learned:

- Just one merit among multiple environmental impacts can not justify an ecomaterial;

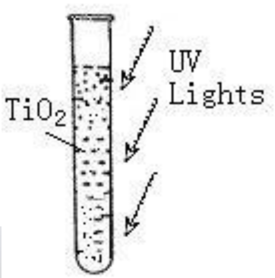
TiO_2 as a photocatalyst for waste water treatment

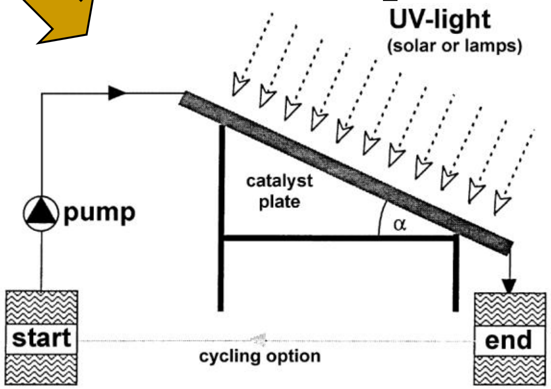
- Production of TiO_2 (per 1kg)

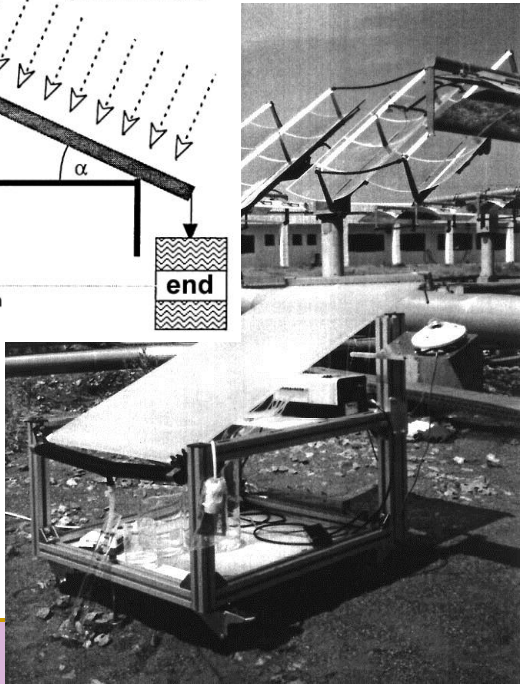
Fresh water	104kg	**V-Ti magnetite**	5.58kg	**Energy**	63.86MJ
Waste acid	6.4kg	**Waste water**	70kg	**CO_2**	7.87kg
$FeSO_4 \cdot 7H_2O$	3.5kg	**Waste solid**	10.5kg	**Dust**	0.3kg

Powder:
hard to image …

Thin film:
less SO_2 needed







Lesson learned:
Environmental information may support or deny the design of experiment.

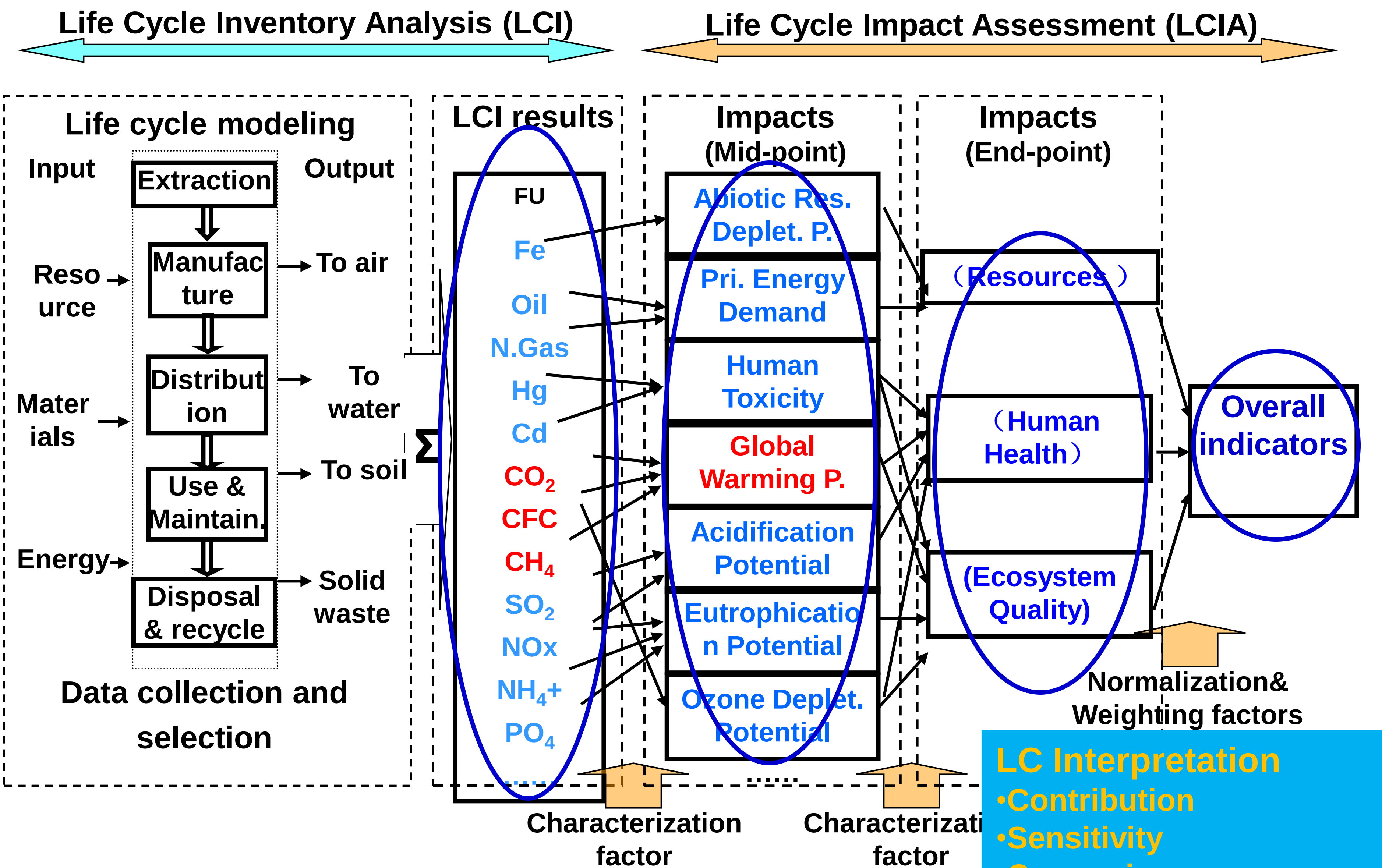
http://netserv.ipc.uni-linz.ac.at

Environmental assessment is missing in MSE

- A method is needed to
  - quantitatively compare different options and trade-offs,
  - cover multiple life cycle stages to avoid environmental burden shifting among stages,
  - cover multiple impact categories to avoid environmental burden shifting among them.
- Life Cycle Assessment (LCA, i.e. ISO14040s) is such a method
  - A scientific and standardized method, which "provides the best framework for assessing the potential environmental impacts of products…"

(EC Integrated Product Policy, 2003)

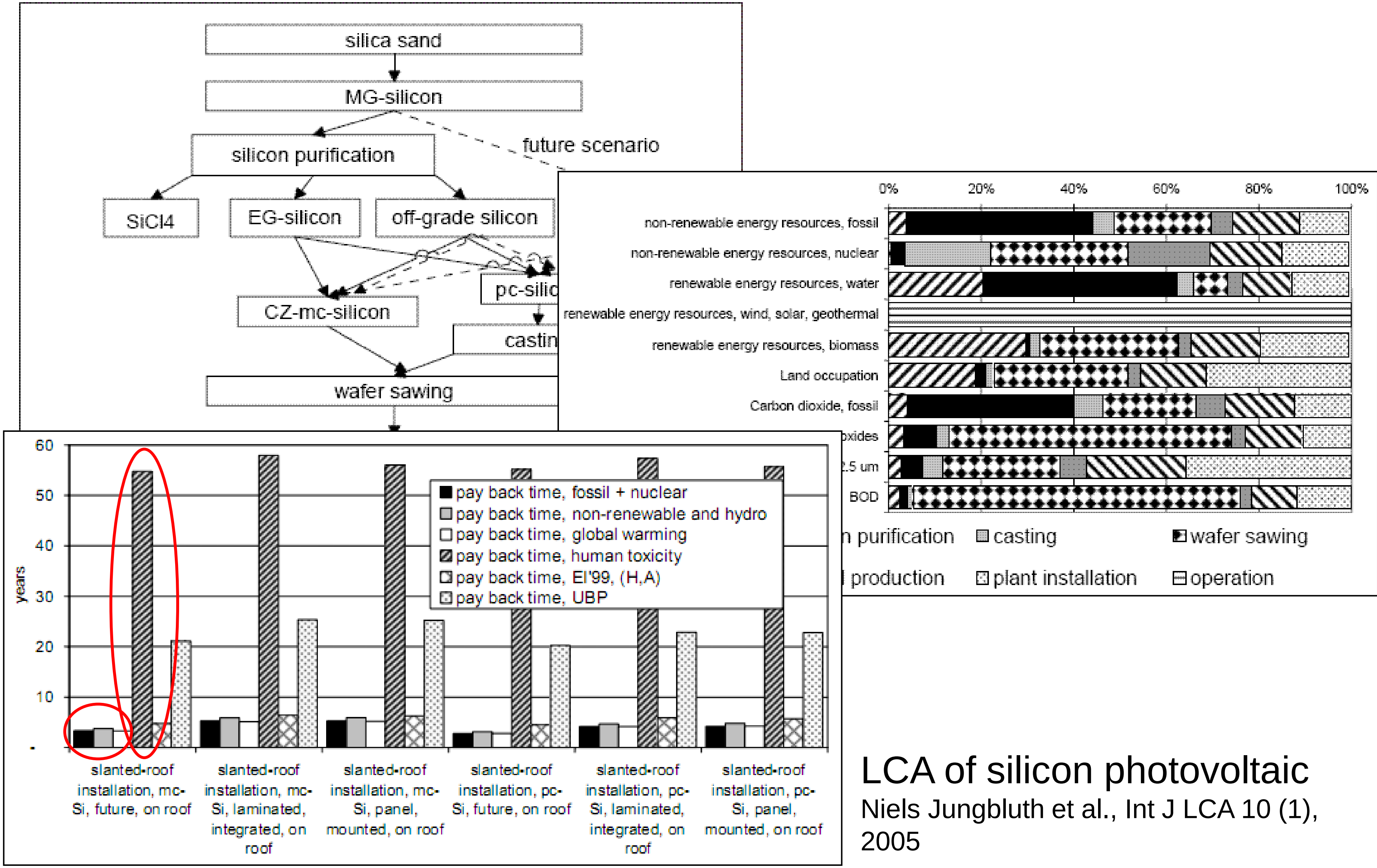
LCA framework – holistic & quantitative



LC Interpretation

- •Contribution
- •Sensitivity
- •Comparison
- •Cost-Benefit

LCA for technology R&D



LCA of silicon photovoltaic

Niels Jungbluth et al., Int J LCA 10 (1), 2005

LCA requirements in EU FP7

EUROPEAN COMMISSION
DIRECTORATE-GENERAL
Joint Research Centre

Joint Research Centre

7th EU RTD Framework Program Activities

- Within the first calls, most waste-technology research projects:
  - have to provide a ISO 14040 compliant **LCA**
  - an **LCC** study
  - and a **Life Cycle Social** Assessment study

  LCA studies provided according to requirements of European Platform for LCA
- Within FP7 DG RTD will explore the possibility of developing an European Methodology for Technology Assessment. The European Technology Assessment will be based on a **Life Cycle Thinking/Assessment** approach.
- **CALCAS** towards a European Life Cycle Sustainability methodology

From Raffaella Bersani, 2006

To ensure environmental consideration embedded in research and delivery of environmentally sound technologies

An example of Call for Proposal in 2009

Fuel Cells and Hydrogen Joint Undertaking (FCH JU)

Budget: EUR 71.3 million

Research areas

- Area 1: Transportation & Refuelling Infrastructure
- Area 2: Hydrogen Production & Distribution
- Area 3: Stationary Power Generation & CHP
- Area 4: Early Markets
- Area 5: Cross-cutting Issues
  - SP1-JTI-FCH.2009.5.5 Development of a framework for Life Cycle Assessment (LCA)

http://www.fc-hyguide.eu

Similar requirements emerging in U.S.

- For the last a few years, LCA has been absorbed by federal as well as state-level rule-making proceedings and policy initiatives.

- Low-Carbon Fuel Standards (LCFSs) and Renewable Energy Standard (RES) set out minimum requirements of biofuels, which include quantitative thresholds of life-cycle Greenhouse Gas (GHG) emission from biofuels relative to that from equivalent amount of fossil fuels.

Sangwon Suh, UCSB, CLCM Conference 2009

Carbon Footprint of Apple

iPad

Environmental Report

Model

MB292, MB293, MB294 (Wi-Fi)
MC349, MC496, MC497 (Wi-Fi + 3G)

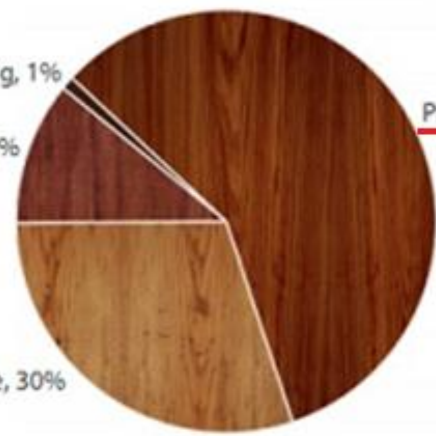
Date introduced

April 3, 2010

Climate Change

Greenhouse gas emissions have an impact on the planet's balance of land, ocean, and air temperature. Most of Apple's corporate greenhouse gas emissions come from the production, transport, use, and recycling of its products. Apple seeks to minimize greenhouse gas emissions by setting stringent design-related goals for material and energy efficiency. The chart below provides the estimated life-cycle greenhouse gas emissions for iPad.

Greenhouse Gas Emissions for iPad (Wi-Fi + 3G model)



Total greenhouse gas emissions: 130 kg CO_2e

Carbon footprint

- Public report due to market demand
- Asking for the data from suppliers
- Improvement based on the data, e.g. selection of aluminum v.s. magnesium alloy

http://www.apple.com/environment/reports/

More products, labels and certification …

working with the Carbon Trust
100g
CO2

working with the Carbon Trust
100g
CO2

Certification programs - LCA

Product Environmental Aspects Declaration
ECO LEAF
製品環境情報
http://www.jemal.or.jp

123g
CO_2

EDP

기후변화대응
100g
CO2

135g
CO2

EPD®
Climate Declaration

For assessment of resource/energy use in China

- Chinese Abiotic Deplete Potential (CADP) : based on CML-ADP$_{world}$ and adjusted by Chinese self-sufficiency ratio

$$ADP_i = \frac{DR_i}{R_i^2} \times \frac{R_{ref}^2}{DR_{ref}} \Rightarrow \boxed{CADP_i = \frac{ADP_i}{SR_i} \times \frac{SR_{ref}}{ADP_{ref}}} \Leftarrow SR_i = \frac{Prod_i}{Consump_i}$$

- CADP factors (partial)

Resource	Production (kg · yr^{-1})	Consumption (kg · yr^{-1})	SR (%)	CML-ADP$_{world}$ (kg Sb eq.)	CADP (kg Sb eq.)
Gold	2.25×10^{5}	2.25×10^{5}	100	3.61×10^{1}	4.80×10^{1}
Silver	2.00×10^{6}	1.73×10^{6}	116	8.42×10^{0}	9.67×10^{0}
Antimony	1.20×10^{8}	9.02×10^{7}	133	1.00×10^{0}	1.00×10^{0}
Tin	1.26×10^{8}	1.16×10^{8}	109	1.15×10^{-1}	1.41×10^{-1}
Vanadium	1.70×10^{7}	1.70×10^{7}	100	4.93×10^{-3}	6.56×10^{-3}
Zinc	2.55×10^{9}	2.93×10^{9}	87	3.65×10^{-3}	5.58×10^{-3}
Titanium	2.79×10^{8}	4.16×10^{8}	67	1.52×10^{-3}	3.01×10^{-3}
Fluorspar	2.70×10^{9}	1.97×10^{9}	137	2.62×10^{-3}	2.54×10^{-3}
Chromium	6.16×10^{7}	9.91×10^{8}	6	1.96×10^{-5}	4.20×10^{-4}
Rare earth	1.19×10^{8}	5.19×10^{7}	229	5.96×10^{-4}	3.30×10^{-4}
Crude oil	1.89×10^{11}	4.05×10^{11}	46.7	9.87×10^{-6}	2.81×10^{-5}
Natural gas	8.52×10^{10}	8.87×10^{10}	96	7.02×10^{-6}	9.73×10^{-6}
Iron	1.54×10^{11}	3.30×10^{11}	47	1.66×10^{-6}	4.73×10^{-6}
Coal	3.05×10^{12}	3.02×10^{12}	101	8.08×10^{-7}	1.06×10^{-6}

ECER weighting method

- A weighting method based on Chinese Energy Conservation & Emission Reduction (ECER) policy targets
- To produce a single score in LCA for decision-making

Energy conservation & emission reduction policy	2011-2015 targets	2011-2015 comparable targets (T_i)
Reduction of energy use per GDP	18%	16%
Reduction of water use per industrial add value	30%	30%
Reduction of CO2 emission per GDP	17%	17%
Reduction of SO2 emission in total	8%	34%
Reduction of COD emission in total	8%	34%
Reduction of NOx emission in total	10%	36%
Reduction of NH3-N emission in total	10%	36%
		* estimated GDP growth = 7%

ECER score:

$$S = \sum_{i=1}^{5} \frac{1}{T_i} \times \frac{A_i}{N_i}$$

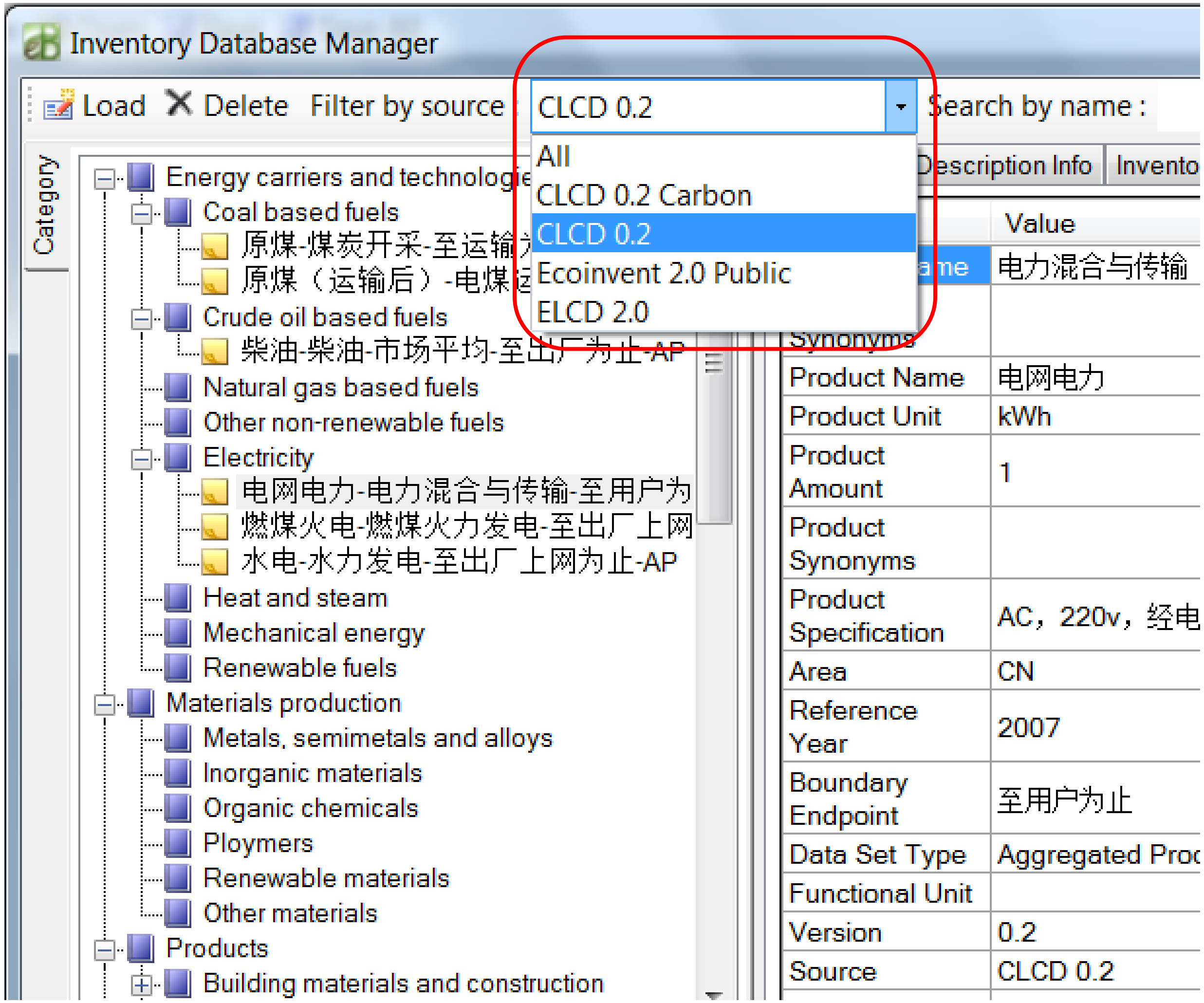
$$\Delta S = \sum_{i=1}^{5} \frac{(A_i^0 - A_i^{'})/A_i^0}{T_i} \times \frac{A_i^0}{N_i}$$

- T_i : *comparable targets (reduction rate in five years per GDP)*
- N_i : normalization references of 2010 in China
- A_i : domestic life cycle sum

CLCD & eBalance software by IKE

- CLCD & eBalance: first LCA database and software in China, released on Sept. 19, 2010
- eBalance equiped with
  - CLCD
  - Ecoinvent
  - ELCD
- Support China related LCA studies

Free download: www.itke.com.cn



CLCD 0.4 (by Aug.2011)

- > 300 unit processes and still growing ……

Sectors	Products/services
Energy	**Oil fuel:** crude oil, diesel, petrol, kerosene… **Coal fuel:** raw coal, coke… **Gas fuel:** natural gas, coke oven gas, LPG… **Electricity:** coal-fired power, hydroelectricity, grid mix… **Heat:** steam
Metal	**Ferro:** cast iron, ferroalloy, steel, alloy steel, … **Non-ferro:** aluminum, copper, zinc, lead, nickle, …
Non-metal	cement, glass, ceramic, limestone ……
Chemicals	**Inorganic:** sulfuric acid, hydrochloric acid, *nitric acid*, soda, sodium hydroxide, titanium dioxide, oxygen, nitrogen, ammonia, chlorine … **Organic:** ethylene, propylene, methanol, ethyne, resin, plastic, painting, *rubber, fibre*…
Transportation	Road, rail, inland water transportation
Waste treatment	**Waste gas treatment:** desulfurization ***Waste water treatment***

Case study: comparison of three flue gas desulfuration technologies

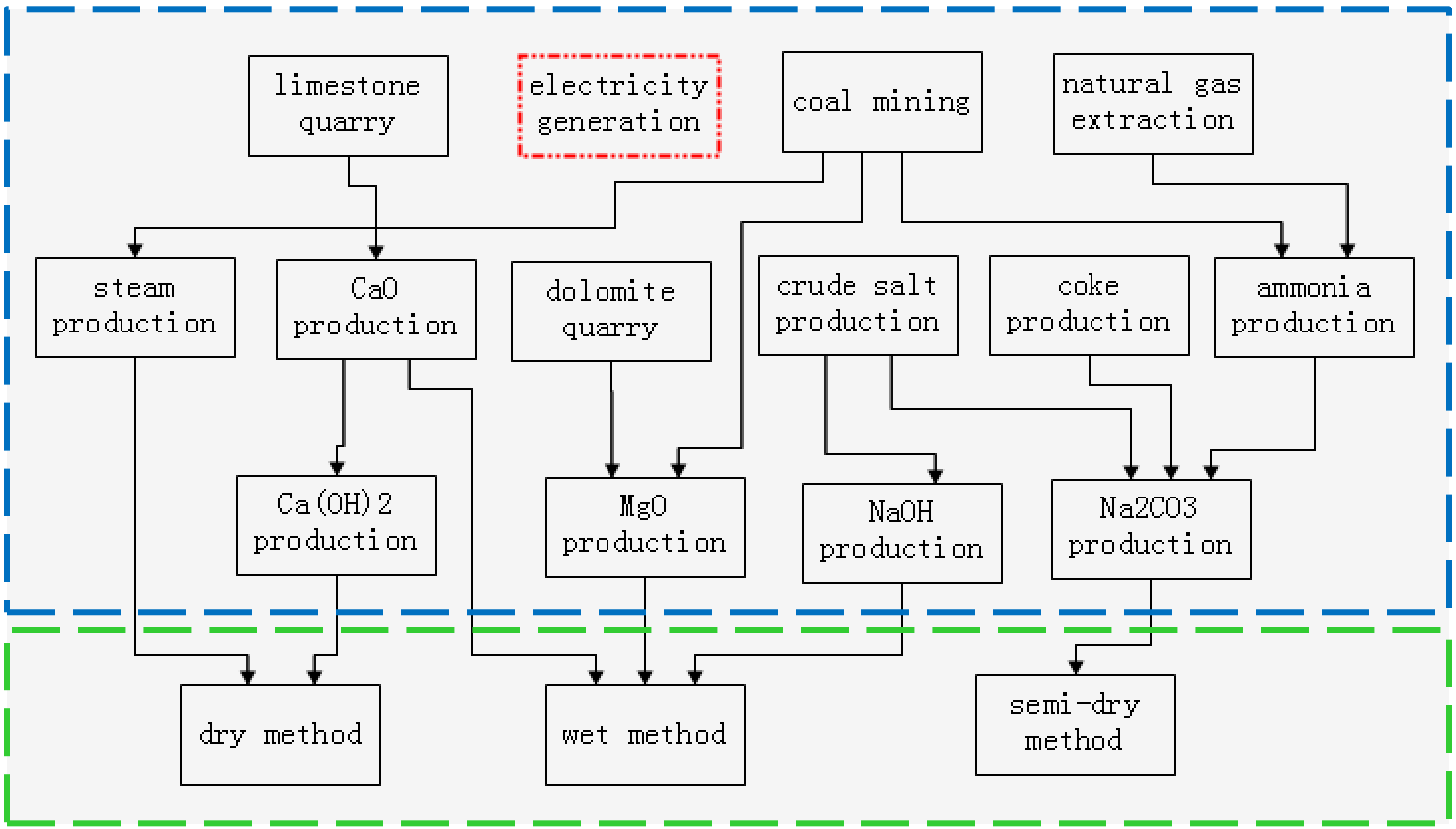
1. Select baseline and comparative schemes

- Non-desulfurization - baseline
- Dry process (Ca(OH)2)
- Wet process (MgO)
- Semi-dry process (Na_2CO_3)

Treatment of flue gas containing 1kg of SO2		Desulfurization schemes				Unit
		Non-desulfurization(baseline)	Dry process (scheme 1)	Wet process (scheme 2)	Semi-dry process (scheme 3)	
Main inventory of desulfurization technologies	Electricity	-	1.222	0.8299	1.0706	kwh
	Steam	-	1.157			kg
	Ca(OH)2	-	1.476	-	-	kg
	MgO	-	-	1.367	-	kg
	CaO	-	-	0.479	-	kg
	NaOH	-	-	0.063	-	kg
	Na2CO3	-	-	-	2.362	kg
	water	-	38.194	49.479	76.144	kg
	SO2	1	0.1	0.1	0.15	kg

2. Build up life cycle model and data collection

Investigate the consumption and emission data of desulfurization process, and trace back to the raw material production.



Secondary data were from CLCD database

Primary data were from on site investigate

(eBalance screenshots)

3. Indicators calculation and comparative analysis

Treatment of flue gas containing 1kg of SO2		Desulfurization schemes					Unit
		Non-desulfurization (baseline)	Target reached scheme	Dry process (Ca(OH)2)	Wet process (MgO)	Semi-dry (Na2CO3)	
LCA indicators	Pri. Energy	-	-	0.64	13.6	1.18	kgce
	Water use	-	-	43.8	60.8	132	kg
	GWP	-	-	2.82	9.52	5.11	kg CO2 e.
	SO2	1	0.54	0.109	0.159	0.165	kg
	COD	-	-	0.00344	0.00414	0.00604	kg
ECER	Pri. Energy	-	-	1.20E-12	2.56E-11	2.22E-12	-
	GWP	-	-	2.01E-12	6.81E-12	3.66E-12	-
	SO2	6.89E-11	3.72E-11	7.50E-12	1.10E-11	1.13E-11	-
	COD	-	-	5.31E-13	6.39E-13	9.33E-13	-
	Water use	-	-	1.13E-12	1.58E-12	3.41E-12	-
	Overall inde	6.89E-11	3.72E-11	1.24E-11	4.56E-11	2.16E-11	-
Improvement (%)			46%	82.0%	33.8%	68.7%	-

Conclusion:

- dry process < semi-dry process << wet process
- wet process failed to reach the political targets due to MgO use

4. Improvement analysis – identify cause and improvement direction

- Contribution analysis: of processes and impact categories. Which are the main contributors?

Desulfurization technology	Process	Pri. Energy use	Water use	GWP	SO2	COD	Overall ECER
Wet process	Desulfurization	0(0.0%)	1.28E-12(2.8%)	0(0.0%)	6.89E-12(15.1%)	0(0.0%)	**8.17E-12(17.9%)**
	Electricity generation	5.97E-13(1.3%)	7.07E-14(0.2%)	6.31E-13(1.4%)	3.85E-13(0.8%)	3.12E-13(0.7%)	**2.00E-12(4.4%)**
	MgO production	2.48E-11(54.4%)	2.09E-13(0.5%)	5.81E-12(12.7%)	3.66E-12(8.0%)	2.88E-13(0.6%)	**3.48E-11(76.3%)**
	CaO production	1.32E-13(0.3%)	6.92E-15(0.0%)	3.37E-13(0.7%)	1.53E-14(0.0%)	2.49E-14(0.1%)	**5.16E-13(1.1%)**
	NaOH production	2.66E-14(0.1%)	6.27E-15(0.0%)	3.45E-14(0.1%)	1.71E-14(0.0%)	1.39E-14(0.0%)	**9.84E-14(0.2%)**
	Total	**2.56E-11(56.1%)**	**1.58E-12(3.5%)**	**6.81E-12(14.9%)**	**1.10E-11(24.1%)**	**6.39E-13(1.4%)**	**4.56E-11(100.0%)**

- Sensitivity analysis: which is most efficient factor to be improved?
- Improvement potential analysis: considering actual room for improvement
- Feasibility analysis: combining with technical, economy/cost, even social considerations

Conclusions

- All materials and processes have environmental impacts along their life cycle that should be reduced.
- But environmental assessment is missing in MSE at large.
- Theoretically, LCA provides the best framework for assessing the potential environmental impacts of materials.
- In practice, LCA is getting mature and ready in terms of database, tools and application.
- Moreover, market-based mechanism is forming.
  - More and more often, LCA is driven by industry, market, even funding agency.

LCA is ready for environmental impact assessment in MSE !

Suggestions

- Research: More demonstrative examples should be explored.
- Education: Textbook and curriculum for MSE education are needed.
- Cooperation with industry and market.

From a pragmatic viewpoint, environmental consideration is changing the definition of materials, there are many to be explored in MSE in order to contribute to a sustainable world.

Biographical summary

Duan WENG

- Professor in Department of Materials Science and Engineering, Tsinghua Univesity, 1995 - present;
- Executive Member of CMRS, 2003 - present;
- Executive Member of International Society for Industrial Ecology, 2004 - 2007;
- Chair of World Recycling Forum, 2005 to 2011 annually;
- Chair of Chinese Life Cycle Management Conference, 2009
- Member of UNEP Resource Panel (special in the program “Environmental Impact of Metals” , 2009 – present;

Biographical summary

Hongtao WANG

- Associate Professor , School of Architecture and Environment, Sichuan University;
- Co-chair, Capacity Development in UNEP/SETAC Life Cycle Initiative;
- Steering committee member, UNEP/SETAC Global Guidance for LCA database;
- Chinese Technical Responser, International Life Cycle Reference Data System (ILCD) with European Commission, Joint Research Center;
- Organizer of Chinese Life Cycle Management Conference;
- UNEP/SETAC LCA Award, first place winner for LCA project in developing and emerging countries, 2009;

谢　谢！

Thank You for Your Attention!

IN TOUCH WITH TOMORROW