Sustainable Nanoproducts through Life Cycle Thinking and Life Cycle Assessment

Sustainable Nanotechnology Conference 2015

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Content of presentation

- Background
- Which kind of nanoapplications we need in future to realise high environmental (sustainable) benefits?
- Nanotechnologies and Environment / Environmental Nano-Innovations
- Comparative Life Cycle Assessment of Nano Innovations: case studies
  - Environmental impact of nanomaterials
  - Environmental impact of nanotechnological based applications

- Faculty 4: Production Engineering
  - Strong focus on material sciences
  - Half of the 20 research groups are active in materials research including nanotechnology
- Department 10: Technological design and development
  - Dealing with issues relating to health, safety and environment. We follow the general approach of shaping technologies oriented at guiding principles (learning from nature: Biomimetics, Industrial Ecology, Resilience).
  - Key topics of the research group on new technologies such as nanotechnologies and synthetic biology
  - More than ten years experience in the field of nanotechnologies
    - EU FP7 Project SUN 2013-2017
    - EU FP7 Project GreeNanoFilms 2014-2017
    - EU FP7 Project NanoSustain, 2010-2013
    - Part of the graduate school nanoToxCom (=Toxic combination effects of synthesized nanoparticles) at the University of Bremen, 2009-2013
    - Ecological profile of selected nanotechnological applications, funded by the Nagano Techno Foundation, of Nagano City, Japan, 2009-2010
    - Environmental Relief Effects through Nanotechnological Processes and Products, funded by the Federal Environmental Agency, Dessau, 2007-2008
    - Sustainability effects through production and application of nanotechnological products, funded by the German Ministry of Education and Research (GMER), Bonn, 2002 – 2004
    - Nanotechnology and Regulation within the framework of the precautionary principle, funded by Scientific and Technological Options Assessment (STOA) of the EU, Brüssel, 2003 – 2004
    - Potential Applications of Nanotechnology based materials, Part 2: Analysis of ecological, social and legal aspects, funded by the Office of Technology Assessment at the German Bundestag, 2002
    - Active participation in German Enquete-, Risk-, NanoCommission

Nanotechnologies and Environment

Reasonable Expectations for Environmental Innovations

Top down Nanotechnologies – Materials (increased control)

- Miniaturisation (dematerialisation)
- Designing materials (avoiding additives and alloys)
- Designing materials (wear resistant, anti-corrosive, lubrication free..)
- Designing surfaces (self-clean, thin film (organic) solar cells …)
- Catalysis (atom efficiency, specifity)
- Substitution of hazardous substances

Problems in a life-cycle view

- Material and energy input for materials purification (waste) and controlled sizes and structures (basic conditions)
- Use of ‘hazardous’ materials (cadmium selenide, lead telluride, gallium arsenide) and hazards from nanoparticles

Nanotechnologies and Environment

Reasonable Expectations for Environmental Innovations

Bottom up Nanotechnologies - Materials

(letting things grow)

- Self-organising molecules and materials (fullerenes, CNTs)
- Smart materials
- Biomimetic materials (synthetic bones, teeth, nacre; bionic adhesives and bonding)
- Self-healing materials

Problems in a life-cycle view

- Use of ‘hazardous’ materials (fullerenes, CNTs)
- Hazards from shift from self-organisation to self-replication

Environmental Nano-Innovations

Typology

End-of-pipe-technologies

- **Pollution control** (filters, membranes, catalysts)
- **Recovery and recycling** (filters, membranes, catalysts, particles)
- **Remediation** (particles)

Integrated solutions (processes, products)

- **Material choice and design for resource efficiency and recycling** (smart materials, coatings)
- **Substitution of hazardous substances** (flame retardant materials)
- **Energy conversion and efficiency** (photovoltaic, fuel cell, hydrogen storage, insulation, light weight construction, lighting and displays)

Comparative Life Cycle Assessment of Nano Innovations

- We need at an early stage of innovation (research and development) of new sustainable nanoproducts
  - prospective information to environmental impacts of nanomaterials and to environmental benefits of nanoproducts
    → (prospective) Life Cycle Assessment
  - information to risk potentials of nanoproducts
    → (preliminary) Risk Assessment, precautionary Risk Management

- Life Cycle Assessment (LCA) is the most extensively developed and standardized methodology for assessing environmental impacts of a product

- Risk aspects, particularly in dealing with nanomaterials, are examined in form of a preliminary assessment

Life Cycle Assessment of nanotechnology-based applications

- What is the environmental impact of the production of nanomaterials?
- What is the influence of these nanomaterials on the environmental impact of new (prospective) applications?
- Which kind of applications we need in future to realise high environmental (sustainable) benefits?

Life Cycle Assessment of the selected nanoproducts and associated materials

- First focus: “Cradle-to-gate” Life Cycle Assessment of selected nanomaterials (MWCNT, nanoZnO, nanoTiO2, Nanocellulose, …) with functional unit: 1kg nanomaterial

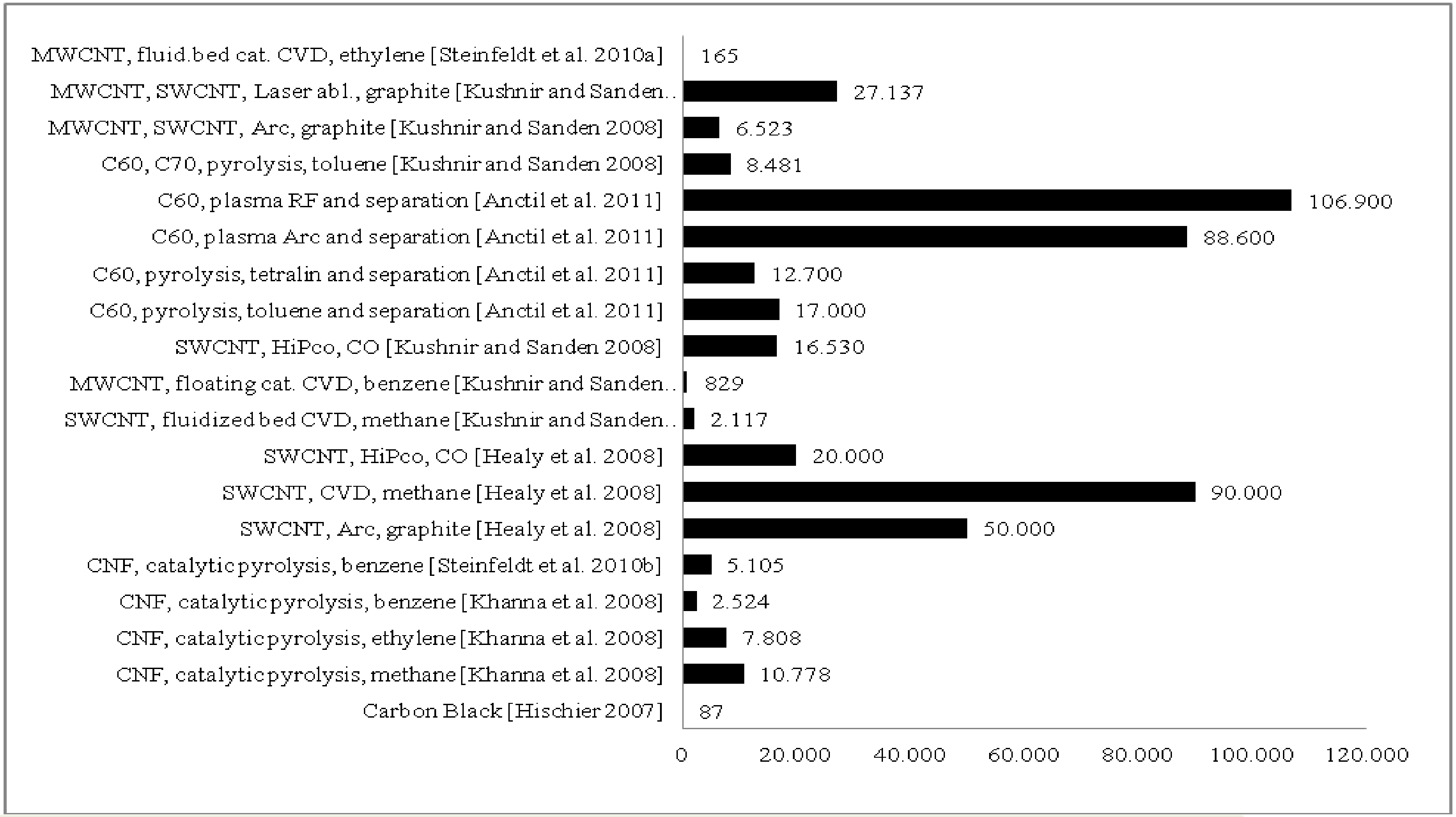
- Second focus: “Cradle-to-grave” (prospective) Life Cycle Assessment of different nanotechnological based applications with functional unit: x kg Nanoproduct
  - In part several production routes
  - Modeling with release factors (Source: REACH/ECHA-Documents (Chapter R.16: Environmental Exposure Estimation, Chapter R.18: Exposure scenario building and environmental release estimation for the waste life stage), ESD, SPERCs ...)
  - Compared to conventional materials/applications

Overview of studies of published LCAs of the manufacture of nanoparticles and nanocomponents

- only 35 publications: "LCA" of Nano-Applications
- only 15 publications: "LCA" of the manufacture of nanoparticles and nanocomponents

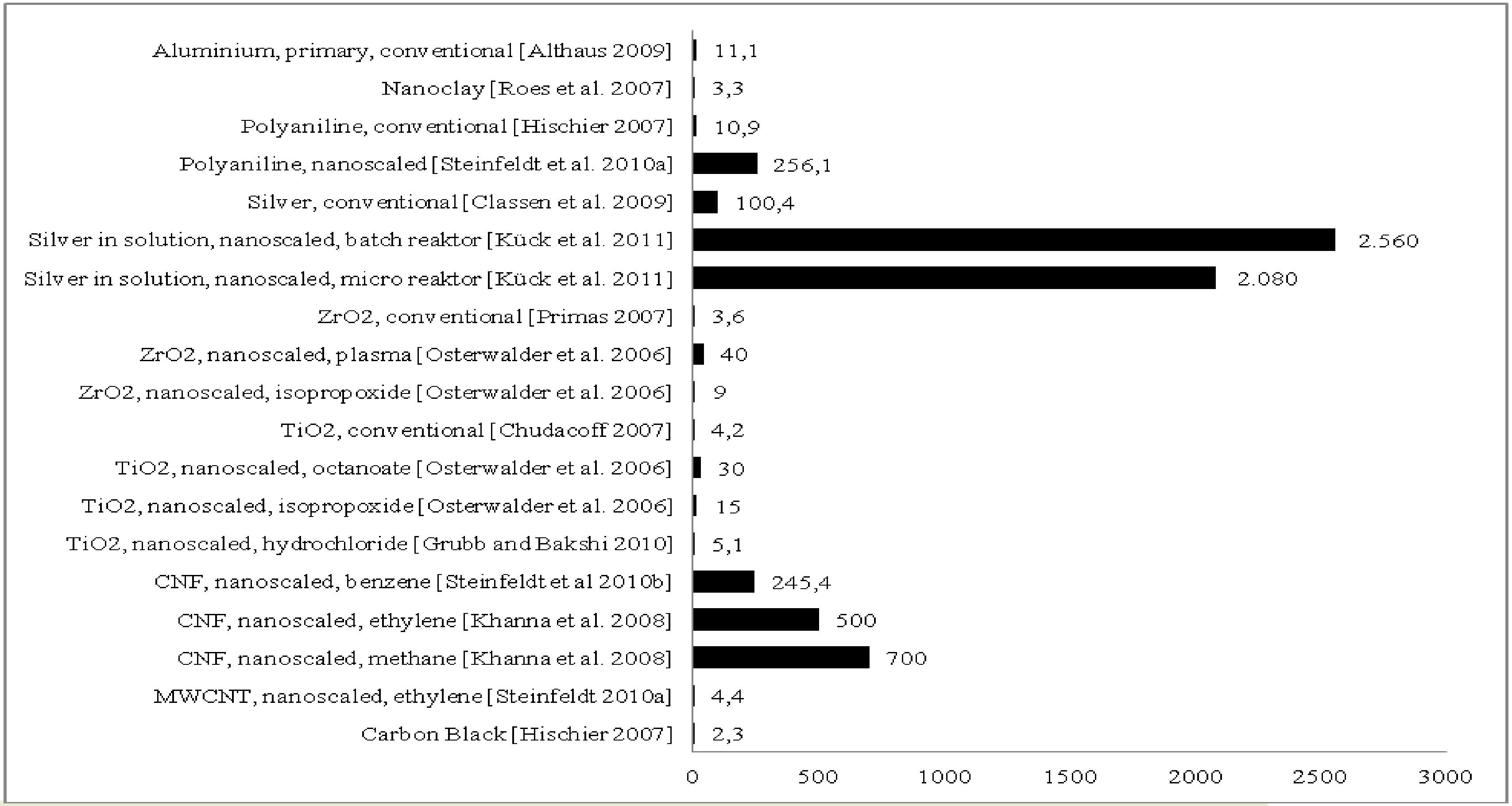
Nanoparticle and/or nanocomponent	Assessed impact(s)	References
Metal nanoparticle production (TiO_2, ZrO_2)	Cradle to gate energy assessment, global warming potential	(Osterwalder, N., Capello, C., Hungerbühler, K. and Stark, W.J. 2006)
Nanoclay production	Cradle to gate assessment, energy use, global warming potential, ozone layer depletion, abiotic depletion, photochemical oxidant formation, acidification, eutrophication, cost	(Roes, A., Marsili, E., Nieuwlaar, E. and Patel, M. K. 2007)
Several nanomaterial syntheses	E-factor Analysis	(Eckelman, M.J., Zimmerman, J.B. and Paul T. Anastas, P.T. 2008)
Carbon nanoparticle production	Cradle to gate energy assessment	(Kushnir, D. and Sandén, B. A. 2008)
Carbon nanotube production	Cradle to gate assessment with SimaPro software, energy use, global warming potential, …	(Singh, A., Lou, H.H., Pike, R.W., Agboola, A., Li, X., Hopper, J.R. and Yaws, C.L. 2008)
Single-walled carbon nanotube (SWCNT) production	Cradle to gate assessment with SimaPro software, energy use, global warming potential, …	(Healy, M. L., Dahlben, L. J.and Isaacs, J. A. 2008)
Carbon nanofiber production	energy use, global warming potential, ozone layer depletion, radiation, ecotoxicity, acidification, eutrophication, land use	(Khanna, V., Bakshi, B. R. and Lee, J. 2008)
Nanoscale semiconductor	Cradle to gate assessment, energy use, global warming potential	(Krishnan, N., Boyd, S., Somani, A., Raoux, S., Clark, D. and Dornfeld, D. A. 2008)
Nanoscaled polyanilin production	Cradle to gate assessment with Umberto software, energy use, global warming potential, …	(Steinfeldt, M., von Gleich, A., Petschow, U., Pade, C. and Sprenger, R.U. 2010)
Multi-walled carbon nanotube (MWCNT) production	Cradle to gate assessment with Umberto software, energy use, global warming potential, …	(Steinfeldt, M., von Gleich, A., Petschow, U., Pade, C. and Sprenger, R.U. 2010)
Nanoscaled Titanium dioxide	Cradle to gate assessment, Ecoindicator 99 methodology, energy use, exergy	(Grubb, G.F. and Bakshi, B. R. 2010)

Comparison of the cumulative energy requirements for various carbon nanoparticle manufacturing processes (MJ-Equivalent/kg material; in parts own calculation)



Source: Steinfeldt (2014)

Comparison of the global warming potential for the production of various conventional and nanoscaled materials (CO_2-Equivalent/kg product; in parts own calculation)



Source: Steinfeldt (2014)

Case study 1: Nano-ZnO UV-Barrier glass coating, pro.Glass Barrier 401

The benefit of the Nano-ZnO glass coating pro.Glass Barrier 401 from Nanogate AG is the possible longer service life time of the product in comparison with other organic UV-Barrier coatings.

Variants

	Functional unit
NanoZnO UV-Barrier glass coating LC	100 m² coated glass
Conv. product LC1	100 m² coated glass
Conv. product LC1.25	125 m² coated glass
Conv. product LC1.5	150 m² coated glass

Gradle to grave - LCA

Preproduction of the raw materials

New Nano-ZnO production or conventional ZnO or organic UV-light barrier production

Enabled product fabrication, pro Glass Barrier 401 Manufacture of the coating, Coating application

Use phase

Recycling/Disposal

Case study 1: Nano-ZnO UV-Barrier glass coating, pro.Glass Barrier 401

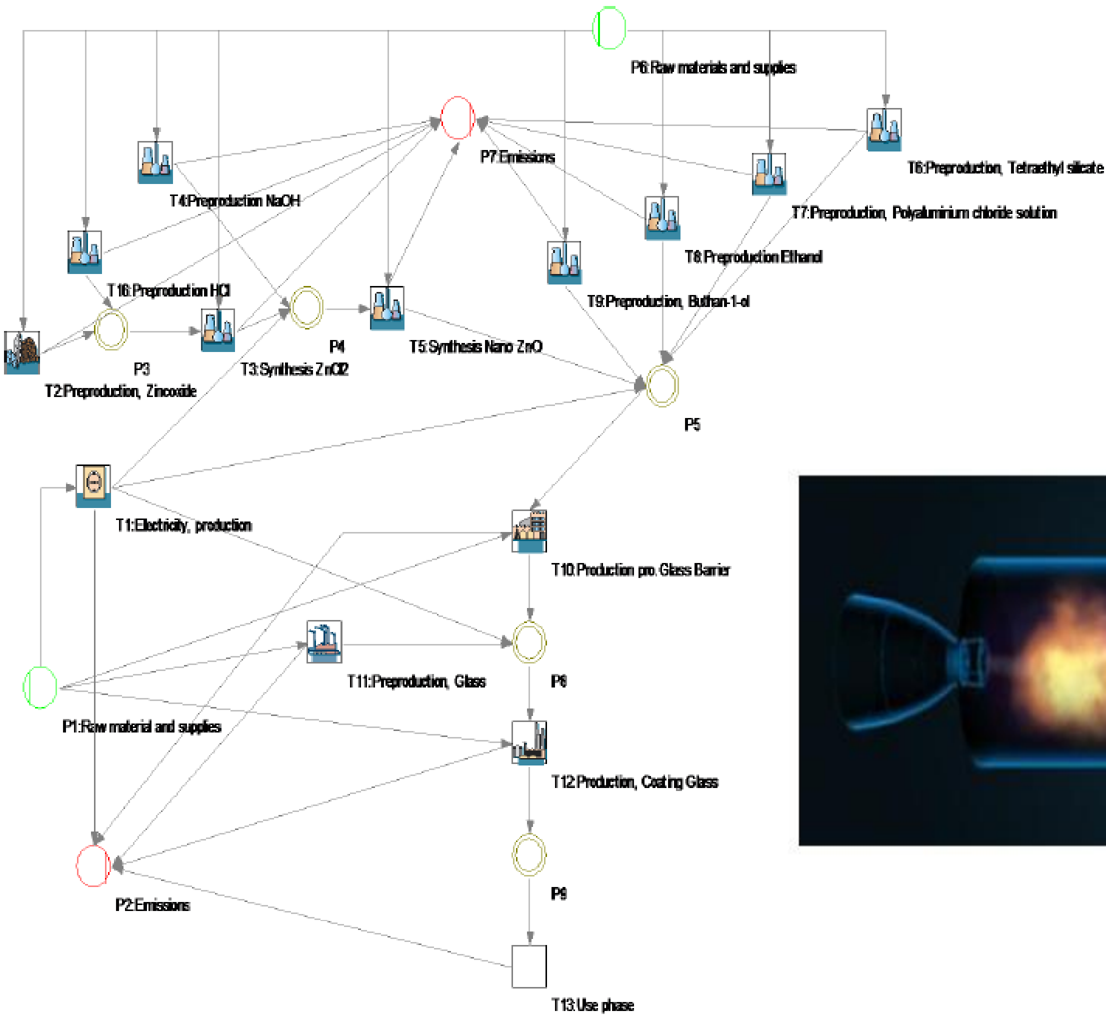


Figure 12: Process model of the nanoscaled application in Umberto for the case study "UV-Barrier for glass"

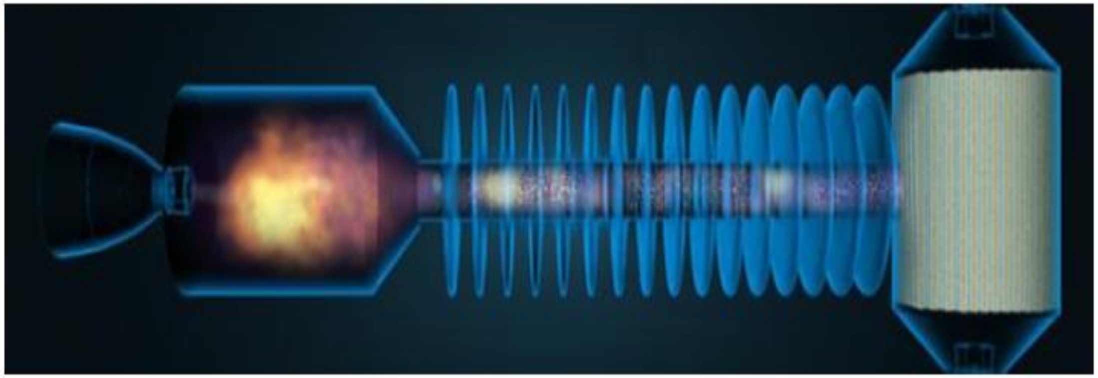


Figure 11: Model of pulsation reactor[11]

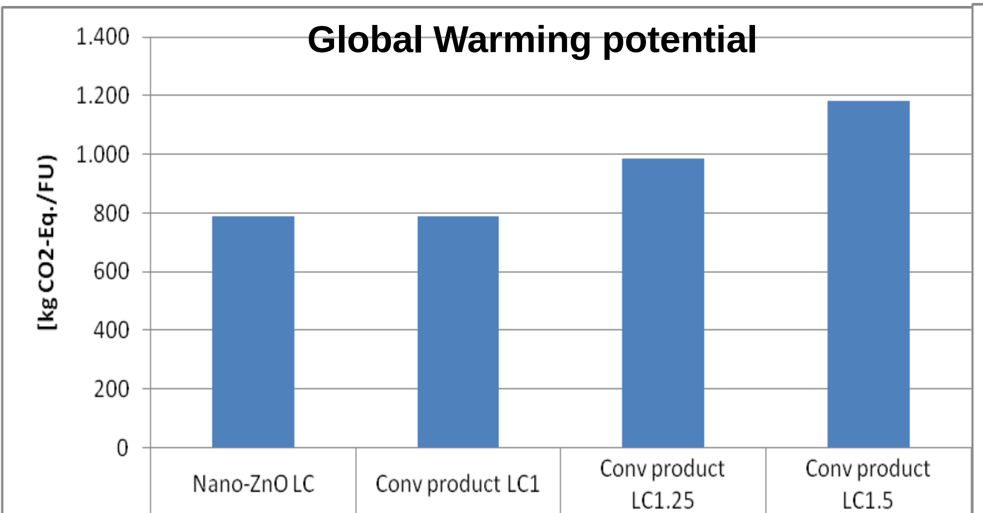
Case study 1: Nano-ZnO UV-Barrier glass coating, pro.Glass Barrier 401

Environmental impacts of the production of 1 kg material

Environmental impact	Unit	Conv. ZnO	Nano-ZnO Pulsation	Nano-ZnO Flame pyrol.
Cumulative energy demand	MJ-Eq/kg	51,36	474,27	3.079,95
Global warming potential 100a	kg CO2-Eq/kg	2,889	21,002	151,397
Acidification potential, average European	kg SO2-Eq	0,003	0,119	0,675
Eutrophication potential, average European	kg PO4-Eq	0,001	0,068	0,432
Human Tox potential, 100a not nanospecific	kg 1,4-DCB/kg	0,582	8,647	41,701
Marine aquatic ecotoxicity, 100a not nanospecific	kg 1,4-DCB/kg	1,498	45,674	265,785

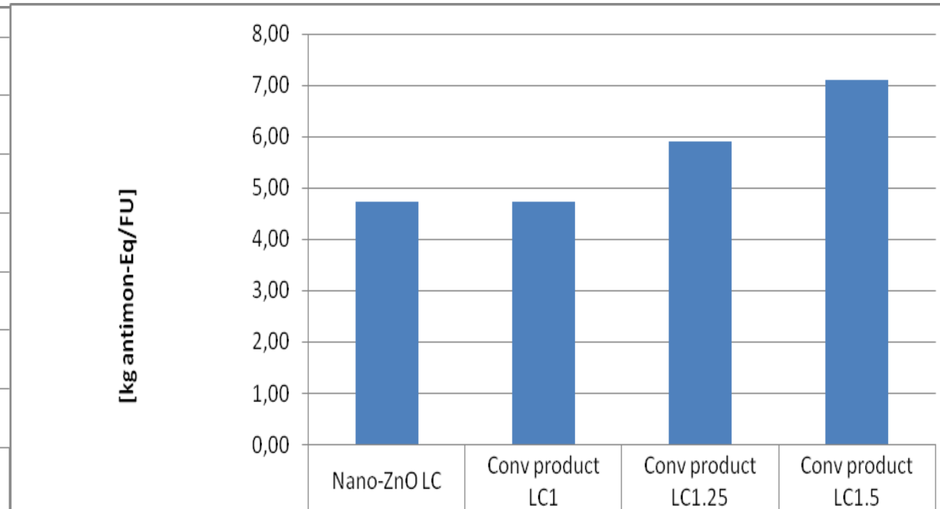
Case study 1: Nano-ZnO UV-Barrier glass coating, pro.Glass Barrier 401

GWP of 'Conv product LC1.25' is 25,01% higher than the Nano-ZnO product



	Nano-ZnO LC	Conv product LC1	Conv product LC1.25	Conv product LC1.5
GWP 100a	788,24	788,33	985,42	1.182,50

Depletion of abiotic recources



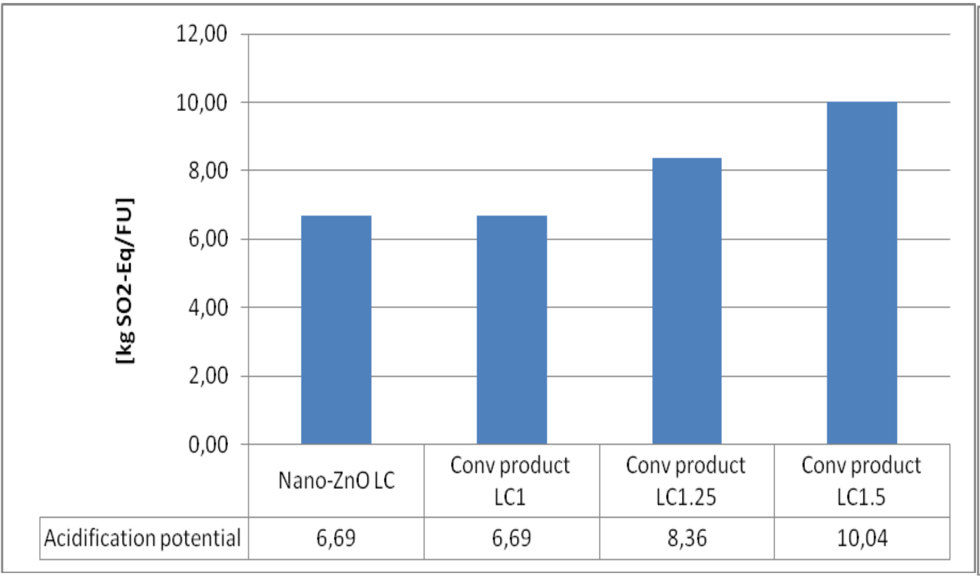
	Nano-ZnO LC	Conv product LC1	Conv product LC1.25	Conv product LC1.5
Depletion of abiotic resources	4,72	4,73	5,91	7,10

The environmental impact through nano-ZnO (production of nanoZnO, preproduction of the materials etc) has a extremely small influence of the balance. A cause for this is the small thickness of the coating of twice 1.6 µm in relation to the 3 mm thick glass

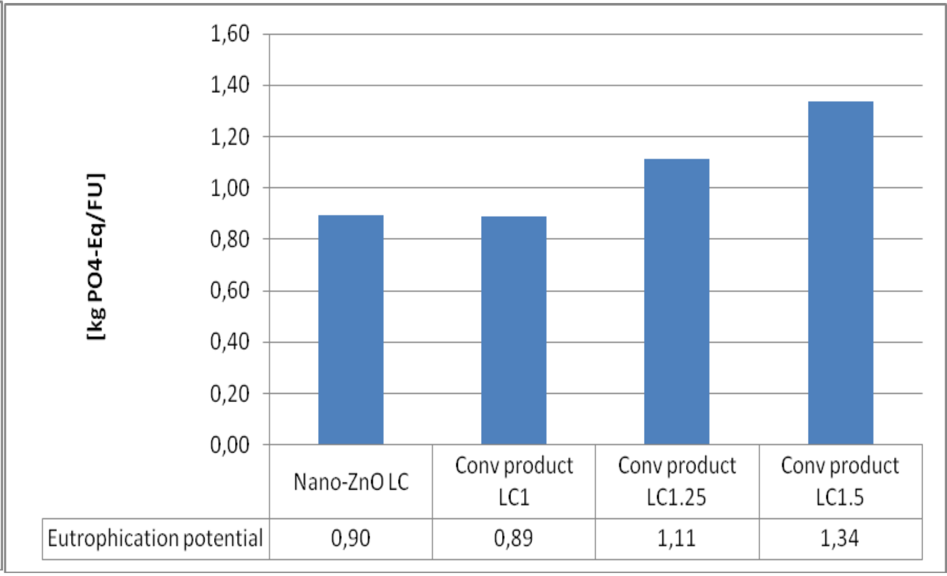
Case study 1: Nano-ZnO UV-Barrier glass coating, pro.Glass Barrier 401

The eutrophication potential of the scenario “Conv. product LC1.25” is 24,31% higher than the scenario “Nano-ZnO product”

Acidification potential



Euthrophication potential



Case study 1: Nano-ZnO UV-Barrier glass coating, pro.Glass Barrier 401

Global warming potential [kg CO2-Eq./100 m2 Glas]

	Acetic acid	Electricity	Tap water	Burdens	Zinc, primary	Ethanol	Butane-1,4-diol	Aluminiumhyd.	Silicontetrachl.	Hydrochloric acid	Flat glass	Disposal, 1	Disposal, 2
■	0.58	11.28	0.00	0.03	0.69	5.76	1.04	0.14	0.34	0.07	979.76	2.72	3.14

The environmental impact through nano-ZnO (production of nano-ZnO, preproduction of the materials etc) has a very low influence of the balance.

Case study 2: Prospective Nanocellulose application as paper additive in kraft paper

The possible benefit of Nanocellulose as paper additive is an increase of the strength and modulus of the paper.

Variants

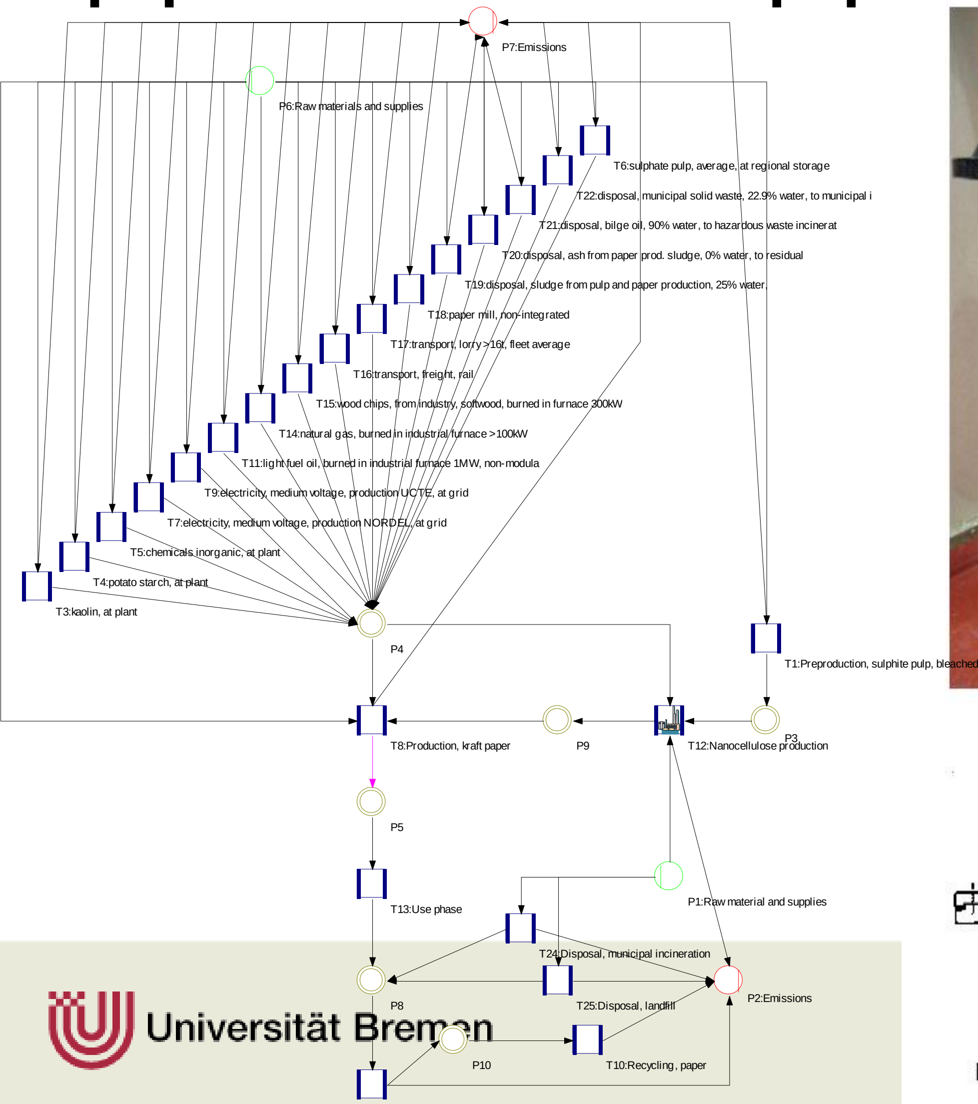
	Functional unit
Kraft paper LC old	1000 kg
Kraft paper LC new, 0% weight reduction	1000 kg
Kraft paper LC new, 5% weight reduction	950 kg
Kraft paper LC new, 10% weight reduction	900 kg

Important input data / assumption:
Consistency of bleached birch pulp: 2 %
Electric energy input: 0.1 kWh/kg wet material
Manufacturing yield: 85%
Nanocellulose substitution rate: 5% by weight

Gradle to grave - LCA

- **Preproduction of raw materials**
- **New nanocellulose production or conventional cellulose production**
- **Application production (kraft paper)**
- **Use phase**
- **Recycling / Disposal of kraft paper**

Case study 2: Prospective Nanocellulose application as paper additive in kraft paper



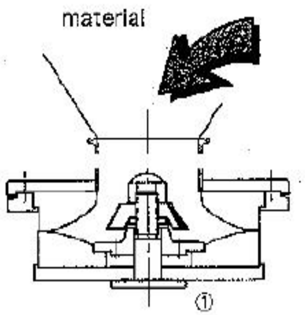


Figure 5: Manufacturing of nanocellulose: Operation Principle of Masuko Grinder with grind stone[7]

Case study 2: Prospective Nanocellulose application as paper additive in kraft paper

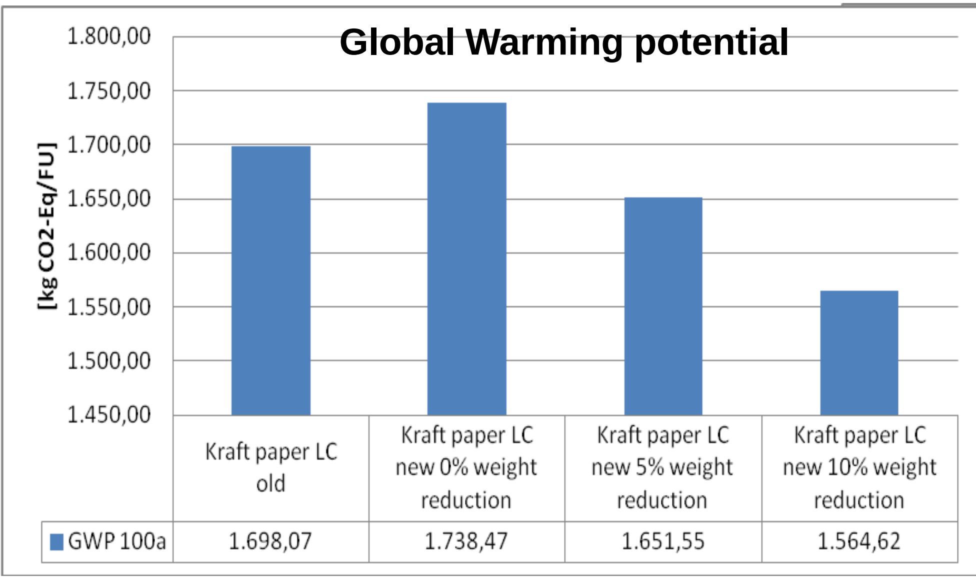
Environmental impacts of the production of 1 kg material

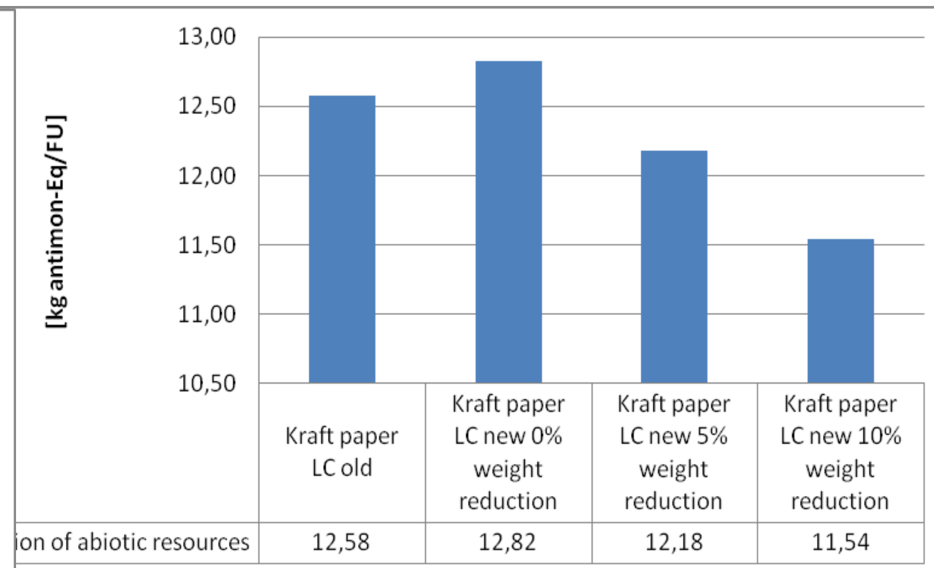
Environmental impact	Unit	Conventional Sulfite pulp	Nanocellulose UPM	Nanocellulose SUNPAP HPH	Nanocellulose SUNPAP CAV
Cumulative energy demand	MJ-Eq/kg	69,922	131,298	155,264	124,837
Global warming potential 100a	kg CO_2-Eq/kg	0,514	1,608	2,354	1,731
Depletion of abiotic resources	kg Antimon-Eq/kg	0,003	0,010	0,016	0,012
Acidification potential, average European	kg SO_2-Eq	0,010	0,015	0,021	0,019
Eutrophication potential, generic	kg PO_4-Eq	0,003	0,005	0,008	0,007
Summer smog potential	kg ethylen/kg	8,72E-05	1,62E-04	2,28E-04	1,91E-04
Stratospheric ozone depletion 10a	kg CFC-11-/kg	4,80E-08	1,29E-07	2,27E-07	1,81E-07
Human Tox potential, 100a not nanospecific	kg 1,4-DCB/kg	0,434	0,845	1,288	1,080
Marine aquatic ecotoxicity, 100a not nanospecific	kg 1,4-DCB/kg	0,890	1,678	3,239	2,848

Case study 2: Prospective Nanocellulose application as paper additive in kraft paper

Improvement of the GWP for scenario “Kraft paper LC new 10% weight reduction” is around 7

Depletion of abiotic recources



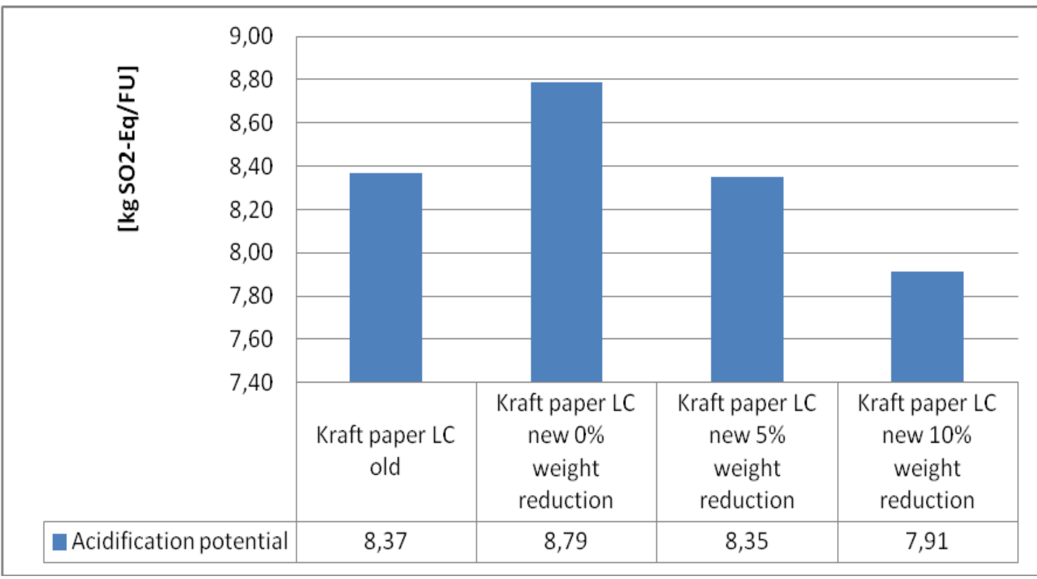


The production of Nanocellulose has a significant influence at the balance. The global warming potential would increase 2,4% without the benefit of a possible reduction in weight.

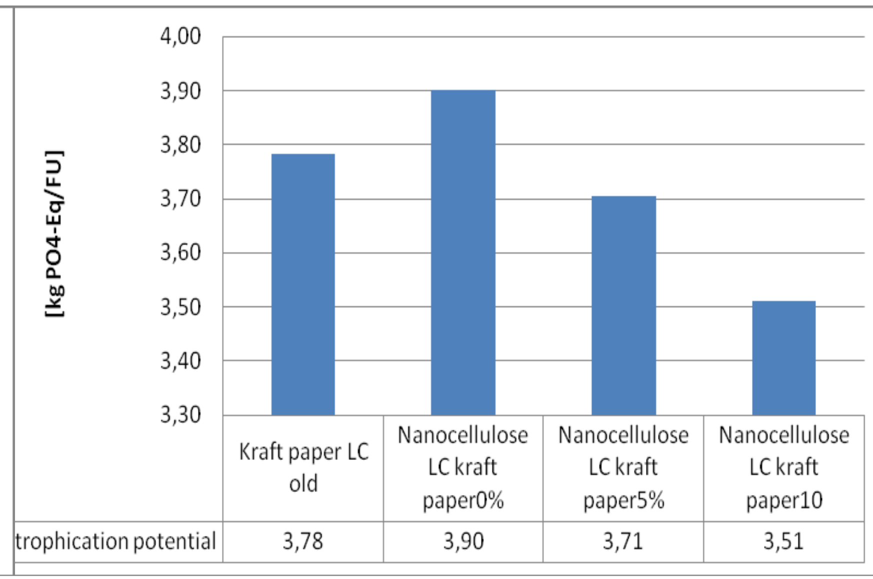
Case study 2: Prospective Nanocellulose application as paper additive in kraft paper

The improvement of the eutrophication potential for scenario "Kraft paper LC new 10% weight reduction" is around 8,2%

Acidification potential



Euthrophication potential



Case study 3: Prospective CNT Composite material, e.g. as rotor blades of wind power plant

The possible benefit of the prospective MWCNT composite material is an increase of the production product reliability and lifetime.

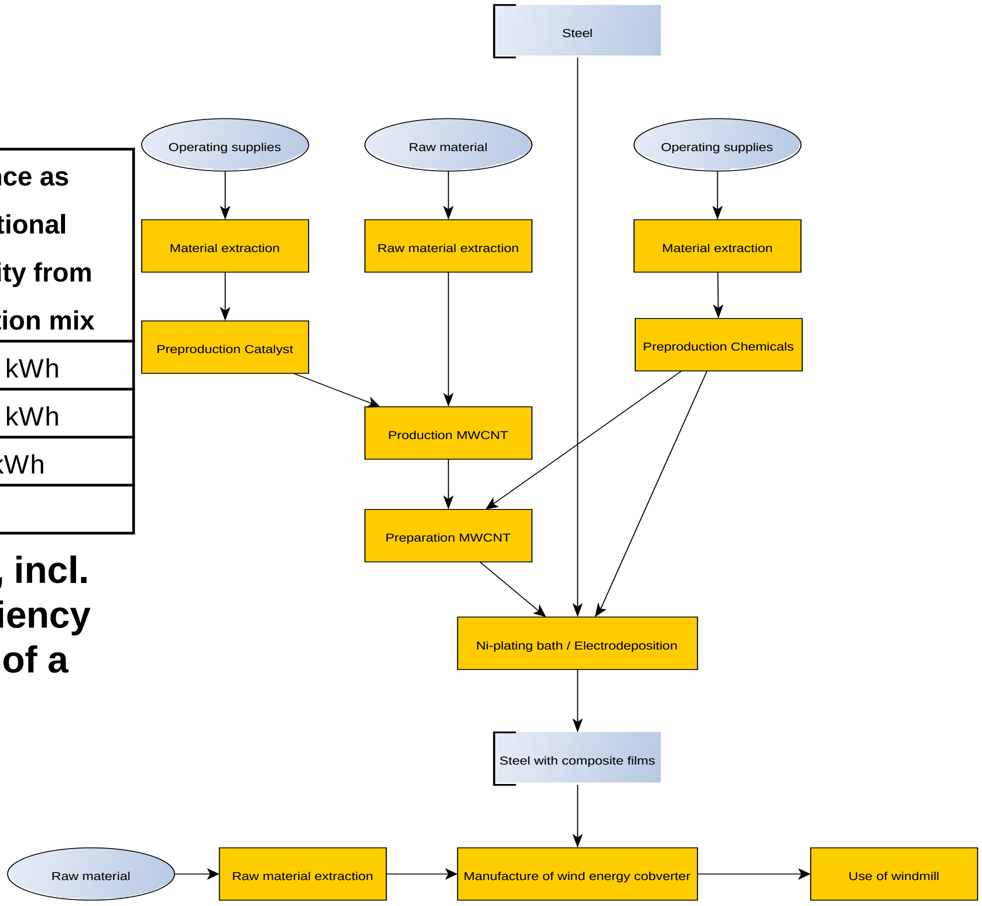
Variants

Name	Increase of the energy production efficiency	Energy yield of the wind power plant, 2MW, offshore	Difference as conventional electricity from production mix
WPP old	-	105.200.000 kWh	177.800 kWh
WPP new0,05	0,05%	105.252.600 kWh	105.200 kWh
WPP new0,1	0,1%	105.305.200 kWh	52.600 kWh
WPP new0,15	0,15%	105.377.800 kWh	---

System boundaries incl. MWCNT production, incl. benefit/credit through increased energy efficiency
Functional unit: prognosticated energy yield of a wind-power plant

Important assumption:
CNT content rate: 0,5% (150kg/WPP)

System limits for the comparative life cycle assessment



Case study 3: Prospective CNT Composite material, e.g. as rotor blades of wind power plant

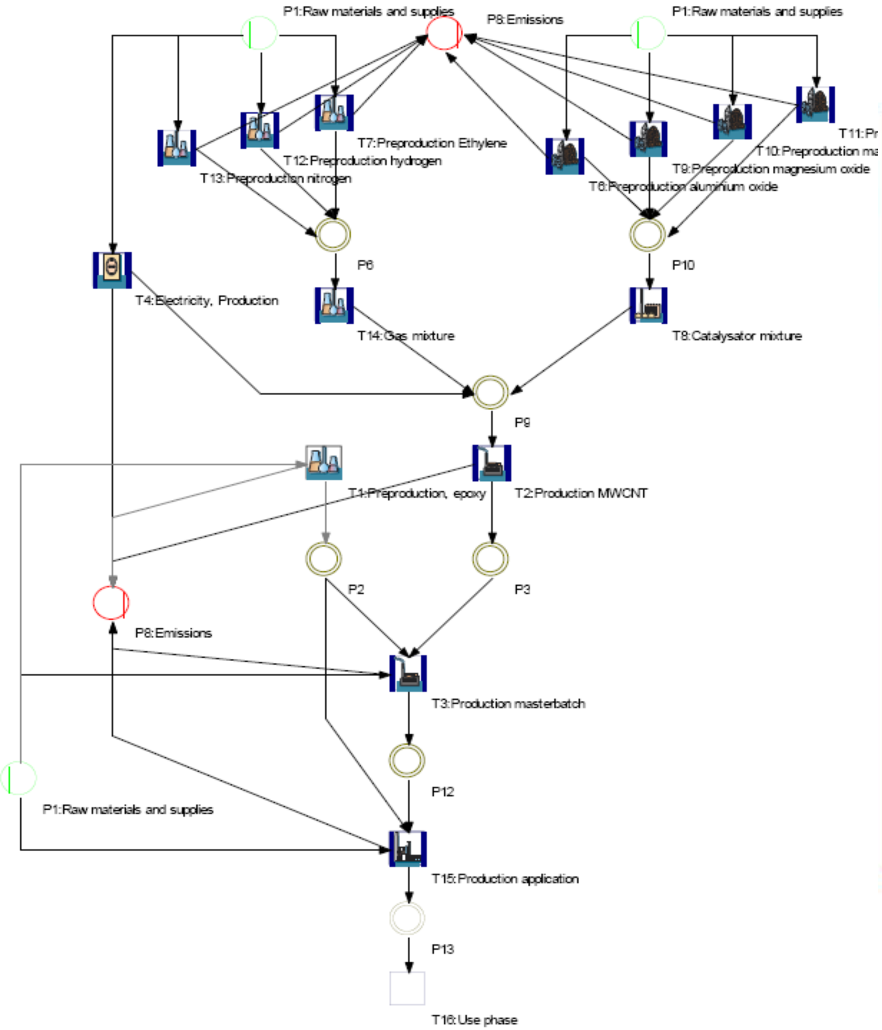


Figure 16: Process model of the nanoscaled application in Umberto for the case study "MWCNT in epoxy plates"

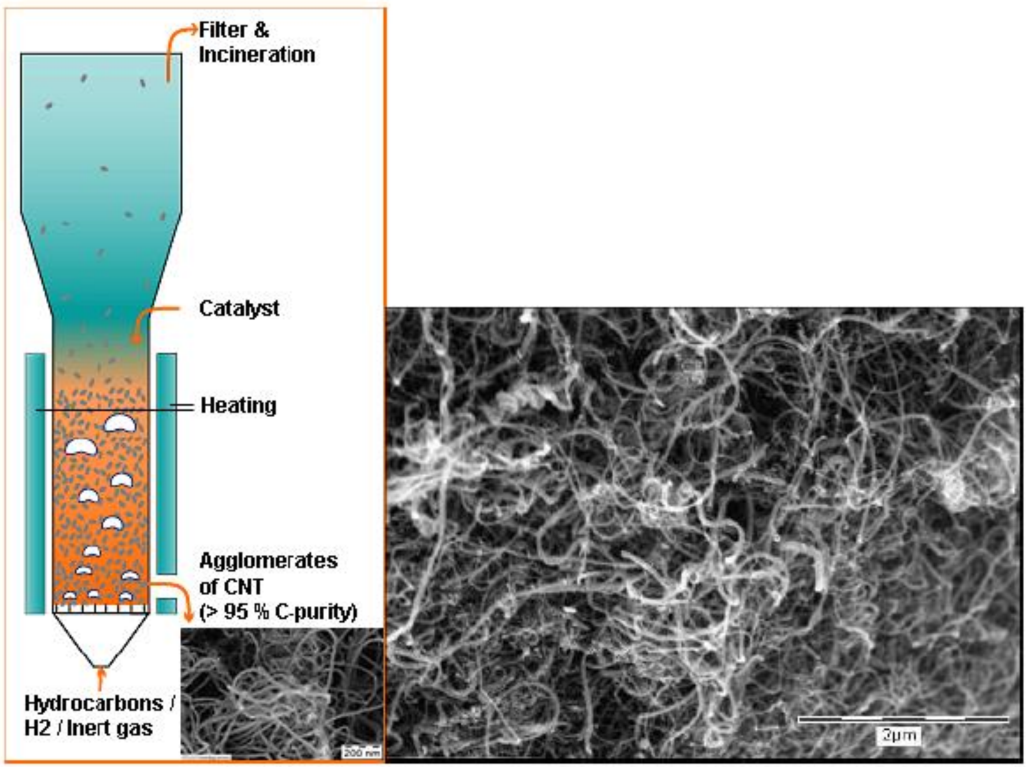
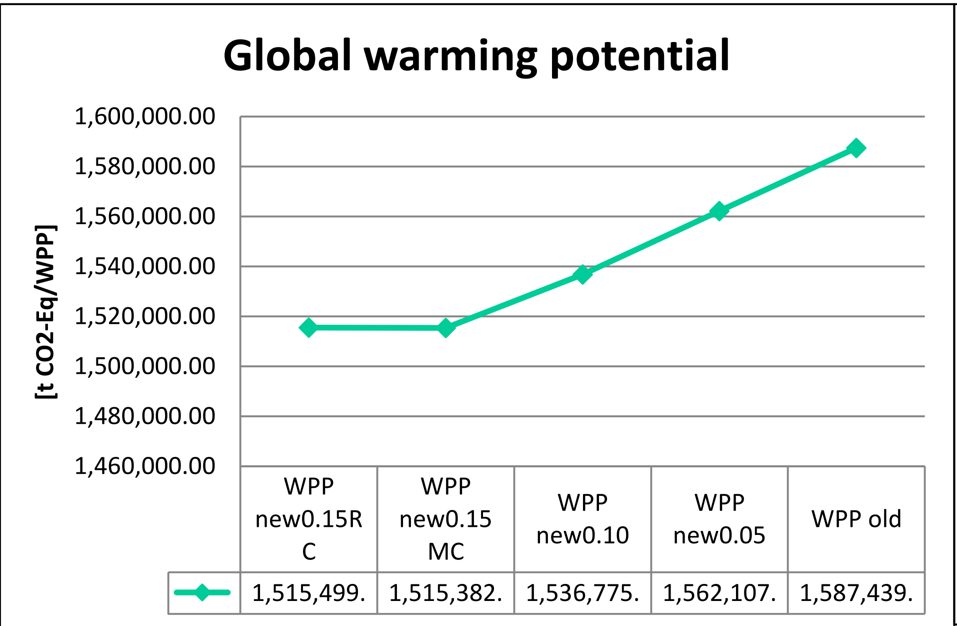


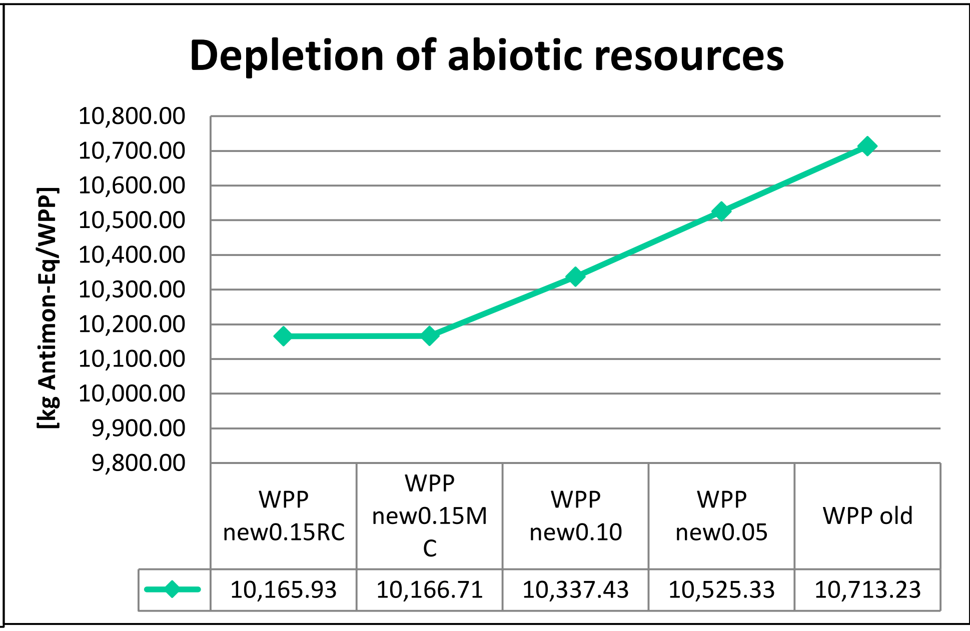
Figure 14: The fluidized bed Baytubes® process[14]

Case study 3: Prospective CNT Composite material, e.g. as rotor blades of wind power plant

WPP new0.15 versus WPP old : improvement around ca. 5,5%;

WPP new0.15 versus WPP old : improvement around ca. 5,1%

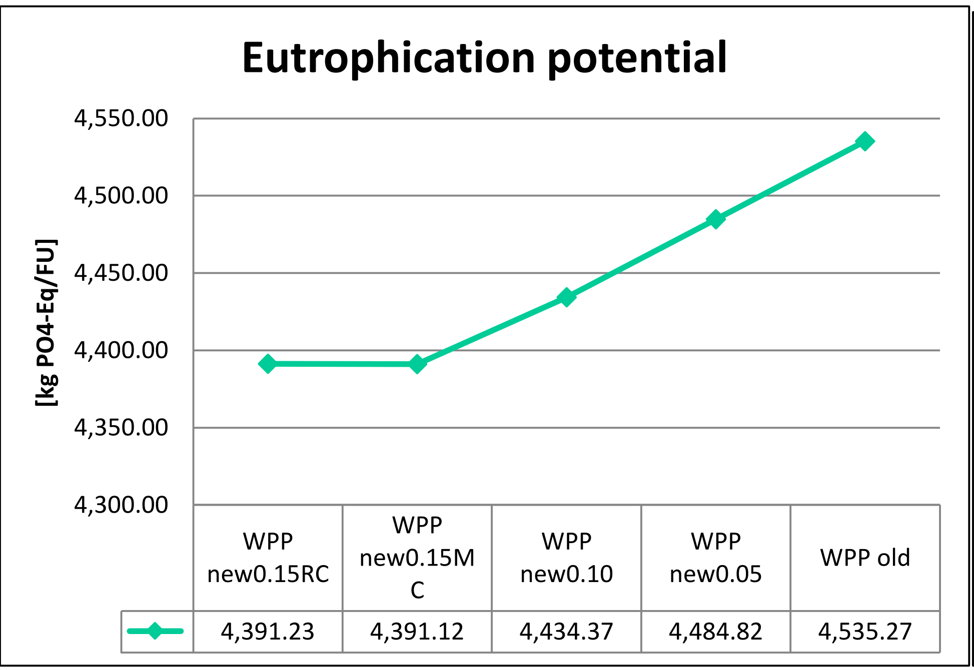




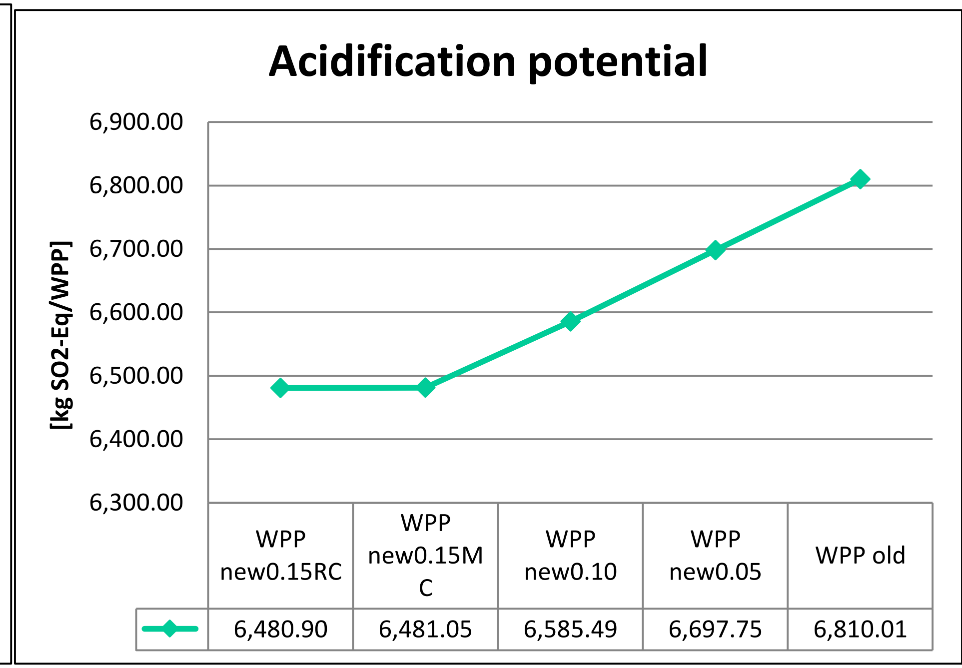
The environmental impact through the multiwalled carbon nanotube (production of CNT, preproduction of the materials etc) has a low influence of the balance.

Case study 3: Prospective CNT Composite material, e.g. as rotor blades of wind power plant

WPP new0.15 versus WPP old: improvement around only ca. 3,2%



WPP new0.15 versus WPP old: improvement around ca. 4,8%



Conclusions

- Environmental impacts of the production of nanomaterials depends on the type of manufacturing process (energy demand, demand of operating supplies, yield, purification rate)
- The potential and prospects for reducing environmental load by nanotechnological products and processes depends on the type and level of innovation (nanotechnology generation, incremental vs. radical, end-of-pipe vs. integrated)
- A varying potential for gains in resource efficiency could be shown and quantified in the case studies (also in life cycle view), but also a lack of data
- Today mostly nanotechnological-based applications on the market are incremental innovations, many applications with higher level of innovation still in the development

Life Cycle Assessment of nanotechnology-based applications

- What is the environmental impact of the production of nanomaterials?
- What is the influence of these nanomaterials on the environmental impact of new (prospective) applications?
- Which kind of applications we need in future to realise high environmental (sustainable) benefits?

Life Cycle Assessment of nanotechnology-based applications

- Questions answered?
- Environmental impact of the production of nanomaterials:
    - Great range of factors (1,2 – 20 (100) higher than microsized materials)
- Influence of these nanomaterials on the environmental impact of new (prospective) applications:
    - Very different
- Kind of future applications with high environmental (sustainable) benefits; very good combination from the environmental perspective:
    - Small content rate with better functionality
    - Environmental benefit in the use phase (higher resource and/or energy efficiency)
    - Long-life (persistent) product
    - Nanomaterials integrated in the product matrix

Department 10 – Technological Design and Development

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Selected publications:

- Steinfeldt, M. (2014): **Life-Cycle Assessment of Nanotechnology-Based Applications.** In: Rickerby, D. (Ed.): Nanotechnology for Sustainable Manufacturing. CRC Press Traylor & Francis Group, Boca Raton, London, New York, p.263-284.
- Steinfeldt, M. (2014): **Precautionary Design of Nanomaterials and Nanoproducts.** In: Michalek, T. et al. (Ed.): Technology Assessment and Policy Areas of Great Transitions. Informatorium, Prague, p. 321-328; 412/413.
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- Steinfeldt, M. (2011): **A method of prospective technological assessment of nanotechnological techniques.** In: Finkbeiner, M. (ed.): Towards Life Cycle Sustainability Management. Springer Dordrecht Heidelberg London New York, p.131-140
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- Steinfeldt, M.; Gleich, A. von; Petschow, U.; Haum, R.; Chudoba, T.; Haubold, S. (2004): **Nachhaltigkeitseffekte durch Herstellung und Anwendung nanotechnologischer Produkte (Sustainability effects through production and application of nanotechnological products).** Schriftenreihe des IÖW 177/04. Berlin.
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