EnviroInfo 2009 (Berlin)
Environmental Informatics and Industrial Environmental Protection: Concepts, Methods and Tools
 ISBN: 978-3-8322-8397-1

Green Chemistry / Green Engineering/ Sustainable Information Technology: Common Concepts and Differences

Kristina Voigt
Helmholtz Zentrum Muenchen, German Research Center for Environmental Health, Institute of Biomathematics and Biometry,
Ingolstaedter Landstr.1, D-85764 Neuherberg
kvoigt@helmholtz-muenchen.de

Abstract

These days the terms green and sustainable are proliferating. The positive aspect concerning the extensive use is that sustainability receives an increasing interest in society. It has become a key concern for consumers and industry. However, coming to understand its implications in the context of daily life is difficult. Important fields in the context of sustainability are e.g. Green Chemistry (Anastas 1998), Green Engineering (Anastas 2003a), sustainable information and communication technologies (Hilty 2008), just to name a few scientific topics. The principles of these fields will be presented in the paper. Furthermore, the interaction of these concepts as well as the differences will be addressed. The inclusion of green / sustainable foci in education will be vital in the future. While tremendous benefit has been derived from vision and value statements on the need for sustainability, scientists and engineers understand that change will only occur when sustainable technologies are implemented in industry and disseminated throughout society. To accomplish this transition, the three main areas: academia (education), industry and governments must work more closely together.

Keywords: sustainability, sustainable chemistry, sustainable engineering, sustainable information technology

1. Introduction

Humanity has exceeded the carrying capacity of the global environment. The only real choices for the future are to bring the throughputs that support human activities down to sustainable levels through human choice, human technology, and human organization, or to let nature force the decision through lack of food, energy, or materials, or through an increasingly unhealthy environment, see Meadows (2004). At the start of the twenty-first century, the problem of global sustainability is widely recognised by world leaders, and a common topic of discussion by journalists, scientists, teachers, students and citizens in many parts of the world. There is a profound paradox. On the one hand, the twenty-first century is widely heralded as the era of sustainability, with a rainbow alliance of government, civil society and business devising novel strategies for increasing human welfare within planetary limits. On the other hand, the evidence is that the global human enterprise rapidly becoming less sustainable and not more.
The core of mainstream sustainability thinking has become the idea of three dimensions, environmental, social and economic sustainability. In practice, development decisions by governments, businesses and other actors do allow trade-offs and put greatest emphasis on the economy above other dimensions of sustainability. This is a major reason why the environment continues to be degraded and development does not achieve desirable equity goals (Adams 2006).
Important fields in the context of sustainability are among others sustainable chemistry and sustainable pharmacy, sustainable engineering, sustainable information and communication technologies. These are chosen as examples because the author is performing some research in the Green Chemistry field, the Technical Committee (TC) 'Environmental Informatics: Informatics for Environmental Protection, Sustainable Development and Risk Management is working in the areas which are associated with Green Engineering and Sustainable Information Technology. Green Chemistry is an integral part of Green Engi-

neering (Kirchhoff 2003). Furthermore, the terms sustainable and green are not exactly the same as sustainable is broader but in literature they are often used synonymously.
Current thinking on sustainable development came out of a United Nations Commission on Environment and Development paper in 1987 (Brundtland Commission 1987), which defined sustainable development as: '. . . meeting the needs of the present without compromising the ability of future generations to meet their own needs.'

2. Green Chemistry / Sustainable Chemistry

With respect to chemicals we speak of sustainable chemistry (SC) and/or Green Chemistry (GC). One important element of sustainable chemistry is commonly defined as chemical research aiming at the optimization of chemical processes and products with respect to energy and material consumption, inherent safety, toxicity, environmental degradability, and so on. An increasing number of assessment systems containing quantitative indicators for these aspects are currently being developed. In addition, however, SC should also address the societal aspect of sustainability. With respect to scientific research, the societal aspect is defined here by two requirements: (1) the assumptions, objectives and implications of chemical research and its technical application should be made more transparent to various societal actors; (2) uncertainty and ignorance should be treated more explicitly in the course of scientific research. Meeting these requirements is necessary in order to lift the division between the allegedly disinterested and non-normative scientific research and the value-laden sphere of societal needs, preferences and decision-making situations. This, in turn, is understood here as a contribution to a more sustainable scientific practice. The societal aspect of SC remains to be recognized more fully in all branches of chemical research. One prerequisite for this is the inclusion of SC into chemical education from the very beginning (Boeschen, 2003).
Over the last years Green Chemistry has gradually become recognized as both a culture and a methodology for achieving sustainability. The concept of Green Chemistry was being formulated, by Anastas (1998) at the US Environmental Protection Agency (EPA), to address the environmental issues of both chemical products and the processes by which they are produced. The guiding principle is the design of environmentally benign products and processes (benign by design) which is embodied in the 12 Principles of Green Chemistry the essence of which can be reduced to the following working definition. Green Chemistry efficiently utilises (preferably renewable) raw materials, eliminates waste and avoids the use of toxic and/or hazardous reagents and solvents in the manufacture and application of chemical products. Concerning the diminishing of waste the so-called e-factor has been generally accepted. This measurement has been introduced more than 10 years ago and can be regarded as a form of green metrics (Sheldon 2007).
A variety of activities already exist in the field of green or sustainable chemistry.
It goes without saying that only a small selection can be named here. To the knowledge no international society of green or sustainable chemistry exists. In Germany a working group named, sustainable chemistry has been established within the German Chemical Society (GDCh) (**http://www.gdch.de/strukturen/fg/nachhaltigechemie.htm**). The International Symposium on Green Chemistry for Environment and Health was held at the Helmholtz Zentrum Muenchen, German Research Center for Environmental Health, October 13-16, 2008, in Munich, Germany (http://www.helmholtz-muenchen.de/en/gc/). The Institute for Environment and Sustainability (IES) is a specialised institute of the Joint Research Centre of the European Commission based at Ispra, Italy. Its mission is to provide scientific and technical support to EU policies for the protection of the environment and contributing to sustainable development in Europe. (**http://ies.jrc.ec.europa.eu/index.php?page=welcome-message**)
The mission of the US Green Chemistry Institute, established in 1997, is to advance the implementation of Green Chemistry principles into all aspects of the chemical enterprise. On January 1, 2001, the ACS Green Chemistry Institute® became part of ACS operations in Washington, D.C. The organization pur-

sues their joint interests in the discovery and design of chemical products and processes that eliminate generation and use of hazardous substances (ACS 2009).

The 12 Principles of Green Chemistry are (Anastas 1998):
1. Prevention
It is better to prevent waste than to treat or clean up waste after it has been created.
2. Atom Economy
Synthetic methods should be designed to maximize the incorporation of all materials used in the process into the final product.
3. Less Hazardous Chemical Synthesis
Wherever practicable, synthetic methods should be designed to use and generate substances that possess little or no toxicity to people or the environment.
4. Designing Safer Chemicals
Chemical products should be designed to effectuate their desired function while minimizing their toxicity.
5. Safer Solvents and Auxiliaries
The use of auxiliary substances *(e.g.,* solvents or separation agents) should be made unnecessary whenever possible and innocuous when used.
6. Design for Energy Efficiency
Energy requirements of chemical processes should be recognised for their environmental and economic impacts and should be minimized. If possible, synthetic methods should be conducted at ambient temperature and pressure.
7. Use of Renewable Feedstocks
A raw material or feedstock should be renewable rather than depleting whenever technically and economically practicable.
8. Reduce Derivatives
Unnecessary derivatization (use of blocking groups, protection de-protection, and temporary modification of physical-chemical processes) should be minimized or avoided if possible, because such steps require additional reagents and can generate waste.
9. Catalysis
Catalytic reagents (as selective as possible) are superior to stoichiometric reagents.
10. Design for Degradation
Chemical products should be designed so that at the end of their function they break down into innocuous degradation products and do not persist in the environment.
11. Real-time Analysis for Pollution Prevention
Analytical methodologies need to be further developed to allow for real-time, in-process monitoring and control prior to the formation of hazardous substances.
12. Inherently Safer Chemistry for Accident Prevention
Substances and the form of a substance used in a chemical process should be chosen to minimize the potential for chemical accidents, including releases, explosions, and fires.

3. Green / Sustainable Engineering

Green Engineering focuses on how to achieve sustainability through science and technology. The need for engineering solutions to prevent pollution from being released into the environment is minimized when Green Chemistry principles are incorporated into feedstock and reagent selection, solvent use, and overall synthetic design. Combining Green Chemistry with Green Engineering at the earliest design stages is an effective strategy for maximizing efficiency, minimizing waste, and increasing profitability (Kirchhoff, 2003).

The 12 Principles of Green Engineering are (Anastas 2003a):
Principle 1: Designers need to strive to ensure that all material and energy inputs and outputs are as inherently nonhazardous as possible.
Principle 2: It is better to prevent waste than to treat or clean up waste after it is formed.
Principle 3: Separation and purification operations should be designed to minimize energy consumption and materials use.
Principle 4: Products, processes, and systems should be designed to maximize mass, energy, space, and time efficiency.
Principle 5: Products, processes, and systems should be "output pulled" rather than "input pushed" through the use of energy and materials.
Principle 6: Embedded entropy and complexity must be viewed as an investment when making design choices on recycle, reuse, or beneficial disposition.
Principle 7: Targeted durability, not immortality, should be a design goal.
Principle 8: Design for unnecessary capacity or capability (e.g., "one size fits all") solutions should be considered a design flaw.
Principle 9: Material diversity in multicomponent products should be minimized to promote disassembly and value retention.
Principle 10: Design of products, processes, and systems must include integration and interconnectivity with available energy and materials flows.
Principle 11: Products, processes, and systems should be designed for performance in a commercial "afterlife".
Principle 12: Material and energy inputs should be renewable rather than depleting.

4. Information Technology and Sustainability

Under the term Green IT we understand the effort to create the use of information and communication technology (ICT) over the whole life cycle in an environmentally benign and resources saving manner. This starts with the design of the systems and the production of components and throughout their use and finally to the disposal or recycling of products (e.g. hardware) (WIKIPEDIA 2009). The IT industry produces today 2 % of the worldwide CO_2 emissions. According to the authors the term Green IT means in the first place the reduction of energy consumption. Business informatics can play a major contribution to the sustainable use of global resources by intelligent combination of economic and production processes (Buhl, 2008).
Recommendations for a sustainable information society are formulated by Hilty (2008, 2009). These recommendations are structured according to the four stakeholder groups or societal actors they address: 1. ICT users, 2. ICT hardware producers, 3. ICT software producers, 4. political decision makers.

1. ICT users:
1.1 Use ICT as a means to a defined end
1.2 Extend the service life of your ICT hardware to an extreme
1.3 Demand and use "green computing" features
1.4. Propagate intelligent room temperature management
1.5. Explore new styles of virtual collaboration and reduce travel
1.6. Use ICT as an enabler for structural change

2. ICT hardware developers:
2.1 Avoid toxic components
2.2 Reduce the material variety
2.3 Explore energy harvesting

3. ICT software developers:

3.1 Avoid software induced hardware obsolescence
3.2 Avoid unmastered complexity
4. Political decision makers:
4.1 Prefer open standards
4.2 Promote life-cycle-oriented labeling for ICT products
4.3 Promote the use of sustainability criteria in public ICT procurement
4.4 Promote renewable power generation

The recommendation are different both in their potential contribution to sustainability and in the challenge they pose to the actors.

5. Common Concepts and Differences

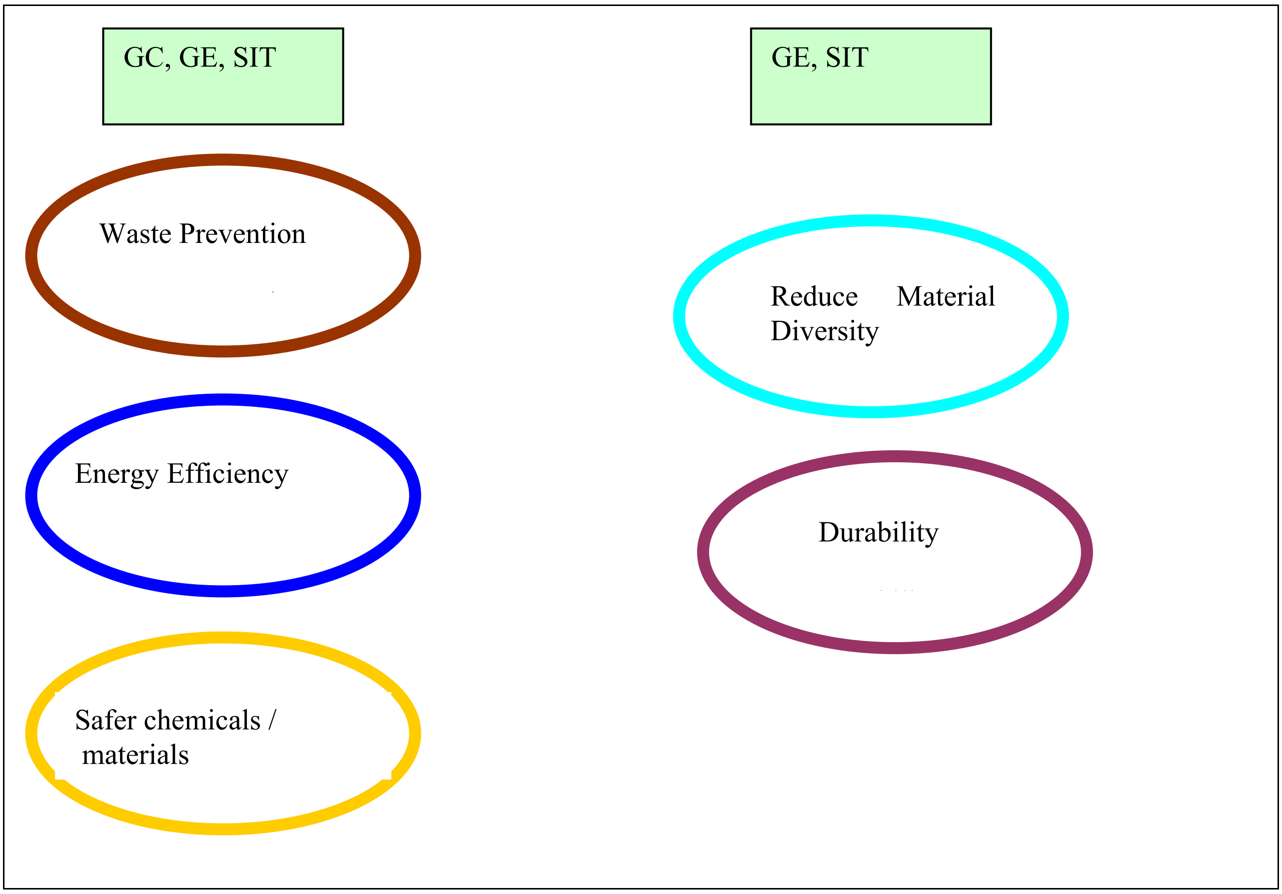

Figure 1: Sustainable / Green Principles in Three Different Disciplines

Figure 1 shows the green / sustainable principles in the three disciplines looked upon: Green Chemistry (GC), Green Engineering (GE), and Sustainability in Information Technology (SIT). All presented sustainable approaches have several aspects in common, namely the topic of waste with respect to its prevention, as well as the topic of energy consumption with respect to its economization. Furthermore, the use of non-hazardous chemicals or the more efficient use of chemical substances is a focus in every sustainability field. Taking a look at the fields Green Engineering (GE) and Sustainability in Information Technology (SIT) the topics of reduction of material diversity as well as the durability are common principles.

The definitions of Green Chemistry and Green Engineering share common language, and the application of both chemistry and engineering principles is needed to advance the goals of sustainability. Green Chemistry: The design of chemical products and processes that reduce or eliminate the use and generation of hazardous substances (1). Green Engineering: The design, commercialization, and use of processes and products that are feasible and economical while minimizing pollution at the source and risk to human health and the environment (2). The connection between Green Chemistry and Green Engineering is particularly strong in ensuring that inputs and outputs, both materials and energy, are as inherently safe as possible (3). Green Chemistry focuses on the design of chemical products and processes that reduce or eliminate the use and generation of hazardous substances. Green Chemistry provides the foundation on which to design the Green Engineering technologies needed to implement sustainable products, processes, and systems. Using inherently safer materials eliminates the need to "engineer out" environmental concerns later in the process (Kirchhoff 2003).
Some of the principles are should be according to the subject different and unique. This holds for example for the topics degradation and catalysis in the set of Green Chemistry principles. These important topics are described in detail by Horvath (2007) and Kuemmerer (2007).

6. Conclusions and outlook

All presented sustainable approaches have several aspects in common, namely the topic of waste with respect to its prevention, as well as the topic of energy consumption with respect to its economization. Furthermore, the use of non-hazardous chemicals or the more efficient use of chemical substances is a focus in every sustainability field.
Although many of the principles have common content not enough effort has been made to apply these principles effectively on a large scale and further research and applications must urgently be initiated.
The need for addressing also the societal aspect of Green Chemistry and Green Engineering is stated by Böschen et al (2003) as well as Davidson et al (2007). One prerequisite for this is the inclusion of green topics into the education for the very beginning (Boeschen 2003). This idea is strongly supported by Shonnard et al (2003b). Green Engineering principles are gaining prominence within engineering education. Shonnard et al describe a general framework for incorporating Green Engineering design principles into engineering curricula, with specific examples for chemical engineering. The framework for teaching Green Engineering discussed in this paper mirrors the 12 Principles of Green Engineering proposed by Anastas and Zimmerman (2003), especially in methods for estimating the hazardous nature of chemicals, strategies for pollution prevention, and approaches leading to efficient energy and material utilization. The key elements in Green Engineering education, which enlarge the "box" for engineering design, are environmental literacy, environmentally conscious design, and beyond-the-plant boundary considerations. The criteria named above as key topics for Green Engineering education are those which I have identified as common principles for all three green disciplines looked upon.
Davidson et al (2007) formulated vital topics for sustainable issues incorporated into engineering curricula.
While tremendous benefit has been derived from vision and value statements on the need for sustainability, scientists understand that change will only occur when sustainable technologies are implemented in industry and disseminated throughout society. The imperative of sustainability has been made clear over the past decade through studies, analyses, and political summits; however, the scientific and technological solutions to address this imperative are only in their most nascent stages. The vital and significant work in Green Engineering to date is a fraction of what is yet needed and realizable (Anastas, 2003b). To accomplish this transition, the three main areas: academia (education), industry and governments must work more closely together. Sustainability deals equally and simultaneously with environmental, social, and economic issues, and necessitates multi-disciplinary, multi-stakeholder work. Satterfield et al (2009) iden-

tified the conventional tendency of organizations to "stove-pipe" or operate within silos as a barrier to sustainability, particularly within academia, industry, and government.

With all of the research successes realized in Green Chemistry over the past 15 years, it is necessary to recognize and understand that the field is in a nascent stage and that some of the most important research questions within it are only now beginning to be identified and pursued. As a research community, it is important to accelerate the pursuit of these research areas by clearly enunciating the great research challenges, the great scientific unknowns within the field of Green Chemistry (Horvath 2007). This also holds true for Green Engineering and Sustainability in Information Technology.

Finally I like to give an example that databases and information systems should be established and used in order to fulfil the requirements of Green Chemistry, Green Engineering and Sustainability in Information Technology. As Keith et al (2007) showed in their recently published review on Green Analytical Chemistry that there already exist many green techniques in the literature and methods in the NEMI (National Environmental Methods Index) database (**http://www.nemi.gov**) which lists over 800 methods, but they have rarely been collected in a manner that highlights these environmentally benign procedures or being useful to the individual analyst. This means that standard tools of computer science, like e.g. information systems and databases are one important tool for the accomplishment of green / sustainable topics in every field.

References

ACS (American Chemical Society), ACS Green Chemistry Institute, http://portal.acs.org/portal/acs/corg/content?_nfpb=true&_pageLabel=PP_TRANSITIONMAIN&node_id=1400&use_sec=false&sec_url_var=region1&__uuid=8f601fb5-ca7a-4aca-8626-c52db23e8a01, 2009.

Adams, W.M. (2006): The Future of Sustainability: Re-thinking Environment and Development in the Twenty-first Century, IUCN, The World Conservation Union, **http://www.iucn.org**.

Anastas, P. T.; Warner, J. C. (1998): Green Chemistry, Theory and Practice: Oxford University Press.

Anastas, P. T.; Zimmermann, J. B. (2003a): Through the 12 Principles Green Engineering, Environ. Sci. Technol., 1, 95-101.

Anastas, P.C. (2003b): Green Engineering and Sustainability. Environ. Sci. Technol., 37, 23, 423A.

Boeschen, S., D. Lenoir, and Scheringer, M. (2003): Sustainable chemistry: starting points and prospects, Naturwissenschaften, 90, 93-102.

Brundtland Commission (1987): Our Common Future, Report of the World Commission on Environment and Development, http://www.worldinbalance.net/agreements/1987-brundtland.php.

Buhl, H.U., Laartz, J. (2008): Warum Green IT nicht ausreicht – oder: Wo müssen wir heute anpacken um damit es uns übermorgen noch gut geht?, Wirtschaftsinformatik, 4, 261-264.

Davidson, C.I., Mathhews, H.S., Hendrickson, C.T., Bridges, M.W., Allenby, B.R., Crittenden, J.C., Chen, Y., Willlians, E., Allan, D. T., Murphy, C.F., Austin, S. (2007): Adding Sustainability to the Engineer's Toolbox: A Challenge for Engineering Educators. I Environ. Sci. Technol., July 15, 4847-4850.

Hilty, L.M. (2008): Information Technology and Sustainability, pp. 1-180, Books on Demand GmbH, Norderstedt.

Hilty, L.M. (2009): An LCA-based framework for the analysis of ICT impacts on the environment, Draft Report EMPA.

Horvath, I.T., Anastas, P.C. (2007): Innovations and Green Chemistry. Chem. Rev., 107, 6, 2169-2173.

Keith. L.H., Gron, L.U., Young, J.L. (2007) Green Analytical Methodologies, Chem. Rev. 107, 2695-2708.

Kirchhoff, M.M. (2003): Promoting Green Engineering through Green Chemistry, Environ. Sci. Technol., 37, 5349-5353.

Kuemmerer, K. (2007): Sustainable from the very beginning: rational design of molecules by life cycle engineering as an important approach for green pharmacy and green chemistry. Green Chemistry, 9, 899-907.

McDonough, W., Braungart, M., Anastas, P.C., Zimmermann, J.B. (2003): Applying the Principles Engineering of Greeen to Cradle-to-Cradle Design, Environ. Sci. Technol., December, 435A-441A.

Meadows, D., J. Randers, and D. Meadows (2004): Limits to Growth, the 30-year update, Chelsea Green Publishing Company, White River Junction, Vermont.

Satterfield, MB, Kolb, CE, Peoples, R, Adams, GL, Schuster, DS, Ramsey, HC, Wood-Black, F, Garant, RJ, Abraham, M. (2009): Overcoming Nontechnical Barriers to the Implementation of Sustainable Solutions in Industry. Environ. Sci. Technol., 43, 4221–4226.

Sheldon, R. A (2007): The E Factor: fifteen years on, Green Chemistry, 9, 1273-1283.

Shonnard, D.R., Kicherer, A., Saling, P. (2003a): Industrial Applications Using BASF Eco-Efficiency Analysis: Perspectives on Green Engineering Principles. Environ. Sci. Technol., 37, 5340-8.

Shonnard, D.R., Allen, D.T., Nguyen, N., Weil Austin, S., Hesketh, R. (2003b): Green Engineering Education through a U.S. EPA/Academia Collaboration, Environ. Sci. Technol., 37, 5453-5462.

Voigt K (2008): Environmental Protection, Sustainable Development & Risk Management with Emphasis in Environmental Chemicals. in: Sànchez-Marrè M. et al. (Eds.), Proceedings of the iEMSs 2008, Barcelona, Catalonia, July 2008, Volume 1, 7-11.

WIKIPEDIA (2009): Green IT, http://de.wikipedia.org/wiki/Green_IT.