PROCESS ENGINEERING FOR SUSTAINABILITY

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Content

Summary

The chapter presents a role of *Process Engineering* in *Sustainable Development*. To this end the chapter defines the idea of sustainable development, by outlining many earlier concepts how to protect our environment. This part of the chapter summarizes the list of the sustainable development principles. Sustainable development depends on appropriate advances in technology that must be safe and economic. Therefore green chemistry and clean technologies were described at the subsequent parts, as the complementary concepts. *Green Chemistry* defines how to develop new products, reaction media, conditions and/or utility of materials. *Clean Technologies* mentioned in next part of the chapter, outlines the industrial processes projected to reduce the impact of on the environment, including reducing the use of energy and raw materials. The process engineering gives the best practical tools for the clean technologies enabling the recycling of the materials by their recovery from wastewaters. The roots of the process engineering stems in the past and therefore many historical achievements of the process

engineering are summarized in the table 1 of this chapter. The use of newest successes in *Process Engineering* such as *microreactors* and *membranes* enables to solve many problems with complete eliminating or separation dangerous substances from our environment. Process Engineering develops tools for optimal design such as hybrid processes, new software and new instruments that are also overviewed. At the end of this chapter some examples of the applications of process engineering in medicine are also mentioned such as artificial organs and controlled release. Controlled release as dosing methods may be also used in agriculture (one of the heaviest contaminator of our environment). These examples shows how process engineering can offer a realistic prospect for sustainable development by the improvement in environmental conditions and health, and simultaneously in production processes by improvements and the savings in resources, energy and costs.

1. Introduction

Earth is currently the only place where life is known to exist. Earth is a home to millions of species including humans. The biosphere, which is living space on Earth, has its boundaries and limited ability to survive. As a closed system, the biosphere must be in a state of equilibrium and well balanced to maintain life. The global ecological system integrating all living beings ranged from the ocean floor upwards to 10 km into the atmosphere, and therefore all substances within this system are limited, including water resources.

The total volume of the water is approximately 1.332 10^9 km^3, but only 4 million km^3, e.g. 0.3 % of total water volume is actually usable for humans. This portion can be available mainly from rivers, lakes and groundwater. If all the land on Earth were spread evenly, water would rise to an altitude of more than 2.611 km; however, only 7.834 meters of this layer would be usable.

In the recent past, human consumption of water has increased dramatically worldwide. The water consumption in 1680 was estimated at 86 km^3, in 1900 this amount had risen to 522 km^3; but in 1980 it had risen to 2120 km^3, and in 2000 to 2,700 cubic km^3 per year. The forecast predicts that human water consumption could triple once more in the next 30 years is alarming. Then at least 40% of the world's population will live in countries that suffer from a chronic shortage of water. Today, already more than 50 countries dramatically suffer from a shortage of water, but the United Nations expects that by 2025, two-thirds of the world population will not have enough drinking water. The water withdrawal estimate based on 160 countries, shown that 62% of the water is used in agriculture. Agriculture and stock farming not only uses but also spoils the largest portion of consumed water because of the massive use of artificial fertilizers (particularly nitrates), pesticides and other chemicals (mainly heavy metals). The water that flows from these fields into river systems or groundwater is heavily polluted. The industry uses 16% -19.5% (Sleeman and Barret, 1996), for instance, between 10,000 and 20,000 liters of water are used to produce only one car. Households consume 18.5%, but the quantity consumed varies enormously in different regions of the world, reaching 295 liters per day in the USA and amounting to 20 liters in rural regions in dry parts of Africa. At least 25 liters per day are needed for drinking, cooking and washing.

In countries like Austria or Germany, the daily per capita consumption stands at some 130 liters.

Water contamination with the heavy metals, biocides and other chemical residues (that enter the water cycle) continuously increase. Some trace contaminants, affects the immunogenic system, and causes gene mutations and new diseases or bad changes in our environment. The changes in ecosystems are unpredictable, irreversible and lot of them may be revealed after a long time. Besides its toxicity, they have long-lasting, latent, and concealed effects. Research has shown that male fishes in rivers downstream of modern wastewater treatment facilities are becoming feminized, which is attributed to the residues of drugs containing hormones.

Economic growth, the exploitation of natural resources**,** unbalanced cycles (water, minerals; organic matter), energy, excessive emissions, and contamination are all factors that will continue to create two main problems, i.e. resources shortage and environmental problems simultaneously. Actually, through intensive agriculture, urban and technological growth, civilization tends to destroy natural habitats and have led to the degradation of the biosphere.

In contrary, the same civilization, i.e. achievements in technology (including process engineering) may possibly be able to avoid the bad scenario. However, in every-day practice there is no stimulus for the application of new safe technologies, which means that there is no stimulus for making life more convenient in global sense. Many of the possible contaminants are not actually removed in existing wastewater treatment plants, despite of the technological potential because of economy and law restrictions. Law and policy should prepare the adequate, necessary conditions, but by now the solutions basing on restrictive regulations are unsatisfactory. The wastes are still subject of common trade which is especially danger for less developed countries. But globally, the amount of contaminants continuously increases. In many cases, wastewaters that were already purified are mixed again with raw wastewaters, for economic reasons, only to adhere the regulatory limits. Municipal wastewater treatment and end-pipe technologies are usually not innovative enough, since conservative attitude of traditional equipment suppliers who keeps their strong position on the market. Moreover, the common anxiety over the environment may even result in increasing costs for clean water and wastewater treatment and may even hamper the innovative solutions as a result. Thus, development of the innovative technologies should be substantially stimulated by concerted actions among different disciplines. The main performers should prepare solutions basing on engineering and science, while conditions are formulated by lawyers, economists, politicians and stakeholders. The water is not only a resource, but also a main part of our environment, and therefore, the problem of water protection must be solved globally, now and for the future.

In 1890, when a group of France's prominent scientists discussed the futuristic topics concerning the impacts of technological development on human life, after a long debate, they concluded that the most serious environmental problem in Paris by the year 1950 would be… horse manure", which was really a serious public nuisance in urbanized areas in the 19th century. Thanks to development, this horrible futuristic vision only became a well-known anecdote. Civilization is the development of human societies generally toward more complex technology, higher population densities, increasing per capita gross domestic product, and other significant advancements. Civilizations have been distinguished by their means of subsistence, types of livelihood, settlement patterns, and forms of government, economic systems, and cultural characters. Our civilization is marked by number of secondary elements, including a developed transportation system, and standards of measurement, legal systems, characteristic art styles, architecture, mathematics, science and technology. However the awareness on environmental protection is raising nevertheless the impact of technological development on our environment is still rather destructive. Therefore, the solution of this problem requires multidisciplinary approach. The main bottleneck is not a technology but the economy (or rather rapacity). Albert Einstein said that: “Problems cannot be solved or foreseen within the mind-set that created them”.

Science, engineering, law, economy and policy have to contribute in sustainable development by investigating natural phenomena, studying, and documenting the fundamental principles, codified by lawyers, and endorsed by politician who understand economical constrains and societal needs. The Process Engineering seems to be the best way to face this problem by develops designing tools to create technology by taking into account the natural laws. Process Engineering provides a new opportunity for sustainable development based on multidisciplinary achievements obtained by scientists, designed by engineers (Wilson et al, 2000; Perry’s chemical engineers’ handbook, 2000; Baker, 2001; Venselaar 2003; Koltuniewicz, 2010; Koltuniewicz and Drioli, 2008). Process Engineering can offer a realistic prospect for sustainable development by the simultaneous improvement in environmental conditions, process and safety improvements and the savings in resources, energy and costs of production. This can be done by using separation or dematerialization techniques for the removal, recovery, reuse, or recycling of various substances and different material streams. Solid waste materials may be also transformed into new feedstock or energy sources (see *Waste Management*).

Generally, to avoid global catastrophe, the balance and the global recycle of the all-material streams, not only water on Earth, must be attained. This holistic water resource approach referred to as the Dublin-Rio principle (Agenda 21, 1992) highlights that fresh water is finite, in danger and is essential to sustain life, economic development and the environment. The term of sustainable development points out that “sustainability must integrate ecological integrity, economic efficiency, and social equity.” (Cote and Cohen-Rosenthal, 1998). Thus, the field of sustainable development can be conceptually broken into three constituent parts: environmental sustainability, economic sustainability and sociopolitical sustainability. The Brundtland Commission defined the goal of the state sustainability within the ecosphere: “To meet the needs of the present without compromising the ability of future generations to meet their own needs.” An "unsustainable situation" occurs when natural capital (the sum total of nature's resources) is used up faster than it can be replenished. The system in which the sustainability is planned to be achieved comprises societies and the surrounding ecosystems. The sustainable development declares to regain harmony with nature. A sustainable development symbolizes a mode of technology that would "...meet the needs of the present without compromising the ability of future generations to meet their own needs." (United Nations, 1987; Smith and Reeves, 1998). The term was used by the

Brundtland Commission which introduced often-quoted definition of sustainable development. Sustainable development ties together concern for the carrying capacity of natural systems with the social challenges facing humanity. Sustainability requires that human activity only uses nature's resources at a rate at which they can be replenished naturally.

2. History of sustainable development

A majority of countries admitted the concept of sustainable development since the debate at the World Conservation Strategy in 1980, the report ("*Our Common Future*") of the World Commission on Environment and Development in 1987 (Brundtland Commission, 1987) and Agenda 21 in 1992. A strategy for sustainable development was agreed upon in Göteborg on June 2001 but this attitude has earlier roots in the past history.

In 1970, the US Congress enacted three important acts, i.e. Clean Air Act (Clean Air Act Amendments of 1970 and 1990, Title III, Hazardous Air Pollutants) 1970, Clean Water Act (US Congress Federal Water Pollution Control Act CWA1972) 1972 and Resource Conservation and Recovery Act, RCRA (Resource Conservation and Recovery Act, RCRA (1976)) (1976), which were the primary sets of federal regulations that governed water quality issues in the United States. Moreover, the international community approved the conventions concerning global pollution, e.g. acts on marine waters: in London 1972, Helsinki 1974, Paris 1974, Barcelona 1976 and 1982; Law of the Sea - the international agreement on resource preservation with 160 signatories; and Ministerial Declaration on the protection of the North Sea was signed in London 1987 by eight countries. Some spectacular examples of international actions against air pollution were the ECE Convention on Long-range Transboundary Air Pollution, which was agreed on November 1979 and entered into force in March 1983. This convention was signed by 34 countries and ratified by 24 countries. In 1985, the UNEP Convention for the Protection of the Ozone Layer was agreed in Vienna. The Helsinki Protocol was signed by 20 countries and entered into force in 1987 and the signatories reduced their national annual sulfur emissions by at least 30 per cent by 1993. The Montreal Protocol from 1987 was added to this convention, in which (46) signatory countries agreed to halve their production of five chlorofluorocarbons (CFCs) and three halons by 2000. This was further agreed upon in London 1990 by about 100 countries. The protocol on nitrogen oxides was signed on October 1988 in Sofia and entered into force when ratified by 16 signatory countries, which agreed to take measures against further increases of NO_x emissions so that national NO_x emissions did not increase beyond 1987 levels after 1994. Recent documents and guidelines, such as Kyoto Protocol (U.N., 1997), Treaties of Maastricht and Amsterdam, Rio and Oslo accords, created the foundation of a global environmental policy. The European Climate Change Program (ECC) was established in June 2000 to help identify the most environmentally and cost-effective EU measures enabling the EU to meet its target under the Kyoto Protocol, e.g. an 8% reduction in greenhouse gas emissions from 1990 levels by 2008-2012. This corresponds to a reduction of 336 Mt CO_2 in 2010 with respect to 1990 (Second ECCP Progress Report Can we meet our Kyoto targets? April 2003, EEA Technical report, Analysis of greenhouse gas emission trends and projections in Europe 2003, Luxembourg: Office for Official Publications of the

European Communities). The next step forward in global environmental policy was the Basel Treaty to control international trade in hazardous waste, which was signed in March 1989 by 34 countries and the EC; the signatories agreed in principle to prohibit and establish notification procedures for all trade in hazardous wastes. The real integration and interaction between nations and companies towards Sustainable Development was commenced at the U.N. Conference on Environment and Development UNCED "Earth Summit", which was held in Rio de Janeiro, Brazil, 1992 (Agenda 21).

Sustainable development stems from the earlier concepts based on the similarities between biological and industrial systems, such as industrial ecosystem, industrial metabolism, and industrial symbiosis. There are many concepts of preventative strategies including Industrial Ecology (Frosch and Gallopoulos, 1989), Ecologically Conscious Management (Capra, 1992), Life Cycle Analysis, and Design for the Environment, Dematerialization, and Design for Efficient Longevity, and Sustainable Product Development.

The so-called Industrial Ecology focuses largely on the physical flows of substances and the physical transformation processes, which was introduced by Elster (1983), who made the observation that industry is similar to biological systems. Ayres (1989) also developed the concept of industrial metabolism, taking into account the material flows. The Industrial metabolism was defined as the whole integrated collection of physical processes that convert raw materials and energy, plus labor, into finished products and wastes in a more or less steady-state condition. Tibbs (1993), Graedel and Allenby (1993, 1995) and Ayres (1989) pointed out a longer-term vision of production within a living system: “To manage the earth’s resources in such a way as to approach and maintain a global carrying capacity for our species which is both desirable and sustainable over time, given continued evolution of technology and quality of life.” (Allenby (1993) Quoted in: Coˆte´ and Hall, 1994) Proactive pollution prevention approaches are to achieve sustainable production capabilities, where environmental and economic systems are balanced. The waste minimization is one of the proactive approaches. The main objective of proactive strategies is the development of clean technologies, defined by the Commission of the European Communities as "any technical measures taken at various industries to reduce or even eliminate at source the production of any nuisance, pollution, or waste, and to help save raw materials, natural resources, and energy". (OECD, 1989)

3. Principles of Sustainable Development

The principles of sustainable development must be based on real assumptions and physical (conservation laws) and biological laws; the biogeochemical cycles; the ecological interdependencies of species; and the anthropogenic influence on the ecosphere. (Holmberg, 2000) The main postulates (so-called system conditions) of sustainability are:

1. Eliminate our contribution to systematic increases in concentrations of substances from the Earth’s crust by substituting certain minerals that are scarce

in nature with others that are more abundant, using all mined materials efficiently, and systematically reducing dependence on fossil fuels.

2. Eliminate our contribution to systematic increases in concentrations of substances produced by society by systematically substituting certain persistent and unnatural compounds with ones that are normally abundant or break down more easily in nature (“green chemistry”), and using all substances produced by society efficiently.
3. Eliminate our contribution to the systematic physical degradation of nature through over-harvesting, introductions and other forms of modification. This means drawing resources only from well-managed eco-systems, systematically pursuing the most productive and efficient use both of those resources and land, and exercising caution in all kinds of modification of nature.
4. Contribute as much as we can to the meeting of human needs in our society and worldwide, over and above all the substitution and dematerialization measures taken in meeting the first three objectives. This means using all of our resources efficiently, fairly and responsibly so that the needs of all people on whom we have an impact, and the future needs of people who are not yet born, stand the best chance of being met. .” [2 3 9]

During the 2000 Seville Conference, industry representatives proposed the IPPC Directive with the requirements for Best Available Techniques (BATs). The "best" means most effective in achieving a high general level of protection of the environment as a whole. As stated in BAT reference documents, the directive should be descriptive rather than prescriptive. Paragraph 11 in Article 2 of the Integrated Pollution Prevention and Control (IPPC) Directive defines "Best Available Technique" as "the most effective and advanced stage in the development of activities and their methods of operation which indicate the practical suitability of particular techniques for providing in principle the basis for emission limit values designed to prevent and, where that is not practicable, generally to reduce emissions and the impact on the environment as a whole." The purpose of the Directive is to achieve integrated prevention and control of pollution arising from the activities, leading to a high level of protection of the environment as a whole (European Commission, 2003). The application of the best available techniques, enable to improve their environmental performance. i.e. specifically (Halog and Schultmann, 2001; IPPC, 2004; Geldermann et al , 1998):

1. Acidification resulting from emissions into the air;
2. Soil and water eutrophication resulting from emissions to air or water;
3. Diminution of oxygen content in water;
4. Global warming;
5. Depletion of the ozone layer;
6. Emission of particles into the air, especially micro particles and metals;
7. Formation of photochemical ozone;
8. Discharge of persistent, bio-accumulative and toxic substances into water or into the soil;
9. Generation of waste, in particular hazardous waste;
10. Vibrations, noise and odors;
11. Over-exploitation of raw material and water resources.

4. Green Chemistry Concept

Sustainable (named “green”) chemistry was introduced by the EPA in 2002 (EPA, 2002). The idea of Green Chemistry is to develop new products, reaction media, conditions and/or utility of materials. More specifically, green chemistry is the design of chemical products that reduce or eliminate the use or generation of hazardous substances by offering environmentally friendly alternatives (Miyake and Kitazume, 2003; Ausley, 2004). Sustainable chemistry technologies can be categorized into the following three focus areas, e.g. the use of alternative synthetic pathways, the use of alternative reaction conditions, and the design of safer chemicals that are less toxic than current alternatives or inherently safer with regard to accident potential. There is equally a dozen Principles of Green Chemistry, namely:

1. Prevent waste, by design chemical syntheses to avoid waste to treat or clean up.
2. Design safer chemicals and products to be fully effective, with no toxicity.
3. Design less hazardous chemical syntheses to use and generate no toxic substances to humans and the environment.
4. Use renewable rather than depleting feedstocks. Renewable feedstock is usually made from agricultural products or is wastes, whereas depleting feedstock is made from fossil raw materials.
5. Use catalysts rather than stoichiometric reagents, which are used in excess and work only once, to minimize waste.
6. Avoid chemical derivatives by using blocking or protecting groups or any temporary modifications if possible. Derivatives use additional reagents and generate waste.
7. Maximize atom economy. Design syntheses so that the final product contains the maximum proportion of the starting materials. There should be minimal amount of the wasted atoms.
8. Use safer solvents and reaction conditions.
9. Increase energy efficiency at ambient temperature and pressure whenever possible.
10. Design degradable chemicals and products to break down to harmless substances after use to avoid their accumulation in the environment.
11. Analyze through real-time monitoring and control during syntheses to minimize or eliminate the formation of byproducts to prevent pollution.
12. Minimize the potential for accidents by designing safer chemicals to minimize the potential for chemical accidents, explosions, fires, and releases to the environment.

The Green Chemistry concept is solving the pollution prevention problem at the molecular level by focusing on chemicals. In this sense, Green Chemistry is complementary to Clean Technologies, which are based on Chemical Engineering rather than pure Chemistry.

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Biographical Sketch

Andrzej Benedict Koltuniewicz is professor at Warsaw University of Technology, Faculty of Chemical and Process Engineering. He was educated and graduated from the Wroclaw University of Technology, where he received his PhD and DSc as well. He was director of Chemical Engineering Institute of Wroclaw University of Technology and co-editor of Chemical Engineering and Processing, the quarterly of Polish Academy of Science PAN in 1985-2008. He is ECC expert for evaluation and assessment of proposals and research projects in FR7 European RTD programs. His areas of experience are membrane processes, hybrid processes, clean technologies, sustainable development, chemical and bioprocess engineering. He is author of the books: *Membranes in the clean technologies-Theory and Practice, (2008 WILEY), Integrated Membrane Operations in Various Industrial Sectors (chapter in: Comprehensive Membrane Science and Engineering (2010 ELSEVIER).* He wrote more than 150 publications and 7 patents to his credit. He is reviewer of several international journals: *Journal of Membrane Science, The Chemical Engineering Journal, Industrial and Engineering Chemistry Research, Separation Science and Technology, Journal of Hazardous Materials, Desalination, etc.* He has chaired several scientific conferences. He interacts with several universities in UK, Netherlands, France, Italy, Portugal, Spain, Germany, and Egypt.