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Green chemistry as systems science*

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Abstract: Green chemistry does not operate as an isolated subsystem, but within higher levels of corporation and society. From an environmental standpoint, the ideal focus is to achieve optimum performance across the system, not at a single systems level. This paper proposes a four-level system for green chemistry and provides examples of performance at each level that can legitimately be termed sustainable.

TECHNOLOGY WITHIN SOCIETY

It is beyond question that technology influences society, and that the inverse is also true. One well-known and obvious example is the automobile and its related systems. Over the past three decades, the environmental performance of various measures of an individual vehicle has improved by factors of between 10 and 100. This laudable technological feat has occurred, however, coincident with a greater number of vehicles and more distance driven per vehicle. The result has been increasing congestion and increasing environmental impacts. Overall, technology has not been sufficient to produce a satisfactory result because the approach has not been to think of the auto exhaust catalyst as part of a larger product, dependent on common infrastructure and strongly influenced by culture and society [1]. In much the same way, green chemistry is part of a larger system, and must be optimized from that perspective.

LEVEL 1: PRODUCT AND PROCESS LEVEL

Green chemistry's analog of the automobile's catalytic converter is the tailored molecule [2] or the tailored process [3]. These are the original emphases of green chemistry and continue to receive substantial research and development effort. As a result, no more need be said here about this first level of the green chemistry system, which is doing well, except that an appropriate longer-term goal would be to reduce emissions to the environment to near zero.

LEVEL 2: CORPORATE LEVEL

The environmental performance of a corporation comprises more than the greenness of its molecules. It is also related to the ways in which processes and facilities are sited, how they are developed (equipment design, building design, materials acquisition), and how they are treated upon obsolescence. These factors can be evaluated throughout streamlined life-cycle assessment techniques at both process and facility level [5]. All life-cycle stages should be assessed: resource provisioning, process implementation, primary process operation, complementary process operation, and end of process life. Green chemistry analyses typically address only the process operation stages.

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Following evaluation of corporate environmental performance, periodic monitoring is required. Many approaches are available; one of the most commonly used is the Global Environment Monitoring Initiative [6].

LEVEL 3: INFRASTRUCTURE LEVEL

The practice of industrial chemistry, green or not, depends in part upon factors related to the national and global economy. An example is the current starting material for many chemical products: crude oil. Only about 3% of crude oil is used as chemical feedstock, most of the rest being used for transportation and energy generation fuel. As a result, the chemical industry is unlikely to control oil's future, which is likely to be both interesting and dramatic. Petroleum geologists estimate that the all-time peak in oil production will occur within the 2010–2020 time frame, and will decline by 80% over the subsequent 30–40 years [7]. Even if approximately correct, it is clear that continued reliance on petroleum feedstocks is an untenable strategy for the industry.

The only feasible replacement for petroleum feedstocks appears to be feedstocks designed for and generated by biotechnology [8]. Such an approach has the potential to satisfy the requirements of quantitative sustainability, which are:

- Choose something you wish to sustain.
- Define quantitatively the sustainability target.
- Choose a time scale over which the target is to be achieved.

In the present case, one could choose, for example, to achieve a 100% transformation into the sustainable feedstock, and to do so by 2050. This might be done on a corporate basis, but could also be carried out on a sectoral or national basis. The resultant "path to sustainability" is shown in Fig. 1.

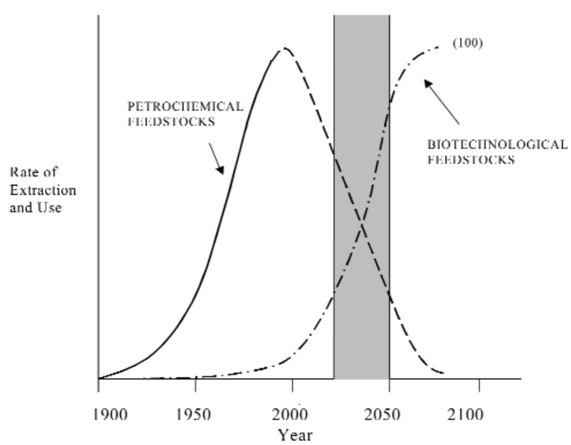

Fig. 1 A scenario for the transformation of industrial chemical feedstocks from petrochemical to biotechnological by 2050.

LEVEL 4: SOCIETAL LEVEL

At the highest structural level, opportunities for and constraints on the chemical industry occur because of the needs, desires, or actions of society as a whole. An example, but only one of many, is the use of water. Currently a precious commodity in several parts of the world, the availability of water will surely be further limited in the next several decades by population growth and perhaps by climate change. Green chemical practice must thus include using no more water than some agreed-upon allocated share.

There are many ways in which water might be allocated. I present here a method almost surely too simple to be directly implementable, but sufficient to begin the discussion of the sustainable use of water. The argument is as follows:

1. Water sustainability must be achieved within each watershed
2. Every person is to be given a reasonable amount of water for drinking, hygiene, and other personal uses. Gleick [9] suggests 50 liters per person per day as appropriate.
3. For a watershed of area A, rainfall rate R, and people P, the amount of water N available for nonpersonal use is

   $N = R - 50P$

4. The allocation of water amount N is to be on the basis of fractional land occupancy. Thus, if a chemical plant has ϕ hectares of land in the watershed, and all nonresidential land in the watershed comprises λ hectares, the water allocation A for the facility is

   $A = (\phi/\lambda)\, N$

For a facility now using water at a 3A rate, for example, the path toward sustainability would follow Fig. 2.

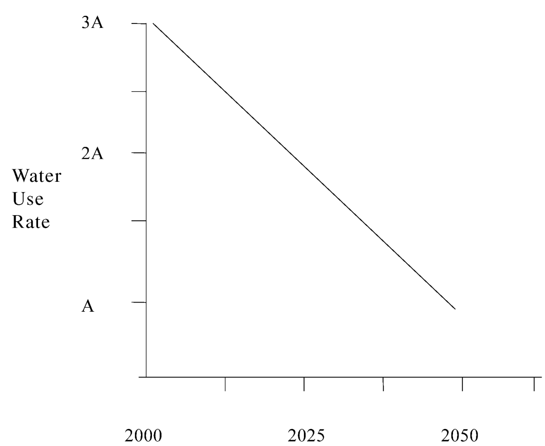

Fig. 2 A scenario for the transformation of an industrial chemical facility from unsustainable to sustainable water use by 2050.

OPTIMIZING THE SYSTEM

Green chemistry does not operate as an isolated subsystem, but as one within higher levels of corporation and society. This paper suggests that a four-level structure is a reasonable construct of the system, as indicated in Fig. 3. The ideal green chemistry focus is not to attempt to optimize one level of the system, but to optimize the system itself. The overall target should be the continued enhancement of useful and profitable products while moving simultaneously on a carefully charted path to sustainability. A few elements of a possible path have been presented; a thorough discussion would include many more [10]. It is clear that a logically constructed green chemistry plan must have a firm target in mind, and the appropriate target is sustainability. Sustainability demands systems thinking. Thus, green chemistry must move "beyond the flask" and become a systems science, challenging though that may be.

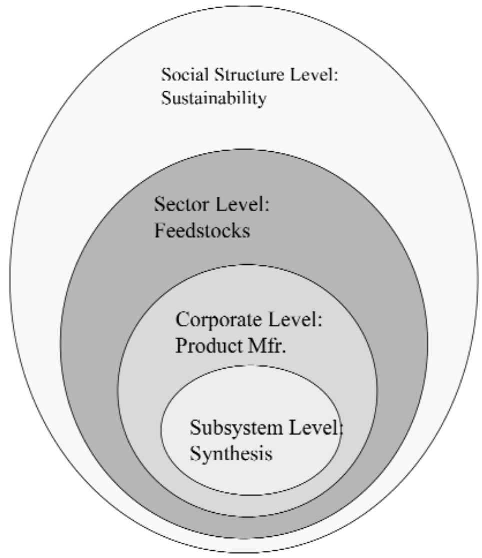

Fig. 3 The four-level system for a sustainable green chemistry.

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