Innovation and Sustainability in Process design by including Ecosystems as Unit Operations

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Despite the critical importance of ecological systems, engineering, like most other disciplines, takes nature for granted. For over a century, processes have been designed without considering the role of nature in supporting them by providing a large diversity of essential goods and services. These benefits from nature, called ecosystem services, include goods such as fossil resources, minerals, water, air and biodiesel; and services such as cycling of materials, photosynthesis, regulation of air and water quality, and soil formation. Such ignorance about nature results in atleast two major shortcomings: 1) Processes designed by engineers may demand more from ecosystems than can be provided without ecological degradation, and 2) Engineering misses opportunities of working with nature to address many industrial needs in an economically and environmentally superior manner. The first reason is a root cause for the inherent unsustainability of many engineering activities, while the second reason reflects the engineering attitude of dominating nature. Recent methods for Sustainable Engineering and life cycle considerations in process design also fail to address these shortcomings. [1]

This presentation will describe progress toward addressing the shortcomings listed above by developing methods for including ecosystems in process design in a manner analogous to unit operations. The ecological components included in this work are a forest ecosystem and treatment wetlands. Services which the trees provide to the manufacturing site include regulating air quality by taking up pollutants, reducing energy consumption in buildings, and reducing water runoff. They could also be a source of fuel for the process, and provide other benefits to the society such as climate regulation, recharging aquifers, and supporting biodiversity. Wetlands can treat a large variety of pollutants, including aliphatic and aromatic compounds, various pesticides, heavy metals and excess nutrients. In addition, they also support biodiversity, help maintain the water table and provide biomass.

In this work, these ecosystems are included in the flowsheet along with conventional unit operations to design a process that develops synergies between technological and ecological systems. The forest ecosystem is modeled using the i-Tree software and the wetland ecosystem by using appropriate non-mechanistic first-order rate equations. Thus, the technological and ecological systems are designed in a mutually beneficial manner. For example, if the wetland cannot treat certain molecules or if some emissions exceed the capacity of the forest to capture them, the technological system may be modified to overcome these constraints. Similarly, the ecological systems are tailored to the types of emissions from the technological equipment and goods and services such as wood from the trees and water from wetlands can be recycled for

process use. Designing such synergies results in innovative designs which cannot be found by the techno-centric approach of conventional engineering.

Sustainability metrics for this integrated system are quantified by the demand and supply of ecosystem services. The demand for such services is created by the emissions and resource use by processes, including wastewater emissions. The supply of ecosystem services is estimated by the capacity of an ecosystem process to capture completely or support and emissions and nutrient that are present in the environmental on a local scale. For designing a sustainable system with effective utilization of natural capital, the demand for ecosystem services should not exceed their supply. The overshoot in demand for multiple services at a particular scale indicates that the process currently does not function within the regenerative capacity of the local ecosystems. To map the demand for an ecosystem service with its supply, details about spatial characterization of functions and its effect on different scales become relevant. Such an approach encourages not just technological improvements, but also restoration and protection of ecosystems.

This approach for achieving Techno-Ecological Synergy is applied to a case study of a soybean – biodiesel production process for the hexane-oil extraction and methanol transesterification phases. The process is designed with different utility generating systems, including a traditional coal combined heat and power, and a biomass co-firing unit where the biomass fuel is derived by harvesting 15% of the trees, resulting in a positive feedback from the forest ecosystem.

Cost analysis for this integrated design indicates that utilization of natural systems and green infrastructure for reducing environmental impacts instead of conventional end-of-pipe control technologies are economically superior and it can provide a multitude of benefits when compared to traditional gray infrastructure. Thus, by designing integrated networks of technological and ecological systems, insight into the trade-offs between the two systems can be obtained, which may encourage industries to reduce the overshoot in demand due to their activities. The ultimate outcome of such efforts is expected to be “engineering within ecological constraints” [2] – a required step toward sustainability. Challenges in the practical implementation of such ideas will also be discussed.

[1] Urban, Robert A., et al. "Towards sustainability of engineered processes: Designing self-reliant networks of technological–ecological systems." Computers & chemical engineering 34.9 (2010): 1413-1420.

[2] National Academy of Engineering. *Engineering Within Ecological Constraints*. Washington, DC: The National Academies Press, 1996