



THE ACS GREEN CHEMISTRY INSTITUTE® PRESENTS

*Design Principles for  
Sustainable Green  
Chemistry & Engineering*

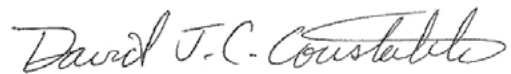


## Introduction to “Design Principles for Sustainable Green Chemistry and Engineering”

Since the word “Green” first started being placed in front of chemistry, many people have argued about what the “right” definition of green chemistry is or isn’t. And, more importantly, what should one actually do to make chemistry “green” or “greener?”

What follows is a collection of design principles that various individuals and groups have proposed over time to answer that question. Most people stop at 12 principles, and most separate chemistry from engineering as if it were possible to do green chemistry in the absence of engineering. I’ve never found a way to do that and I firmly believe that there are no two disciplines, and no two communities more intimately tied to making the world more sustainable than chemistry and engineering. What you will find on the following pages is an attempt to organize various principles of green chemistry and engineering and present them in a way that helps people to make their chemistry and engineering “greener” and more sustainable. I hope you find this particular way of combining and presenting these principles to be helpful and useful.

Sincerely,



David Constable, Director, Green Chemistry Institute ®

# MAXIMIZE RESOURCE EFFICIENCY

## DESIGN

**OUTPUT-PULLED vs. INPUT-PULLED**  
Products, processes, and systems should be “output pulled” rather than “input pushed” through the use of energy and materials\*\*

**ATOM ECONOMY**  
Synthetic methods should be designed to maximize the incorporation of all materials used in the process into the final product \*

**FIND ALTERNATIVES**  
The use of auxiliary substances (e.g., solvents, separation agents) should be made unnecessary whenever possible and innocuous when used\*

**REDUCE DERIVATIVES**  
Unnecessary derivatization (blocking group, protection-deprotection, and temporary modification of physical / chemical processes) should be avoided whenever possible \*

**USE CATALYSIS**  
Catalytic reagents (as selective as possible) are superior to stoichiometric reagents \*

## MEASURE

**MASS BALANCES**  
Establish full mass balances for a process\*\*\*\*

**HEAT AND MASS TRANSFER**  
Anticipate heat and mass transfer limitations\*\*\*\*

**CONVERSION**  
Report conversions, selectivities, and productivities\*\*\*\*

**BY-PRODUCT FORMATION**  
Identify and quantify by-products\*\*\*\*

**UTILITIES**  
Quantify and minimize the use of utilities\*\*\*\*

## BE EFFICIENT

**REDUCE**  
Separation and purification operations should be designed to minimize energy consumption and materials use\*\*

**MINIMIZE**  
Energy Requirements should be recognized for their environmental and economic impacts and should be minimized. Synthetic methods should be conducted at ambient temperature and pressure\*

**OPTIMIZE**  
Products, processes, and systems should be designed to maximize mass, energy, space, and time efficiency\*\*

**INTEGRATE**  
Design of products, processes, and systems must include integration and interconnectivity with available energy and materials flows\*\*

**PREVENT**  
Strive to prevent waste\*\*\*

## BE SUSTAINABLE

**MINIMIZE**  
Minimize depletion of natural resources.\*\*\*

**CONSERVE AND IMPROVE**  
Conserve and improve natural ecosystems while protecting human health and well-being \*\*\*

 CHEMISTRY

 ENGINEERING

### REFERENCE:

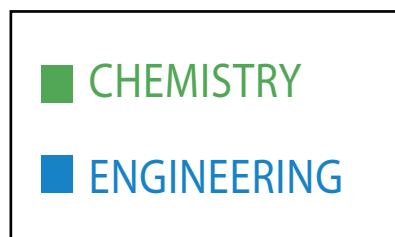
\* Anastas, P. T.; Warner, J. C. Green Chemistry: Theory and Practice; Oxford University Press: New York, 1998; p 30.

\*\* Anastas, P. T.; Zimmerman, J. B. Design through the Twelve Principles of Green Engineering. Environ. Sci. Technol. 2003, 37(5), 94A-101A.

\*\*\* Abraham, M. A.; Nguyen, N. “Green Engineering: Defining the Principles” - Results from the San Destin Conference, Environmental Progress, 2003, 22(4), 233-236.

\*\*\*\*Winterton, N. Twelve more green chemistry principles? Green Chem. 2001, 3, G73-G75.

# ELIMINATE & MINIMIZE HAZARDS & POLLUTION



## DESIGN

### AVOID PERSISTENCE

Chemical products should be designed so that at the end of their function they do not persist in the environment and break down into innocuous degradation products\*

### INHERENTLY NON-HAZARDOUS

Designers need to strive to ensure that all material and energy inputs and outputs are as inherently nonhazardous as possible\*\*

### SYNTHETIC METHODS

Wherever practical, synthetic methodologies should be designed to use and generate substances that possess little or no toxicity to human health and the environment \*

### SAFER PROCESSES

Substances and the form of a substance used in a chemical process should be chosen so as to minimize the potential for chemical accidents, including releases, explosions, and fires. \*

### PREVENTION

It is better to prevent waste than to treat or clean up waste after it is formed. \*

## MEASURE

### REAL-TIME ANALYSIS

Analytical methodologies need to be developed further to allow for real-time in-process monitoring and control prior to the formation of hazardous substances\*

### LOSSES

Measure catalyst and solvent losses in aqueous effluent\*\*\*\*

### THERMOCHEMISTRY

Investigate basic thermochemistry\*\*\*\*

### INCOMPATIBILITIES

Recognize where safety and waste minimization are incompatible\*\*\*\*

### WASTE

Monitor, report, and minimize laboratory waste emitted\*\*\*\*

## BE SUSTAINABLE

**CONSERVE AND IMPROVE**  
Conserve and improve natural ecosystems while protecting human health and well-being\*\*\*

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## DESIGN

### HOLISTICALLY

Engineer processes and products holistically, use systems analysis, and integrate environmental impact assessment tools\*\*\*

### USE LIFE CYCLE THINKING

Use life cycle thinking in all engineering activities\*\*\*

### END OF USE

Products, processes, and systems should be designed for performance in a commercial "afterlife"\*\*\*

### DURABILITY

Targeted durability, not immortality, should be a design goal\*\*

### CONSERVE COMPLEXITY

Embedded entropy and complexity must be viewed as an investment when making design choices on recycle, reuse or beneficial disposition\*\*

### MINIMIZE MATERIAL DIVERSITY

Material diversity in multicomponent products should be minimized to promote disassembly and value retention\*\*

### MINIMIZE CHEMISTRY IMPACTS

Consider the effect of the overall process on the choice of chemistry\*\*\*\*

### COLLABORATE WITH ENGINEERS

Consult a chemical or process engineer\*\*\*\*

### CONSIDER INCOMPATIBILITIES

Recognize where safety and waste minimization are incompatible\*\*\*\*

■ CHEMISTRY

■ ENGINEERING

## BE SUSTAINABLE

### THINK LOCALLY

Develop and apply engineering solutions while being cognizant of local geography, aspirations and cultures\*\*\*

### ENGAGE

Actively engage communities and stakeholders in development of engineering solutions \*\*\*

### APPLY MEASURES

Help develop and apply sustainability measures\*\*\*\*

### INNOVATE TO ACHIEVE

Create engineering solutions beyond current or dominant technologies; improve, innovate and invent (technologies) to achieve sustainability\*\*\*

### USE RENEWABLES

A raw material feedstock should be renewable rather than depleting whenever technically and economically practical\*

Material and energy inputs should be renewable rather than depleting\*\*

#### REFERENCE:

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