Green and Sustainable Technologies
2 Credits
Lesson 2: Basic Principles

Dr. Renuka Ariyawansha

Department of Environmental Technology, Faculty of Technology

renukaa@sltc.ac.lk

SLTC Research University

What we have discussed so far?

- Introduction to sustainability
- Sustainable Development Goals: A Brief Introduction
- The Blue-Green Economic Policy: The Creator of New Prospects in the Economy
- What is green technology?
- Importance of green technology
- Evolution of green technology
- Emerging green technologies
- Why is Green Technology Necessary?

Outline

- Introduction
- Principles of Green Engineering
- Green chemistry
  - 12 key principles of green chemistry
- Summary

Introduction

- Green engineering is **the design, commercialization, and use of processes and products in a way that reduces pollution, promotes sustainability, and minimizes risk to human health and the environment without sacrificing economic viability and efficiency**. (that are economically feasible and reduce the risk to human health and the environment)
- Green engineering embraces the concept that decisions to protect human health and the environment can have the greatest impact and cost-effectiveness when applied early, in the design and development phase of a process or product.
- Green engineering focuses on how to achieve sustainability through science and technology

https://whatisengineering.com/topic/what-is-green-engineering/

Green engineering processes and products:

- Holistically use systems analysis and integrate environmental impact assessment tools.
- Conserve and improve natural ecosystems while protecting human health and well-being.
- Use life-cycle thinking in all engineering activities.
- Ensure that all material and energy inputs and outputs are as inherently safe and benign as possible.
- Minimize depletion of natural resources.
- Strive to prevent waste.

www.shutterstock.com · 198980597

Additionally, green engineering:

- Develops and applies engineering solutions while being cognizant of local geography, aspirations, and cultures.
- Creates engineering solutions beyond current or dominant technologies; improves, innovates, and invents (technologies) to achieve sustainability.
- Actively engages communities and stakeholders in the development of engineering solutions.

https://www.youtube.com/watch?v=UoyDcNx7rUA

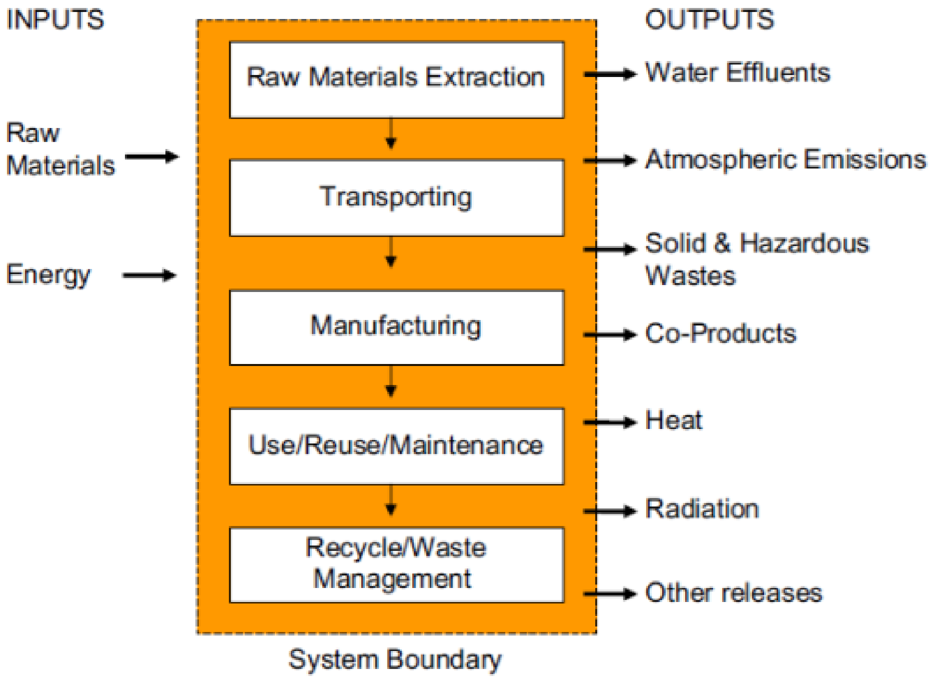
Principles of Green Engineering

- The 12 Principles of Green Engineering provide a framework for scientists and engineers to engage in when designing new materials, products, processes, and systems that are benign to human health and the environment.
- A design based on the 12 principles moves beyond baseline engineering quality and safety specifications to consider environmental, economic, and social factors.
- The breadth/scope of the principles' applicability is important.
- When dealing with design architecture, whether it is
  - the molecular architecture required to construct chemical compounds,
  - product architecture to create an automobile, or
  - urban architecture to build a city,
    - the same green engineering principles must be applicable, effective, and appropriate.

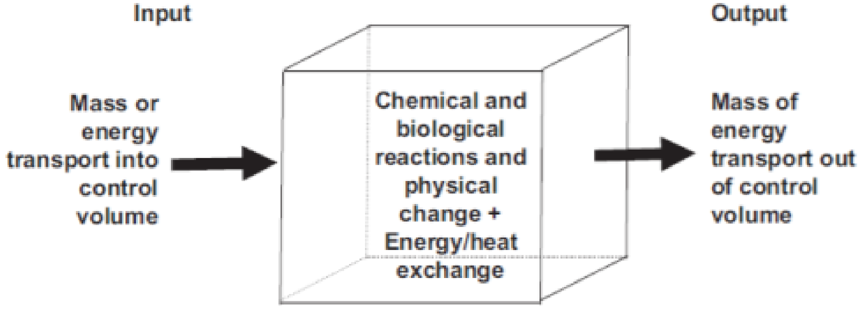
- Otherwise, these would not be principles but simply a list of useful techniques that have been successfully demonstrated under specific conditions.
- Just as every parameter in a system cannot be optimized at any one time, especially when they are interdependent, the same is true of these principles.
- There are cases of synergy in which the successful application of one principle advances one or more of the others

- Just as every parameter in a system cannot be optimized at any one time, especially when they are interdependent, the same is true of these principles.
- There are cases of synergy in which the successful application of one principle advances one or more of the others
- In other cases, a balancing of principles will be required to optimize the overall system solution.
- two fundamental concepts that designers should strive to integrate at every opportunity:
  - life cycle considerations
  - the first principle of green engineering, inherency.

Green Engineering and Sustainable Design Aspects of Waste Management



Life cycle stages of a process



$$\text{Efficiency} = \frac{E_{\text{in}} - E_{\text{out}}}{E_{\text{in}}} \times 100$$

Life cycle and inherency

The materials and energy that enter each life cycle stage of every product and process have their own life cycle

If a product is environmentally benign but is made using hazardous or nonrenewable substances, the impacts have simply been shifted to another part of the overall life cycle.

Eg:

- A product or process is energy efficient or even energy generating (e.g., photovoltaics),
- but
- the manufacturing process consumes energy to a degree that offsets any energy gains,
- there is no net sustainability advantage

- Designers should consider the entire life cycle, including those of the materials and energy inputs.
- The life cycles of materials and energy begin with acquisition (e.g., mining, drilling, harvesting) and move throughout manufacturing, distribution, use, and end of life.
- It is the consideration of all of the impacts that is needed when applying the green engineering principles.
- This strategy complements the selection of inherently benign inputs that will reduce the environmental impact across life-cycle stages.

- Making products, processes, and systems more environmentally benign generally follows one of the two basic approaches:
  - changing the inherent nature of the system
  - changing the circumstances/conditions of the system

    Eg:

    - Although inherency may, for example, reduce the intrinsic toxicity of a chemical;
    - a conditional change can include controlling the release of, and exposure to, a toxic chemical.

- Inherency is preferable for various reasons, most importantly to prevent "failure".
- By relying on technological control of system conditions, such as air scrubbers or effluent treatment, there is a potential for failure that can lead to a significant risk to human health and natural systems.
- However, with an inherently more benign design, regardless of changes in conditions or circumstances, the intrinsic nature of the system cannot fail.

12 Principles of Green Engineering

1. Inherent Rather Than Circumstantial

2. Prevention Instead of Treatment

3. Design for Separation

4 Maximize Efficiency

5. Output-Pulled Versus Input-Pushed

6. Conserve Complexity

7. Durability Rather Than Immortality

8. Meet Need, Minimize Excess

9. Minimize Material Diversity

10. Integrate Material and Energy Flows

11. Design for Commercial "Afterlife"

12. Renewable Rather Than Depleting

- The 12 Principles of Green Engineering provide a structure to create and assess the elements of design relevant to maximizing sustainability.
- Engineers can use these principles
  - as **guidelines to help ensure that designs for products, processes, or systems have the fundamental components, conditions, and circumstances necessary to be more sustainable**.

https://www.youtube.com/watch?v=i2198IF_ZfU

1. Inherent Rather Than Circumstantial

Designers need to strive to ensure that all materials and energy inputs and outputs are as inherently nonhazardous as possible.

- Although the negative consequences of inherently hazardous substances (whether toxicological, physical, or global) may be minimized, this is accomplished only through a significant investment of time, capital, material, and energy resources.
  - Generally, this is not an economically or environmentally sustainable approach.
- Designers should evaluate the inherent nature of the selected material and energy inputs to ensure that they are as benign as possible as a first step toward a sustainable product, process, or system.
- Similarly, molecular designers are developing methods and technologies to create inherently benign material and energy sources.

1. Inherent Rather Than Circumstantial

For cases in which inherently hazardous inputs are selected,

- Hazard will either be removed in the process, usually during purification or cleanup steps, or incorporated into the final output.
- Hazards that are eliminated in-process from the final product
  - by optimized operating conditions
  - will require constant monitoring and containment and
  - may also require eventual removal to a permanent off-site storage and disposal facility.
- Each step requires engineered safety precautions that could fail.

What if these hazards are not removed but instead incorporated into the final product?

- Strategies for incorporating hazards into a product or process as long as the hazard is continually recycled and reused do exist,
- but this approach requires resource expenditure for monitoring and control throughout the hazard's lifetime.
- These methodologies depend on the transport of these hazards to maintain "closed-loop" cycling, thereby increasing the risk of release through accidents, spills, and leaks.
- Ideally, inputs to the system will be inherently less hazardous, which significantly reduces the risks of failure and the resources expended on control, monitoring, and containment

2. Prevention Instead of Treatment

Waste is assigned to material or energy that current processes or systems are unable to effectively exploit for beneficial use

- It is better to prevent waste than to treat or clean up waste after it is formed.
- Regardless of its nature, the generation and handling of waste consumes time, effort, and money.
- Furthermore, hazardous waste demands even greater additional investments for monitoring and control.
- There are many tools available to engineers and chemists to reduce the amount of waste that is formed in a process
- If one includes the cost of waste disposal into the process optimization, then manipulating the process parameters allows will the engineer to adjust the performance of the system to achieve the least costly overall solution, and the one that produces the lowest amount of waste.

Technologies targeted toward waste-free design at any scale are based on the same fundamental concept: inputs are designed to be a part of the desired output.

This concept has been described at the molecular scale as "atom economy" and can be extended across design scales as the "material economy".

3. Design for Separation

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

- More applications of energy efficient, but often more capital intensive technologies, will have to be developed
- A key enabler will be the combination of highly selective materials that can “grab” or “pass” certain molecules from those that are closely related in size or other properties, with manufacturing technologies, such as hollow fiber membranes, to lead to scalable energy efficient separation methods.

- Product separation and purification consume the most energy and material in many manufacturing processes.
  - Many traditional methods for separations require large amounts of hazardous solvents, whereas others consume large quantities of energy as heat or pressure.
- Appropriate up-front designs permit the self-separation of products using intrinsic physical/chemical properties, such as solubility and volatility rather than induced conditions, decrease waste and reduce processing times.
- A similar design strategy can be applied across scales such that the final product, process, or system is shaped from components with desired properties.
  - This approach minimizes the energy and materials necessary to isolate the desired output from a complicated matrix of undesirable and valueless extraneous matter.
  - The components of the unwanted matrix are often classified as waste, which requires time, money, and resources for handling, transportation, disposal, and possible monitoring.

- **Design decisions at the earliest stage can impact the ease of product separation and purification for later reuse and recycling of components.**

- Greatest obstacles to recovery, recycle, and reuse: Economic and technical limitations in separating materials and components
  - These obstacles can be overcome by avoiding permanent bonds between two different materials wherever possible.

- Up-front consideration for separation and purification avoids
  - the need to expend materials and energy to harvest the desired output across all design scales and throughout the life cycle

4. Maximize mass, energy, space, and time efficiency

Products, processes, and systems should be designed to maximize mass, energy, space, and time efficiency.

- This is achieved by informing scientists and engineers to create designs that maximize efficiency in multiple areas such as mass, energy, space (i.e. real estate) and time.
- This is a simple and logical path that should be taken and the benefits gained can be quite significant.
- Processes and systems often use more time, space, energy, and material than required, the results could be categorized as “inefficiencies”
- If a system is designed, used, or applied at less than maximum efficiency, resources are being wasted throughout the life cycle.
- The same design tools traditionally used by engineers to increase efficiency can be even more broadly applied to increase intensity
    - That is, space and time issues can be considered along with the material and energy flow to eliminate waste.

◦In optimized systems there is a need for real-time monitoring to ensure that the system continues to operate at the intended design conditions

5. Output-Pulled Versus Input-Pushed

Products, processes, and systems should be “output pulled” rather than “input pushed” through the use of energy and materials

- Manufacturing systems can be based on “just-in-time” manufacturing—goods produced to meet end user demand exactly for timeliness, quality, and quantity.
  - This can be more broadly defined such that the end user can be the final purchaser of the product or another process further along the production line.
  - Just-in-time manufacturing requires that equipment, resources, and labor are only available in the amount required and at the time required to do the job.
  - Only the necessary units are produced in the necessary quantities at the necessary time by bringing production rates exactly in line with demand.

5. Output-Pulled Versus Input-Pushed

Planning manufacturing systems for final output eliminates

- the wastes associated with overproduction,
- waiting time,
- processing,
- inventory,
- and resource inputs.

6. Conserve Complexity

- Embedded entropy and complexity must be viewed as an investment when making design choices on recycle, reuse, or beneficial disposition.
- The amount of complexity that is built into a product, whether at the macro, micro, or molecular scale, is usually a function of expenditures of materials, energy, and time.
- The complexity in a beginning state depends on factors such as the number of atoms and/or functional groups present in a molecule, the type, quality and quantity of energy within a system, and the economic value in a starting material or process.
- This concept of retaining complexity can also be applied to the end-of–life (EOL) considerations for products.

- Attention is being directed towards designing products with characteristic that are favorable for recycle, reuse and repurposing.
- Such approaches include
  - products made with construction techniques that allow for easy, fast and safe disassembly,
  - use of materials that have minimal complexity and are abundant,
  - modular structures that allow for upgrades of the technical components without the need to entirely replace the product, and
  - utilization of the fewest number and least different types of materials.
- While this is only one approach for EOL considerations in product design, this approach clearly demonstrates the application of holistic thinking

6. Conserve Complexity

- High complexity should correspond to reuse,
- Substances of minimal complexity are favored for value-conserving recycling, where possible, or beneficial disposition, when necessary.
- End-of-life design decisions for recycle, reuse, or beneficial disposal should be based on the invested material and energy and subsequent complexity across all design scales.

7. Durability rather than Immortality

Targeted durability, not immortality, should be a design goal.

- Products that will last well beyond their useful commercial life often result in environmental problems, ranging from solid waste disposal to persistence and bioaccumulation.
- It is therefore necessary to design substances with a targeted lifetime to avoid immortality of undesirable materials in the environment.
- This strategy must be balanced with the design of products that are durable enough to withstand anticipated operating conditions for the expected lifetime to avoid premature failure and subsequent disposal.
- Effective and efficient maintenance and repair must also be considered, so that the intended lifetime can be achieved with minimal introduction of additional material and energy throughout the life cycle.

- By targeting durability and not immortality as a design goal, the risk to human and environmental health at end of life is significantly reduced.

  Eg: 1

  - single-use disposable diapers consisting of several materials, including nonbiodegradable polymers, have represented the single largest nonrecyclable fraction of municipal solid waste. Although this product has a short useful lifetime, it remains a significant environmental problem well beyond its targeted and defined need.
  - One solution is a new starch-based packing material, Eco-fill, which consists of foodgrade inputs (starch and water) that can be readily dissolved in domestic/industrial water systems at the product's end of life, and is competitive with traditional polystyrene packing.

  Eg. 2:

  using biologically based polylactic acid to create plastics and fibers instead of petroleum-based polyacrylic acid, which is not biodegradable

- By designing durability, but not immortality, into this product, Eco-fill achieves its intended use without long-term environmental burdens

8. Meet Need, Minimize Excess

Design for unnecessary capacity or capability (e.g., “one size fits all”) solutions should be considered a design flaw.

- Anticipating the necessary process alertness and product flexibility at the design stage is important.
- However, the material and energy costs for overdesign and unusable capacity or capability can be high.
- There is also a tendency to design for worst-case scenarios or optimize performance for extreme or unrealistic conditions, which allow the same product or process to be used regardless of local spatial, time, or physical conditions.
- This requires incorporating and subsequently disposing and treating components whose function will not be realized under most operating conditions.

9. Minimize Material Diversity

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

- Products as diverse as cars, food packaging, computers, and paint all have multiple components. In an automobile, components are made from various plastics, glasses, and metals.
- Within individual plastics there are various chemical additives, including thermal stabilizers, plasticizers, dyes, and flame-retardants.
- This diversity becomes an issue when considering end of-useful-life decisions, which determines the ease of disassembly for reuse and recycle.
- Options for final disposition are increased through up-front designs that minimize material diversity yet accomplish the needed functions.

At the process level,

- This is being done by integrating desired functionality into polymer backbones (contains a nitrogen-containing functional group and a metallate anion bonded to nitrogen in the functional group by ion pairing through Coulomb attraction) and
- thereby avoiding additives at a later stage in the manufacturing process.
- Tailoring polymer properties can have a positive environmental effect in cases in which leaching of additives may be an issue and in cases in which ease of recycling is important.

On the product scale,

- Selected automobile designers are reducing the number of plastics by developing different forms of polymers to have new material characteristics that improve ease of disassembly and recyclability.
- This technology is currently applied to the design of multilayer components, such as door and instrument panels.

For example,

  - Components can be produced using a single material, such as metallocene polyolefins, that are engineered to have the various and necessary design properties.
  - Through the use of this monomaterial design strategy, it is no longer necessary to disassemble the door or instrument panel for recovery and recycling.

On the molecular scale,

this principle is illustrated with “one-pot” or cascading reactions, or self-assembly processes that replace multistep reactions

10. Integrate Material and Energy Flows

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

- The principle of Integrating Material and Energy Flows reminds us to treat processes as an entire system, and use the inter-relationships of the parts to our advantage.
- Chemical Engineers would recognize this as the application of Process Integration.
- Process integration is best understood as a holistic, systematic framework to optimize the mass and energy required for a given process.
- By taking advantage of existing energy and material flows, the need to generate energy and/or acquire and process raw materials is minimized.

At the process scale,

- this strategy can be used to take the heat generated by exothermic reactions (An exothermic process releases heat, causing the temperature of the immediate surroundings to rise) to drive other reactions with high activation energies.
- Byproducts formed during chemical reactions or through purification steps can become feedstocks in subsequent reactions.
- Cogeneration energy systems can be used to generate electricity and steam simultaneously to increase efficiency.
- In this manner, “waste” material and energy can be captured throughout the production line, facility, or industrial park and incorporated into system processes and final products.

10. Integrate Material and Energy Flows

- It is important to consider the availability of energy and material for a product or process.
- Energy inputs from sources, such as waste heat from adjacent processes or incorporation of already existing materials,
  - may significantly benefit the life cycle, reducing the need for raw materials and energy acquisition and requiring less processing and disposal.

11. Design for Commercial “Afterlife”

- Products, processes, and systems should be designed for performance in a commercial “afterlife.”
  - How often do you get a new computer, gaming console, phone?
  - Do you know what happens to the old ones when you are more concentrated in finding out how the features work in the new device?
- Principle 11 helps us to think about those aspects as we are designing new processes, products and services.
- The idea is to make it easy for the user to do the right thing, and avoid unnecessary impacts after a product or process has reached the end of its usable life.
- If we do not take into consideration end-of-life aspects, we can have literally tones of materials either in landfills or being savaged in less than safe conditions.

- In many instances, commercial end of life occurs as a result of technological or stylistic obsolescence/uselessness, rather than a fundamental performance or quality failure.
- To reduce waste, components that remain functional and valuable can be recovered for reuse and/or reconfiguration.
- This strategy encourages up-front modular design,
  - which reduces the need for acquiring and processing raw materials by allowing the next-generation designs of products, processes, or systems to be based on recovered components with known properties.

By incorporating commercial “afterlife” into the initial design strategy, rather than as an afterthought at end of life,

- the value added to molecules, processes, products, and systems could be recovered and reused at their highest value level as functional components.
- This case is most compelling when end of life is premature and not a fundamental quality failure, as in the case of personal electronics.

Eg: Cellular telephones, personal digital assistants, and laptop computers are often retired as styles change or technology advances; however, the physical components are still fully functional and therefore valuable.

- Embedded ISO 11469 identification codes for plastic type on plastic parts increase the chances of reuse and make it easier to sort materials that are in demand.
- Thin-walled plastic design conserves the amount of material needed while maintaining strength requirements and yields extra environmental benefits by reducing the amount of fuel needed to transport new, lighter products.
- Non-painted plastics make recycling and recovery easy.

- Designing products with components that can be recovered would significantly reduce end-of-life burdens and manufacture of duplicate components in the next-product generation.
  - For example, approximately 90% of Xerox equipment is designed for remanufacture (36).
- Converting old industrial buildings to housing is an example at the systems scale.

Xerox ® Uses Remanufactured Modules (https://www.researchgate.net/publication/301796291_A_Compilation_of_Design_for_Environment_Guidelines/figures?lo=1)

12. Renewable Rather Than Depleting

Material and energy inputs should be renewable rather than depleting.

- The nature of the origin of the materials and energy inputs can be a major influence on the sustainability of products, processes, and systems.
- Whether a substance or energy source is renewable or depleting can have far-reaching effects. Every unit of finite substance used in a consumptive manner incrementally moves the supply of that substance toward depletion.
- Certainly, from a definitional standpoint, this is not sustainable.
- Because virgin substances require repetitive extractive processes, using depleting resources causes ongoing environmental damage.

- Renewable resources, however, can be used in cycles in which the damaging processes are not necessary or at least not required as often.
  - Biological materials are often cited as renewables.
  - However, if a waste product from a process can be recovered and used as an alternative feedstock or recyclable input that retains its value, this would certainly be considered renewable from a sustainability standpoint.
  - Examples include recovering biomass feedstocks, treating wastewater with natural ecosystems and biobased plastics.

Green chemistry

- The approach in chemical sciences that efficiently uses renewable raw materials, eliminating waste and avoiding the use of toxic and hazardous reagents and solvents in the manufacture and application of chemical products.
- Green chemistry takes into account the environmental impact and seeks to prevent or lessen that impact through several key principles outlined below.

12 key principles of green chemistry as formulated by P.T. Anastas and J.C. Warner, in *Green Chemistry: Theory and Practice*, 1998.

1. **Prevention**. It is better to prevent waste formation than to treat it after it is formed.

2. **Atom economy.** Design synthetic methods to maximize incorporation of all material used into final product.

3. **Less hazard**. Synthetic methods should, where practicable, use or generate materials of low human toxicity and environmental impact.

4. **Safer chemicals**. Chemical product design should preserve efficacy whilst reducing toxicity.

5. **Safer solvents**. Avoid auxiliary materials - solvents, extractants - if possible, or otherwise make them innocuous.

https://www.youtube.com/watch?v=ATn92XwdgC4

6. **Renewable feedstocks**. Raw materials should, where practicable, be renewable.
7. **Reduce derivatives**. Unnecessary derivatization should be avoided where possible.
8. **Smart catalysis**. Selectively catalyzed processes are superior to stoichiometric processes.
9. **Degradable design**. Chemical products should be designed to be degradable to innocuous products when disposed of and not be environmentally persistent.
10. **Real-time analysis for pollution prevention**. Monitor processes in real time to avoid excursions leading to the formation of hazardous materials.
11. **Hazard and accident prevention**. Materials used in a chemical process should be chosen to minimize hazard and risk for chemical accidents, such as releases, explosions, and fires.

12. Atom economy. Design synthetic methods to maximize incorporation of all material used into final product.

Prevention

- Simply, "Less Waste is directly proportional to Less Pollution“.
- Prevention. It is better to prevent waste formation than to treat it after it is formed.
- Generally, it describes the ability to update chemical transformations in order to limit the generation of hazardous waste as a significant advancement towards contamination or pollution avoidance.
- By preventing waste generation, the risks associated with waste storage, transportation, and treatment could be limited.
- A solid example can be the pulp and paper industry, usage of chlorine compounds in processes produce toxic chlorinated organic waste.
- Green chemistry developed a method to convert wood pulp into paper using oxygen, water, and polyoxometalate salts while producing only water and carbon dioxide as by-products.
- Isn’t that great!

Green Chemistry Control Keys

Green Chemistry Control Keys

So, what are possible avenues for changing the existing practices towards the minimum-risk alternatives?

There are several controls that can be manipulated at different stages of a chemical manufacturing process.

- **Using alternative feedstock or starting materials**: Selection of the starting materials has a major effect through the whole synthetic pathway.
- ***Using alternative reagents***: Reagents are needed to transform the starting molecules into a target substance. At this point, a chemist must balance the criteria of chemical efficiency and availability with potential hazards.

Using alternative solvents:

- Many of the currently used solvents are volatile organic compounds. Many of those are responsible for air quality problems (smog, etc.) when released to air.
- While the traditional organic solvents are easily available, well characterized, and regulated, there is a push for alternative systems that are more environmentally benign in the long run – aqueous solvents, ionic liquids, immobilized solvents, supercritical fluids, etc.
- (Principle #5) The choice of an alternative solvent requires careful and specific analysis, which determines if the new process would be as efficient or as cost-effective.
- How such trade-offs are resolved is discussed later in this lesson.

Changing target product:

- Chemistry is function oriented – the target chemical is needed to perform a certain function or possess certain properties.
- This avenue is related to the search of the alternative final product, which may require radical change in the way synthesis is done (Principle #3).
- Through chemical research, it is possible to identify those parts of a molecule that provide the chemical with a desired function as well as those parts that provide toxicity.
- Maximizing the former and minimizing the latter is a worthy challenge for chemical design.

Process monitoring:

- Real time measurements (sensing) of process parameters and concentrations sometimes provide valuable information and hints how the process should be tuned to avoid adverse effects or risk (Principle #11).
- Also, process monitoring may open avenues for making the process more cost-effective.

- ***Alternative catalysis***: Catalysis bears enormous benefits not only from the standpoint of technical efficiency.
- Environmental benefit results from the use of a much smaller amount of reagents in catalyzed reactions, which otherwise would contribute to waste stream. Using less chemicals is also economically profitable.
- It should be noted, though, that many classes of catalysis (e.g., heavy metals) are very toxic.
- Hence, the challenge of alternative catalysis is to develop environmentally benign options (Principle #9).

Summary

- Innovation in design engineering has resulted in feats ranging from the microchip to space travel.
- Now, that same innovative tradition must be used to design sustainability into products, processes, and systems in a way that is scalable.
- By using the 12 Principles of Green Engineering as a framework, the conversation that must take place between designers of molecules, materials, components, products, and complex systems can occur using a common language and a universal method of approach.
- The principles are not simply a listing of goals, but rather a set of methodologies to accomplish the goals of green design and sustainability.

- Because of practical, logistical, economic, inertial, and institutional reasons, it will be necessary in the near term to optimize unsustainable products, processes, and systems that are currently in place.
- This is an important short-term measure, and the green engineering principles provide a useful framework for accomplishing this optimization.
- Through re-engineering of entire systems (e.g., personal transportation systems), greater degrees of freedom with potential benefits for sustainability are obtained, and therefore, the principles become more essential.
- Ultimately, a redefining of the problem, from the molecular to the systems level, is where fundamental and even inherent sustainability can be achieved.
- This is where the 12 principles are most powerful.

- Although each principle can be demonstrated at each scale, the 12 principles have neither been implemented systematically nor across all scales.
- Systematic integration of these principles is key toward achieving genuine sustainability in the design of molecules, products, processes, and systems, for the simultaneous benefit of the environment, economy, and society, and the ultimate goal of sustainability.

References

- https://www.e-education.psu.edu/eme807/node/534
- https://www.epa.gov/green-engineering/about-green-engineering
- https://www.acs.org/content/acs/en/greenchemistry/principles/12-design-principles-of-green-engineering.html
- https://pubs.acs.org/doi/pdf/10.1021/es032373g
- https://www.waternz.org.nz/Attachment?Action=Download&Attachment_id=1351
- https://www.michigan.gov/documents/deq/deq-oea-tou-GCE101-Principles_Reddy_514449_7.pdf