3. **Green Engineering: Fundamental Principles and Applications**

3.1. **Introduction to Green Engineering**

In the last decades scientists in developed and developing human societies became aware that rapid economic growth and unrestrained use of natural resources caused substantial environmental problems and disrupted the future sustainability of many regions of the world. It has been recognised that pursuing high growth objectives without considerations of environmental degradation and natural resources depletion threatens sustainability.

The environmental movements of the 1960s and 1970s protested for the trends in economic growth and the inevitable environmental pollution on regional, national and global scale. Major environmental problems, like the ozone hole in the stratosphere, the global warming and the greenhouse effect, the spread of environmental pollution by polychlorinated compounds in remote places of the planet, plastic pollution of the oceans, the depletion of natural resources of fresh water, desertification, etc, are some of the problems causing international concern.

Green chemistry as a scientific movement of the 1990s for better design and innovations in the chemical industry was extended to “Green Engineering” which covers technological applications, engineering processes and products.

According to Environmental Protection Agency (EPA): "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 to the design and development phase of an industrial process or product. The goal of the Green Engineering is to incorporate risk related concepts into chemical processes and products designed by academia and industry..

Green Engineering is aiming to four major sections of the scientific and technological community: academia, university teachers (instructing students on new thinking in engineering processes and applications, through academic lectures and workshops that disseminate green engineering material), Software scientists (to provide engineers with integrated risk based tools for assessing hazards in process design and other programmes), industrial chemical engineers and other scientists (continuing education courses, providing new academic material, methodologies and case studies which illustrate green engineering alternatives in chemical process, new designs and technological innovations with green credentials for engineers), Continuous dissemination of sources and green engineering materials to academia and industry (continuous flow of information and ideas for new case studies and process design methodologies of green engineering).
The term Green Engineering in Greek has some problems in translation of the word “Engineering” in 2009 the (Πράσινη Μηχανική ή Τεχνολογία) which can mean also “technology”. The ΤΕΕ (Τεχνικό Επιμελητήριο Ελλάδος, Technical Chamber of Greece) with more than 100,000 members encompassing all the engineering disciplines as well as architecture in Greece) in 2009 (1.4.2009) organized a series of lectures on the term of “engineering”. The speakers though that the pest terminology was μηχανοτεχνία. The term for “Green Engineering” was proposed “Πράσινη Μηχανική (“Μηχανοτεχνία”, or “Τεχνολογία”). In this chapter we use the term “Green engineering” in terms of technology (processes, products, design).

Figure 3.1. Green Engineering is a substantial addition to Green Chemistry with very similar aims and principles which lead to sustainable developments through engineering and new design of processes and products.

In fact “Green Engineering” is the process and design of products aiming to conserve natural resources leading to sustainability goals. Also, green engineering aims to reduce the impact of processes and products to the natural environment. The term “green engineering” is applied to a variety of products, like houses, vehicles, consumer products (materials, electrical and electronic equipment) and devices that requires engineering technologies in the construction or making.

Green engineers can now graduate from various university engineering departments in developed industrialised countries. Other engineering graduates can have special training on various fields, attending special classes to understand how materials and other components can be made in an environmentally-friendly way. For example, engineers and architects concerned with home design may learn about the latest building materials and techniques. Green engineering and design is nowadays an important additional qualifications for every aspect of engineering.
3.2. The Twelve Principles of Green Engineering

Green Engineering (GE) focuses on how to achieve sustainability through science and technology. As in the case of Green Chemistry, Green Engineering are covered by 12 principles which were presented for the first time by Paul T. Anastas and Julie B. Zimmerman (Environmental Science and Technology, March 1, 95A-, 2003).\(^1\)

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. The breadth of the principles’ applicability is important. The Green Engineering principles must be applicable, effective, and appropriate. Otherwise, these would not be principles but simply a list of useful techniques. It is also useful to view the 12 principles as parameters in a complex and integrated system. 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.

The twelve principles of Green Chemistry cover the fundamental aspects of chemistry, chemical engineering and technology. In the case of Green Engineering the twelve principles are similar aspects of basic aims and goals for attaining sustainability through green engineering principles. The 12 Principles of Green Engineering have been implemented by scientists of American Chemical Society (ACS).

<p>| Principle No. 1. Materials and energy must be inherently non-hazardous, rather than circumstantial |
| Designers need to strive to ensure that all materials and energy inputs and outputs are as inherently nonhazardous as possible. |
| Principle No. 2. Prevention of waste instead of treatment |
| It is better to prevent waste than to treat or clean up waste after it is formed. |
| Principle No. 3. Design for separation and purification processes |
| Separation and purification operations should be designed to minimize energy consumption and materials use. |
| Principle No. 4. Maximize efficiency in products and processes |
| Products, processes, and systems should be designed to maximize mass, energy, space, and time efficiency. |
| Principle No. 5. Output-pulled versus input-pushed |
| Products, processes, and systems should be &quot;output pulled&quot; rather than &quot;input pushed&quot; through the use of energy and materials |
| Principle No. 6. Conserve complexity |
| Embedded entropy and complexity must be viewed as an investment when making design choices on recycle, reuse, or beneficial disposition. |</p>
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<th>Principle No. 7. Durability Rather than Immortality</th>
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<td>Targeted durability, not immortality, should be a design goal for products. After useful use of a product to disintegrate under natural conditions</td>
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<th>Principle No. 8. Meet Need, Minimize Excess (Products)</th>
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<td>Design for unnecessary capacity or capability (e.g., &quot;one size fits all&quot;) solutions should be considered a design flaw.</td>
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<th>Principle No. 9. Minimize Material Diversity</th>
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<td>Material diversity in multicomponent products should be minimized to promote disassembly and value retention</td>
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<th>Principle No. 10. Integrate Material and Energy Flows</th>
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<td>Design of products, processes, and systems must include integration and interconnectivity with available energy and materials flows</td>
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<th>Principle No. 11. Design for Commercial &quot;Afterlife&quot;</th>
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<td>Products, processes, and systems should be designed for performance in a commercial &quot;afterlife.&quot;</td>
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<th>Principle No. 12. Renewable Rather Than Depleting</th>
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<td>Material and energy inputs should be renewable rather than depleting</td>
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**Figure 3.2.** Green Engineering is an added qualification. Green Engineers design and apply green principles in their design of chemical processes and products to achieve sustainability and environmental protection.
Principle No. 1. Inherent rather than circumstantial. There is a need for all materials and energy inputs to be Inherently non-hazardous as possible

Many industrial starting materials are inherently hazardous from the beginning and their products inevitably will be toxic and cause environmental problems. Although the trend now is to minimise their negative aspects by investing in environmental mitigation processes, this is no an environmentally sustainable approach. The initial design of the products must evaluate the inherent nature of the selected material (toxicological and physicochemical properties) and calculate the energy inputs required. The first step must aim for a sustainable product and process with materials that are non-hazardous. Designers must developed methods and technological innovations to create inherently non-hazardous materials, for humans and the environment. If there is no alternative material, the design and the process must strive to remove the hazard in the final steps of the process. These can be achieved during purification or the cleanup steps of the product.\(^4\)\(^6\)

The ideal case will be to use materials and inputs of energy and other reagents that are less hazardous, thus reducing the risks for environmental impacts and the cost to monitor, control and contain the environmental pollution caused by the rejection of the product as waste.

Principle No. 2. Prevention is best than treatment. Prevention of waste is better than to clean up afterwards

The initial design of industrial processes and products contains the intention to produce minimum waste (“zero-waste”) but the notion is criticised from other scientists as ignoring the laws of nature. These laws are the first and second thermodynamic axioms and rules of enthalpy in systems.\[*\]

\[* In order to remind the readers the thermodynamic laws, briefly “...The first Law of thermodynamics distinguishes between two physical processes: energy transfer as work, and energy transfer as heat. It tells how this shows the existence of a mathematical quantity called the internal energy of a system. The internal energy obeys the principle of conservation. The first law of thermodynamics states that perpetual motion machines of the first kind are impossible. The second law of thermodynamics distinguishes between reversible and irreversible physical processes. It tells how this shows the existence of a mathematical quantity called the entropy of a system, and it expresses the irreversibility of actual physical processes by the statement that the entropy of an isolated macroscopic system never decreases....”.

Waste is assigned to material or energy that the present processes or systems are unable to effectively exploit for beneficial use. It is natural when we use energy in the production of products that this energy is absorbed and the entropy decreases. With the use of the products the “disturbance” increases (entropy), the products disintegrates and is transformed into waste. The scientists of green chemistry indicate that the concept of waste is human. There are no inherent properties in energy or products which inevitably will transform them into waste. Waste generation can be avoided or prevented wherever possible.

PT. Anastas and JB. Zimmerman in their pioneering article (2003),\(^1\) stated that “....Green chemistry scientists will like to redesign products and use of energy in industrial processes in such a way so that waste is minimized. The generation of waste and its handling costs efforts and money.
There are new technologies that aim towards waste-free design at any scale and are based on the same concept: inputs are designed to be part of the desired output. This concept at the molecular scale (chemical reactions) has been described as “atom economy” and can be extended across design scales as the “material economy”…”. There are now many options for energy generation that do not produce waste, one of these systems is fusion energy which can lead us to energy sustainability. 8-12

**Principle No.3. Design strategy for separation and purification.** Processes for products with minimum energy consumption and material use

The traditional methods of manufacturing processes until now consume vast amounts of energy for separation of the products and cleaning with toxic solvents. Heat and pressure is applied in most conventional processes which increase the demand for energy. Green technologists would like to change this trend and reduce the use of energy. This can be achieved by radical changes in the design of the process. Green technologies will like to take design decisions at the earliest stage of manufacturing process so that self-separation and purification will be included in the process.

Economic and technical limitations in separating materials and components are among the greatest obstacles to recovery, recycle and reuse of materials and reagents. Green engineers studied how these obstacles can be overcome. Avoiding permanent bonds between two different materials is one solution. Fasteners that are designed for disassembly can be incorporated into the design strategy. At the molecular level in the chemical industry and in the laboratory the separation and purification is performed with distillations and column chromatography. Both methods are energy intensive and consume large quantities of toxic solvents. Scientists should aim to reduce the need for these wasteful processes. Design of self-separation and purification will be included in the process.

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**Principle No. 4. Maximize mass, energy, space and time efficiency.** By better designing in chemical processes and systems

Efficiency in very important in every manufacturing process and makes economic sense. Materials, energy, time and space are important variables that green engineers can take into account when designing their alternative innovations in industrial processes. Large batch reactors in chemical manufacturing is a typical example of how things were made in the conventional way. These are considered now “old‖ technology. Microreactors that operate continuously at very low volume with efficient mixing, high productivity and digitalized information of the process are considered more efficient. The reduction in scale of the production can be applied also to other factors, such as eco-industrial plants in cities with easy access for the workers (less car dependency, less suburban sprawl, less time consuming).16-18
Figure 3.3. Green Engineering and its principles can maximize efficiency in manufacturing processes and minimize waste and environmental pollution. Designing in the early stages and alternative innovations for the conventional chemical processes can improve substantially their sustainability.

**Principle No. 5. Output-pulled versus input-pushed.**

More energy or material ("input-pushed") can increase output, but the same output can be achieved by new designing where chemical processes are "pulled" (e.g. removing products from reaction system) without additional energy or material.

Chemists and chemical engineers know from experience that a chemical reaction or transformation under high temperature, pressure, and additional material, will "puss" the balance the reaction forward, i.e. produce higher output of a desired product. (Le Châtelier’s Principle, system at equilibrium under stress). Chemical engineers in their desire to increase output of a manufacturing reaction were adding more energy (heat, pressure) or starting material to shift the equilibrium and get the desired output.

An example at the molecular level which can describe the chemical transformation is condensation reactions with the production of water. In order to increased the yield the water was eliminated from the product stream and thus the reaction was "pulled" to completion without additional energy or material. This is the new thinking in green engineering processes, the transformations must be "pushed" without extra energy and material with planning in advance manufacturing systems.

Another important aspect of manufacturing processes is the “just-in-time” manufacturing, which means products can be produced to meet the demand of the end user (final purchaser of the product) for the on exact for timeliness, quantity and quality. The good planning of manufacturing systems for the final output of a product can overcome waste, which is associated with overproduction, waiting time, processing, inventory and resource inputs.19-21
Principle No. 6. Conserve complexity. Products with high complexity should correspond to reuse, products with minimal complexity are favoured for value-conserving recycling or beneficial disposition.

This is another very important aspect of manufacturing products with in-build complexity. The higher the complexity of a product the higher the expenditure on materials, energy and time.

A good example is the computer chips that have a significant level of complexity invested in them. To recycle a silicon chip may not be efficient method for recovering the value of the starting material. Whereas, for the paper bag the complexity is very low, but in this respect the value of the product and its material do not warrant the energy for collection, recycling and remanufacturing of the same product. Green engineers must thing in the designing stage about the end-of-life of a product. How important are the decisions to recycle, reuse or have a beneficial disposal, based on the invested material and energy for the product and its complexity.22,23

Principle No. 7. Durability rather than immortality. Design goal for products that will last beyond their useful commercial life

It is desirable that products are well constructed and durable during their useful commercial life, but not to be persistent and result in environmental problems. These two properties, durability and persistence after use are two contrasting and must be balanced in the designing stages by green engineers. The design must aim at products that are durable enough to withstand operating conditions during their lifetime, and avoid premature disposal. Efficient maintenance and repair of a product without added material is an advantage. Immortality or persistence to environmental conditions after disposal are not desirable properties because through bioaccumulation can be dangerous to living organisms.

A very good example for this principle is the single-use disposable diapers. The durability is very important and manufacturers invest on several materials, especially non-biodegradable polymers (polystyrene). The disposal of diapers is now one of the most important environmental problems for landfills of municipal solid waste. Green chemists, after long research studies, have proposed the solution of starch-based packing material Eco-fill, that can be readily dissolved in water.24,25 In the last few years there are in the market diapers which can be cleaned and reused many times.26

The case of disposable plastic bags that everybody uses now for carrying consumer goods has become an international environmental problems due to the persistence of plastic in the water. Polymers made from biologically based materials is a new green chemistry initiative which replaces the petroleum-based polyacrylic acid polymers. Polyactic acid or polylactide is a thermoplastic aliphatic polyester derived from renewable resources, such as corn starch, tapioca products (roots) or sugarcanes. Lactic acid id produced by bacterial fermentation of starch. Polyactic acid is a product of green chemistry, can biodegrade under certain conditions, such as the presence of oxygen, and is difficult to recycle.27,28
Figure 3.4. Go green has become a slogan. Green Engineering is applied to many aspects of chemical manufacturing and new electronic products. Green engineering concentrates on how to promote sustainability through science and technology. Green engineers are engaged in designing new materials, products, processes and systems.

**Principle No 8. Green Engineering can meet needs and minimize excess.**

The global economic competition of the last decades has changed dramatically the new technological advances in great variety of consumer products. Although new technology covered most of human consumer needs and social aspirations, it contributed also to many excesses, waste and environmental degradation. New materials, natural resources, energy and technology were wasted in many industrialised countries for overdesign and unusual capabilities of various products. Many products after their commercial life cycle cause increasing environmental problems as waste due to their complexity, extreme persistence and difficulty in recycling.

A good example is the disinfection of drinking water by chlorine. The technology is very useful to protect human life. The centralised location of disinfection causes excess chlorination in short distances and reduced disinfection in further distances. An alternative and sustainable policy will be to install actuator and control system to regulate the dose of chlorination. Chemical industry can apply a new strategy to limit material, energy and other reagents by introducing the use of enzymes as catalysts that operate at mild conditions.  

**Principle No. 9. Minimize material diversity.** Reducing multiple components in products increases the possibility of useful reuse or recyclability

Most of the consumer products of today (cars, electric and electronic equipments, food packaging, etc) are made in such a way that include multiple components. Even plastic materials contain a variety of other chemicals, such as plasticizers, dyes, stabilizers, flame –retardants. These
added chemicals and in general material diversity increases the properties and useful function of products. But when these products come to the end of their life cycle they present a series of problems when considering disassembly, reuse and recyclability. Some products can be produced from one material than two or three. A good example is the new technology which is applied in plastics for cars. Different forms of polymer can have diverse properties and used for the construction of doors and instrument panels (metallocene and polyolefins have these properties and can be engineered to the different design properties). On the molecular level the example is the “one-pot” or cascading reactions that replace the multistep synthetic reaction in organic chemistry.\textsuperscript{32-34}

**Principle No. 10. Integrate local material and energy flows.** Products and processes must integrate with available energy and materials flows, Industrial parks can take advantage of the existing framework of energy. Industrial products and processes must take advantage of local and existing energy and material flows in the area where they operate, so that they can minimize the need for imports or transport from far away places of energy and raw materials. Also, at the local level they can exchange heat from other industrial units if there are exothermic operations. Byproducts from one industrial unit can become feedstocks for subsequent reaction processes in other industrial operations. In industrial parks, “waste” materials and energy can be captured throughout the production line and incorporated in other processes and other final products.\textsuperscript{35-38}

**Principle No. 11. Design for commercial “afterlife”.** Products and processes and components that remain functional can be recovered and reused.

Many commercial products, processes and systems after reaching their end of life become obsolete and have to be thrown away as waste. Green engineers have to take into account when designing these products. In order to reduce waste, some components or part of some processes as long as they remain functional can be reused or recovered as materials for another useful operation. Incorporating commercial “afterlife” properties into the initial design strategy of products and processes can save lots of material and energy with reuse and recovery of various parts. Mobile phones, computers, electrical equipment, printers, other commercial machines in offices or in the house become outmoded premature and had to be replaced with modern items. Designing products so that part of the components can be recovered would significantly reduce waste, and energy and materials for future products. Commercial “afterlife” is part of the green engineering design of new products.

There are many good examples of electrical machines and electronic products that have “end-of-life” design features so that can be disassembled into components, recycled, or reused with maintenance and easy repair. Xerox printers are designed so that after their commercial use, can be converted and be remanufactured. Various other big industrial companies have introduced green engineering design features in their products for easy repairs, recyclability or reuse after maintenance ((AT&T, General Electric, IBM, Procter & Gable, Whirlpool, etc).\textsuperscript{39-41}
In the last decade there is a major shift in the way industrial manufacturers have changed the design of their products in order to reduce the end-of-life burdens to the environment. The Product Life Cycle (PLC) analysis has become a standard method following the various stages of a product’s life. From starting materials, manufacture and final disposition the life of a product is analysed quantitatively from its environmental impact and natural resources use. It is represented with a cycle: Design—Manufacturing—Distribution—Customer—End-of-Life. Many software programmes have been developed recently dealing with PLC. The PLC is associated with engineering tasks, materials and energy, but also can involve marketing activities and new product development.

Figure 3.5. The Life Cycle of a product is considered a very valuable analysis of the manufacturing processes and the environmental problems which might be caused by the circulation of a certain product.

**Principle No. 12. Renewable rather than depleting. Materials and energy for manufacturing must be renewable for sustainable development**

The 20th century was characterized by a rapid economic growth that did not pay attention to natural resources and energy sources. This was the main cause for the extended environmental pollution and the depletion of valuable natural resources. Scientists and technologists agree that human civilization can not continue its path to material “prosperity” without renewable resources. Sustainability is in danger and societies can collapse from lack of natural resources. Renewable natural resources, that have the ability to be replaced through biological or other natural processes, can be used in sustainable cycles without damaging effects, but even in this situation there are limits. Renewable natural resources (material and energy) need to be managed carefully and to avoid exceeding their capacity to replenish. Renewability of natural resources and appropriate use is the key for sustainable development and protection of the environment.

Renewable natural resources are considered all biological materials, (biomass), solar energy, winds, geothermal energy, tides and any natural elements that are replenished with time. In the other end of the scale are depleting natural resources (which are cheaper and used extensively now),
such as coal, natural gas, petroleum (fossil fuels), minerals, agricultural land, the seas, fresh water, etc.\textsuperscript{44,46}

The framework of Green Engineering through its 12 principles covers some of the most important industrial processes and technological issues developed in the last decades. The 12 principles of Green Engineering are not a list of goals, but a set of the important methodologies that need changing in order to achieve these goals and promote sustainable development.

Education of engineers and changes in attitude and methods of the old professionals are the key components for green design and innovative alternatives. The new engineers have to be educated for the systematic integration of the 12 principles in molecular design, products, processes and manufacturing methods for the benefit of the society and the environment. The “old” ways of manufacturing have to be changed. We need to redefine the problems of sustainability, renewable materials, new energy sources and strategies to meet needs but at the same time environmental protection.

The American Society for Engineering Education, for example, has establish a Green Engineering programme to teach and promote issues of green design in industrial processes and systems. But also, many universities offering engineering courses in industrialized countries started in recent years new courses for Green Engineering and “clean” or “green” production technologies.

Two new books of Allen and Shonnard for Green Engineering are thought to be very important for the teaching of Green Engineering principles and practices at university level.\textsuperscript{47,48}

A new journal of Green Engineering that promotes innovative ideas and new research projects has started in October 2010 in Denmark (Journal of Green Engineering).\textsuperscript{49}
References


49. Journal of Green Engineering (River Publishers, October 2010, Aalborg, Denmark)