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Article

Engineering Sustainability: A Technical Approach to Sustainability

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Abstract: Sustainability is a critically important goal for human activity and development. Sustainability in the area of engineering is of great importance to any plans for overall sustainability given 1) the pervasiveness of engineering activities in societies, 2) their importance in economic development and living standards, and 3) the significant impacts that engineering processes and systems have had, and continue to have, on the environment. Many factors that need to be considered and appropriately addressed in moving towards engineering sustainability are examined in this article. These include appropriate selection of resources bearing in mind sustainability criteria, the use of sustainable engineering processes, enhancement of the efficiency of engineering processes and resource use, and a holistic adoption of environmental stewardship in engineering activities. In addition, other key sustainability measures are addressed, such as economics, equity, land use, lifestyle, sociopolitical factors and population. Conclusions are provided related both to pathways for engineering sustainability and to the broader ultimate objective of sustainability.

Keywords: engineering; engineering sustainability; sustainable development; resources; environmental impact; efficiency; processes; economics

1. Introduction

Engineering is the application of scientific and mathematical principles for practical purposes such as the design, manufacture, and operation of products and processes, while accounting for constraints invoked by economics, the environment and other sociological factors. Many technical advances are brought about through engineering. Engineering activities are significant contributors to economic development, standards of living and well-being of a society, and impact its cultural development and environment. Engineering is continually evolving as a profession [1,2], and engineering education is correspondingly continually changing [3].

Sustainable development is increasingly becoming a goal to which numerous countries throughout the world aspire. Overall sustainability has been defined in many ways, and is often considered to have three distinct components: environmental sustainability, economic sustainability and social sustainability. These three factors when considered separately usually pull society in different directions (e.g., economic sustainability may be achieved at the expense of environmental and social sustainability). Overall sustainable development in general requires the simultaneous achievement of environmental, economic and social sustainability. Achieving this balance is indeed a challenging task.

Although engineering is not directly one of the three components of sustainability cited above, it is indirectly linked to each. That is, engineering uses resources to drive much if not most of the world's economic activity, in virtually all economic sectors, e.g., industry, transportation, residential, commercial, *etc*. Also, resources used in engineering, whether fuels, minerals or water, are obtained from the environment, and wastes from engineering processes (production, transport, storage, utilization) are typically released to the environment. Finally, the services provided by engineering allow for good living standards, and often support social stability as well as cultural and social development. Given the intimate ties between engineering and the key components of sustainable development, it is evident that the attainment of sustainability in engineering is a critical aspect of achieving sustainable development, in individual countries and globally. In fact, Kreith [4] writes on sustainability, "no subject is more important to the engineering profession or the wider world that we live in."

The facts that all countries utilize engineering services and consume resources, and that impacts on the environment of engineering processes span from local to global, and that the world's economy is becoming increasingly globalized, together suggest that the quest for sustainable engineering is global in nature.

Engineering sustainability is taken here to be a comprehensive concept. That is, engineering sustainability is taken to involve the sustainable application of engineering in systems. Such systems include processes and technologies for harvesting resources, converting them to useful forms, transportation and storage, and the utilization of engineering products and processes to provide useful services such as operating computers, providing healthcare or sheltering people. Thus, engineering sustainability goes beyond the search for sustainable resources, and implies sustainable engineering systems, *i.e.*, systems that use sustainable resources, and that process, store, transport and utilize those resources sustainably.

Despite its importance, engineering sustainability is not well understood or widely accepted. According to Kreith [4], "Engineers are still trying to understand how the concept of sustainability fits in with our profession." He provides a partial explanation by noting that "It's reasonable that engineers would have trouble with (…) sustainability: There are no equations (…) that can optimize it and no widely agreed upon standards to which we can adhere. In fact, the concept is (…) nebulous."

The objective of this article is to identify and examine the key factors that need to be addressed to achieve engineering sustainability, as a way of outlining an engineering approach to sustainability that permits us to engineer sustainability into many facets of society. A pragmatic perspective is taken, and an illustration is presented to provide an example of a practical future sustainable engineering activity.

This article expands on a previous article by the author on energy sustainability [5,6], and somewhat parallels the approach taken in that article.

2. Approach

The focus of this article is on technical aspects of the quest for engineering sustainability, and less on the roles of economics, politics and other non-technical factors. Consequently, the present article is not necessarily the approach that would likely be taken by economists, business and industry leaders, politicians or sociologists, who have different foci and different paradigms through which they view engineering sustainability. Although these other perspectives can be useful and informative, the approach taken here is intentional and is considered by the author to be critical for addressing the fundamental issues and challenges relating to engineering sustainability.

Some reasons for this viewpoint follow:

- The economics and politics of many engineering questions vary spatially and temporally. Yet, the actual issues involved in achieving engineering sustainability often are mainly of a technical nature, and are not strongly dependent on locational jurisdiction and time.
- Prices of some of the products and services provided by engineering are somewhat artificial, in that they are influenced by political measures like taxes, rebates, incentives, penalties, limits, *etc*. For instance, notable variations can be observed in prices of commodities like metals and petroleum from one country to the next. Thus factors like costs and prices are sometimes akin to tools that politicians and society can use to achieve objectives. If the aim is engineering sustainability, then economic tools can be applied to foster the objective, but first one needs to determine the most advantageous method for achieving engineering sustainability, and this remains primarily a technical problem.
- A sound technical basis helps avoid confusion regarding engineering issues. For instance, the term "conservation," although commonly used by lay people, is often nonsensical technically because mass and energy are conserved quantities based on the laws of physics, even though they can be degraded. Conservation, as an aim, is thus confusing and misleading. The actual goal implied by lay people is the conservation of high-quality and useful commodities (e.g., refined materials, natural gas). The resources utilized to provide products and services ultimately become wastes, in the same quantity as supplied (in terms of mass and energy). But, the wastes are typically of low quality and usefulness. These illustrations demonstrate that a sound technical approach is often useful for addressing engineering sustainability rationally.
- The general concept of sustainability is relatively modern and is often vague and lacking in rigour. Approaches to sustainability often lack solid technical and scientific foundations, and corresponding rigorous methods [4,7]. Some propose the need for a science of sustainability, and initial steps have been taken in this direction [8–10]. The present author feels that a discipline of engineering sustainability is needed, providing part of the motivation for this

article. The technical approach taken in addressing engineering sustainability in this paper is intended to avoid vagueness, and to provide a pathway towards engineering sustainability.

Note that taking a technical approach is not intended to diminish the importance of non-technical factors like economics, sociology and politics in engineering sustainability, and that the approach is not necessarily comprehensive. The approach ultimately must be integrated with approaches of others, e.g., economists, ethicists and social scientists, given the importance of integrating engineering methods with other methods of achieving sustainability. In fact, economic, cultural, technological, institutional, and social factors reduce significantly the degrees of freedom which engineers are able to exercise in the real world, because, unlike social scientists or activists, engineers must perform work that not only is responsible societally (e.g., environmentally sensitivity), but also that functions in the world as it is. The approach adopted here seeks to assist efforts to move civilization towards engineering sustainability in particular and overall sustainability in general.

3. Sustainability and Sustainable Development

To appreciate the concepts underpinning engineering sustainability, it is informative to consider the concept and definitions of sustainability and sustainable development. Sustainable development was defined by the 1987 Brundtland Report of the World Commission on Environment and Development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." This definition implies that actions of present societies should not threaten cultures or living standards for societies. Other definitions and descriptions have been presented. The degree to which sustainable development can be achieved by countries varies, since countries differ according to such characteristics as size, wealth, living standards, culture, and political and administrative systems. Wealth and advanced technology may make it easier for industrialized countries to strive for sustainable development, but this is not always the case. The basic motivations and desires of societies, countries, cultures and people to advance appear not to have changed, and these aspirations usually require increasing use of engineering, consumption of resources and often yield correspondingly increasing emissions.

4. Engineering and Sustainability

Engineering is used in almost all facets of living and in all countries, and makes possible the existence of human civilizations. Different regions and societies adapt to their environments and determine their own resources and uses for engineering. The standards of life achieved in countries are often a function of engineering-related factors. Recently, efforts have increased to make engineering activities more sustainable and, simultaneously, attempts have been made to describe engineering sustainability and the requirements for it.

In some ways, the concept of engineering sustainability is simply the application of the general definitions of sustainability to engineering. In other ways, engineering sustainability is more complex and involved. That is, engineering sustainability involves the provision of engineering services in a sustainable manner, which in turn necessitates that engineering services be provided for all people in ways that, now and in the future, are sufficient to provide basic necessities, affordable, not detrimental to the environment, and acceptable to communities and people. Although this definition has some circular aspects, it emphasizes some of the essential points of engineering sustainability. A universal agreement on a definition of engineering sustainability has not yet been achieved.

Engineering-related sustainability definitions have been presented for some specific areas, like energy [4,11–18], although universal agreement on a definition has not yet been achieved. In some ways, the concept of energy sustainability provides a parallel case to engineering sustainability. Rosen [5,6] defines energy sustainability as the provision of energy services for all people in a sustainable manner, *i.e.*, in ways that, now and in the future, are sufficient to provide basic necessities, affordable, not detrimental to the environment, and acceptable to communities and people.

Increasing investigations are carried out into aspects of engineering sustainability, as well as the overall concept. On a broad basis, for instance, sustainability engineering is investigated from the perspective of it being a new emerging discipline (along with sustainability science) [19], while research in science to engineering sustainability is examined by Kajikawa [20]. A conceptual framework for sustainable engineering design is proposed [21], and the theory and practice of sustainable engineering are described [22,23]. A guide for sustainable engineering and design is developed [24], and the application of engineering to problem solving related to sustainability is examined [25]. The relation between sustainable development and professional practice is investigated [26]. The socio-technology of engineering sustainability is considered [27]. The sustainable use of natural resources and appropriate indicators are described [28]. The utilization of engineering sustainability to help improve efficiency is investigated [29]. On a more sub-disciplinary level, Hammond [30] has examined engineering sustainability from thermodynamic and environmental perspectives. Bakshi and Fiksel [31] have examined challenges for process systems engineering, in the context of the broader quest for sustainability. Concepts and practices, as well as needs, for sustainable manufacturing and design have been studied [32] and applied [33,34]. The extension of systems engineering for sustainable development is described [35]. Much research has been devoted to improving the sustainability of energy processes and utilization [5,6,36], e.g., a methodology has been proposed for evaluating the sustainability of a national energy conversion system and applied to Canada [37,38], while sustainability aspects have been investigated for energy conversion in urban electric trains [39]. Applications of sustainable practices to large-scale engineering operations have also been reported, e.g., sustainable development of the Red-Mediterranean-Dead Seas Canal project has been examined [40].

5. Key Requirements for Engineering Sustainability

There are several distinct components to the manner in which engineering can be practised sustainably in society, each of which is a requirement for engineering sustainability:

1. Sustainable resources
2. Sustainable processes
3. Increased efficiency
4. Reduced environmental impact
5. Fulfillment of other aspects of sustainability

Note that this list stems from the technical approach used in this article and is based on the author's premise that addressing the first four items makes addressing the fifth item more tractable. Although this approach causes this article to have a technical slant, it is not intended to diminish the importance of non-technical aspects of sustainability and the important of integrating these with technical ones. Also note that the requirements in this list are not necessarily independent, but rather exhibit overlaps.

In the following sections, each of these aspects of engineering sustainability is described and examined. Although the aspects are discussed separately here, the previous observation regarding overlaps suggests that the requirements are best addressed concurrently, rather than independently, in practice.

6. Requirement 1: Sustainable Resources

Most engineering activities utilize resources that are derived from nature. Such resources include water (fresh and salinated), materials (virgin and recycled) and energy. The degree to which resources are sustainable depends on many factors, including their scarcity and importance to ecosystems. Scarcity is a particularly important sustainability factor for endangered species where they constitute resources. Some ecosystems are significantly dependent on components that may otherwise be viewed as resources (e.g., rainforests).

Sometimes engineering resources are sustainable, in that they can be replenished at a rate equal to or greater than the usage rate. Wood and biomass resources when used in a controlled manner provide examples. More often, the resources used in engineering activities are available in finite quantities and not sustainable in the longer term (e.g., metal ores, fossil fuels). Sometimes resources available in finite quantities can be viewed for practical purposes as sustainable, depending on the reserves available and the rate of use. For instance, some researchers suggest that a resource can be treated as sustainable when the ratio of these quantities exceeds some value, e.g., 50 or 100 years [23]. Indicators for the sustainable use of natural resources have been developed [28].

Wastes that would otherwise be discarded are also sometimes used as input resources to engineering processes, usually reducing or eliminating the need for new resources from nature. Wastes can be used directly in some activities or converted to more useful forms. For example, material wastes can be recovered and recycled or reused, while waste energy can be utilized to provide heating directly or indirectly through incineration.

Energy resources constitute an important subset of resources, given the pervasiveness of energy use globally. Use of sustainable energy resources can contribute significantly to the broader use of sustainable resources. Various renewable and non-renewable energy sources are listed in Table 1. The most common non-renewable energy sources are fossil fuels, which are the basis for most industrialized countries. Other non-renewable energy resources include alternative hydrocarbons, uranium and fusion material (e.g., deuterium). Renewable energy includes solar radiation and energy forms that result from that radiation (e.g., falling and running water, and biomass such as wood, plants and other forms of organic matter), as well as energy from such other natural forces as gravitation and the rotation of the earth. Solar energy, which is received on the earth at a rate of 1.75×10^{17} W, or about 20,000 times the present global energy-use rate, can be converted electricity in photovoltaic devices or collected as heat. Although diverse, non-fossil fuel energy resources generally are associated with little greenhouse gas emissions and thus often facilitate sustainable energy solutions. Waste energy materials and energy that would otherwise be discarded are also sometimes considered renewable energy. Nuclear energy and renewable energy resources avoid most of the greenhouse gas emissions associated with climate change, although some like biomass can lead to such emissions if not managed carefully. The lifetimes (and thus sustainability) of nuclear fuel accounting for breeder reactors and other advanced nuclear technologies is still not clear.

Table 1. Energy Sources

Renewable	**Non-renewable**
Solar energy	Fossil fuels (coal, petroleum, natural gas)
Water-based energy, e.g., hydraulic, wave, tidal, ocean thermal (from temperature difference between surface and deep waters)	Other hydrocarbons (oil sands and shales, peat)
Wind energy	Uranium
Geothermal energy (internal heat of earth and ground-source energy)	Fusion material (e.g., deuterium)
Biomass (if use rate ≤ replenishment rate)	Biomass (if use rate > replenishment rate)
Wastes (if use rate ≤ generation rate)	Wastes (if use rate > generation rate)

7. Requirement 2: Sustainable Processes

Resources are used in engineering processes and operations to yield products and/or services. An important requirement of sustainable engineering is the use of sustainable processes. This implies that the engineering processes utilized must exhibit sustainable characteristics in terms of the operations and steps they involve, and the energy and materials they utilize. For instance, processes that are sustainable typically utilize widely available materials, while avoiding toxic or hazardous materials as much as feasible, and technologies that are available where needed and operable in the settings in which they will be placed. The waste outputs of processes must also not hinder sustainability for a process to be deemed sustainable. Sustainable processes also incorporate sustainable transportation, distribution and storage systems, where these are necessary. Sustainable approaches to manufacturing and design are also required [32], as are advanced monitoring and control of processes to help them become and remain sustainable.

As many engineering processes are energy intensive, the concept of sustainable processes suggests that the energy carriers utilized should be sustainable. Energy carriers include secondary chemical fuels, ranging from such conventional ones as petroleum products (e.g., gasoline, diesel fuel, naphtha), coal products (e.g., coke) and synthetic gaseous fuels (e.g., outputs of coal gasification), to non-conventional chemical fuels like hydrogen, methanol and ammonia. Many energy carriers do not exist naturally, including such energy forms as work, electricity and non-ambient thermal energy. Various material and non-material energy carriers are listed in Table 2. Conversion systems are often needed to render energy resources more sustainably and conveniently utilizable. Some examples of sustainable energy carriers and their characteristics follow:

- Thermal energy (heat or cold) can often be transported to users over long distances in a sustainable manner via district heating and/or cooling systems, compared to providing heating and cooling onsite.
- Hydrogen is considered by many to be a sustainable energy carrier (although it is not an energy resource) because it facilitates the use of non-fossil fuels by allowing them to be converted to two main classes of energy carriers: hydrogen (and hydrogen-derived fuels) and electricity. The former allow humanity to meet most of its chemical energy needs, while the latter can satisfy most non-chemical energy demands, providing a suitable combination of energy carriers to support sustainability. Such a hydrogen economy has been investigated for several decades [17,18,41–44].

Table 2. Energy Carriers

Material	**Non-material**
Fossil fuels	Work
Fossil fuel-derived fuels	Electricity
Petroleum products (e.g., gasoline, diesel fuel, naphtha)	Electromagnetic radiation
Synthetic gaseous fuels (e.g., from coal gasification)	Thermal energy
Coal products (e.g., coke)	Heat (or heated medium)
Secondary chemical fuels (e.g., hydrogen, methanol, ammonia)	Cold (or cooled medium)

8. Requirement 3: Increased Efficiency

High efficiency allows the greatest benefits, in terms of products or services, to be attained from resources, and thus aid efforts to achieve engineering sustainability. Efficiency improvements taken broadly efforts include direct measures to increase the efficiency of processes, devices and systems as well as

- resource conservation
- improved resource management
- resource demand management
- resource substitution
- better matching of energy carriers and energy demands
- more efficient utilization of resources in terms of both quantity and quality

These concepts are often best considered via the use of advanced methods and tools. For example, exergy analysis often reveals insights that help improve the efficiency of processes. Also, for energy processes and systems, energy storage is often a key element of improving the sustainability of energy systems [45,46].

Exergy Methods

Exergy analysis (an alternative to the more conventional energy analysis) is a tool based primarily on the thermodynamic quantity exergy [47–49]. Exergy is similar to energy, but differs by providing a measure of the usefulness or quality of material or energy quantities. Exergy is based on the conservation of energy and non-conservation of entropy principles, and is defined as the maximum work which can be produced by a flow of matter or energy as it comes to equilibrium with a reference environment (often chosen to mimic the natural environment). Exergy analysis identifies meaningful efficiencies and thermodynamic losses in an overall process and its steps and consequently is beneficial in the analysis, design and improvement of energy systems and processes. Exergy analysis can reveal whether or not, and by how much, it is possible to design more efficient energy systems by reducing the inefficiencies. The exergy method thus greatly assists efforts to achieve engineering sustainability. The exergy method is particularly useful for attaining more efficient energy-resource use because it identifies efficiencies that are true measures of the approach to ideality, and enables the locations, types, magnitudes and causes of inefficiencies (both wastes and internal losses) to be determined. Key features of exergy and energy methods are compared in Table 3.

Although exergy analyses have been performed in numerous areas, e.g., electricity generation and cogeneration, chemical and fuel processing, manufacturing and energy storage [47], the contributions that exergy can make to energy sustainability are broader than efficiency improvements. Exergy methods can also be applied in economics [47,50–52], environmental and ecological management [15,47,53,54], and other areas beyond thermodynamics. The use of exergy in environmental fields is to improve understanding of and mitigate environmental impact and to develop better predictors and indicators. This use is premised on the observation that exergy provides as a measure of the departure of a substance from equilibrium with a specified reference environment, which is often modeled as the natural environment. As exergy is a measure of potential of a substance to cause change, the exergy of an environmental emission is measure of its potential to change or impact the environment. The exergy of an emission is zero only when it is in equilibrium with the environment and thus benign. Exergy was recently proposed as an environmental indicator in industry by University of California-Berkeley's Consortium on Green Design and Manufacturing [16].

Table 3. Comparison of Exergy and Energy Methods

Exergy Analysis	**Energy Analysis**
Utilizes exergy balances (with exergy not conserved, but instead destroyed due to irreversibilities)	Utilizes energy balances (with energy conserved)
Accounts for energy quality	Neglects energy quality
Provides efficiencies that measure approach to ideality	Does not necessarily provide efficiencies that measure approach to ideality
Indicates margin for efficiency improvement	Does not generally indicate margin for efficiency improvement
Provides a measure of disequilibrium with environment and potential for impact	Does not provide a measure of disequilibrium with environment and potential for impact

9. Requirement 4: Reduced Environmental Impact

Numerous environmental impacts associated with engineering processes are of concern and must be addressed in efforts to attain engineering sustainability. These include impacts to the atmosphere, the lithosphere and the hydrosphere, and can be exhibited in many forms (e.g., damage to the ecosystems, health, aesthetics). Some important environmental impacts associated with engineering processes of concern regarding engineering sustainability follow:

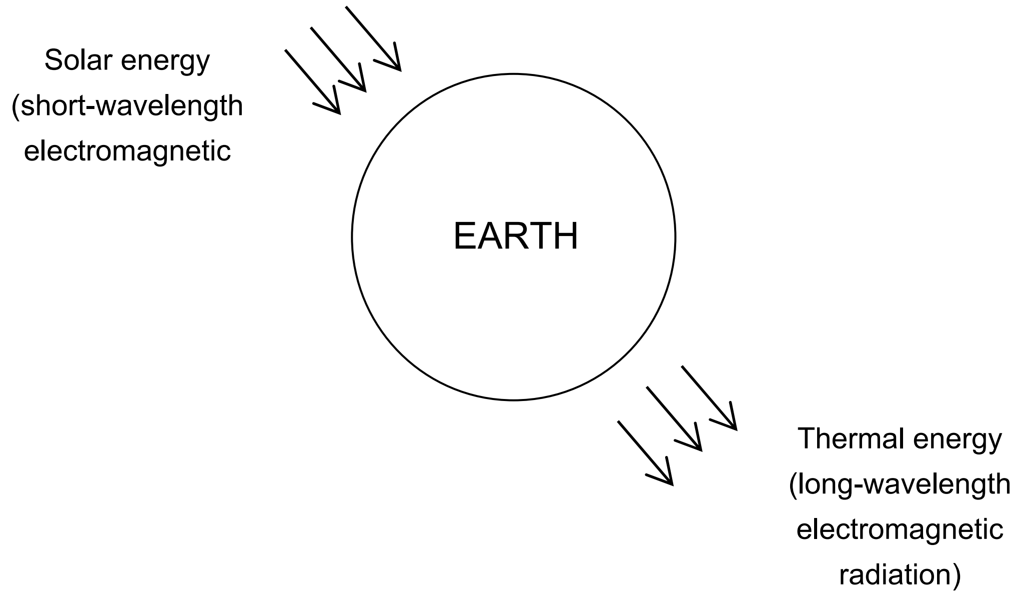
- global climate change (mainly due to greenhouse gas emissions which cause global warming)
- ozone depletion (due to destruction of the atmospheric ozone layer and subsequent increases in ultraviolet reaching the earth's surface)
- acidification, and its impact on soil and water (due to acidic emissions)
- abiotic resource depletion potential (due to extraction of non-renewable raw materials)
- ecotoxicity (due to exposure to toxic substances that lead to health problems)
- radiological impacts (such as radiogenic cancer mortality or morbidity due to internal or external radiation exposure)

To be comprehensive and meaningful, the consideration of the environmental impact of an engineering activity must consider the entire life cycle of the activity, from acquisition of the resources, to their utilization and ultimate disposal.

Global climate change is viewed by many as the most significant environmental impact facing civilization and humanity. Global warming is associated with an anthropogenic disruption of the earth-sun-space energy balance, which normally has most of the energy entering the earth’s atmosphere (short-wave solar radiation) eventually exiting back to space as long-wave thermal radiation (see Figure 1). Atmospheric “greenhouse gases” generally absorb radiation in the 8 to 20 micrometer region, and disrupt the earth-sun-space energy balance by reducing the energy output from the earth and its atmosphere while the energy input remains constant, leading to an increase in the average temperature of the Earth. Eventually, if concentrations of greenhouse gases in the atmosphere stabilize at new levels, the energy balance is re-established but at some higher average planetary temperature. Non-fossil fuel energy options are needed to help humanity combat climate change, in that they avoid or greatly reduce emissions of greenhouse gases, particularly carbon dioxide, an inherent product of hydrocarbon combustion. This important attribute often allows non-fossil fuel energy sources to provide a foundation for the supply of sustainable energy services, which are one requisite for energy sustainability and sustainable development [49].

Note that this article emphasizes environmental aspects because of the significance that some of these potentially have on civilization, but this emphasis is not intended to diminish the cultural and social aspects of sustainability as used in engineering.

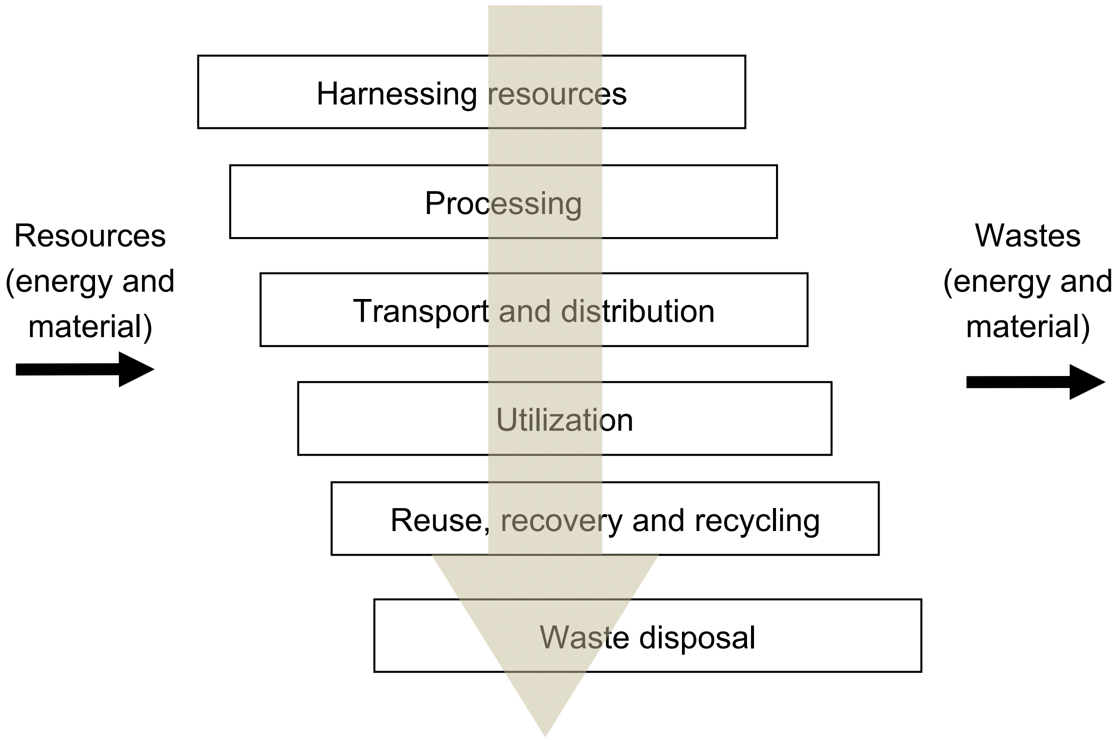
Figure 1. Earth-sun-space energy balance, showing main energy flows: solar energy input and thermal energy emission to space at longer wavelengths.



Life Cycle Assessment

An approach which considers the full life cycle of a product or process is needed to properly assess environmental impact and efficiency. Life cycle assessment (LCA) is a useful technique for assessing and improving the environmental performance of a product, process or activity, considering all steps over its life, *i.e.*, from "cradle to grave" (see Figure 2). For a process, LCA is effective for creating an inventory of emissions and other environmental effects like resource depletion, waste generation and energy consumption, and for identifying and evaluating their environmental impacts (e.g., acid precipitation, ozone depletion and climate change) [23]. LCA allows environmental issues to be quantified and related specifically to the part of the life cycle that is responsible for them. The processes usually included in LCA include pre-operation steps (extraction or collection of raw resources, manufacturing and processing, transportation and distribution of materials and energy and, where relevant, storage); operation (use of the engineering to provide services and tasks); and post-operation steps (recovery and re-use of outputs that would otherwise be wasted, recycling of wastes and disposal of final wastes). Principles, methodologies and guidelines for LCA have been developed by, among others, the Society for Environmental Toxicology and Chemistry (SETAC) and the International Organisation for Standardisation, e.g., ISO 14040:2006 Life Cycle Assessment—Principles and framework, ISO 14044:2006 Life Cycle Assessment—Requirements and guidelines, ISO 14049:2012 Life Cycle Assessment—Illustrative examples on how to apply ISO 14044 to goal and scope definition and inventory analysis [55]. LCAs have been reported for various processes [56–58].

Figure 2. Scope of life cycle assessment of a product or process, showing steps in the life cycle vertically and inputs and outputs horizontally.

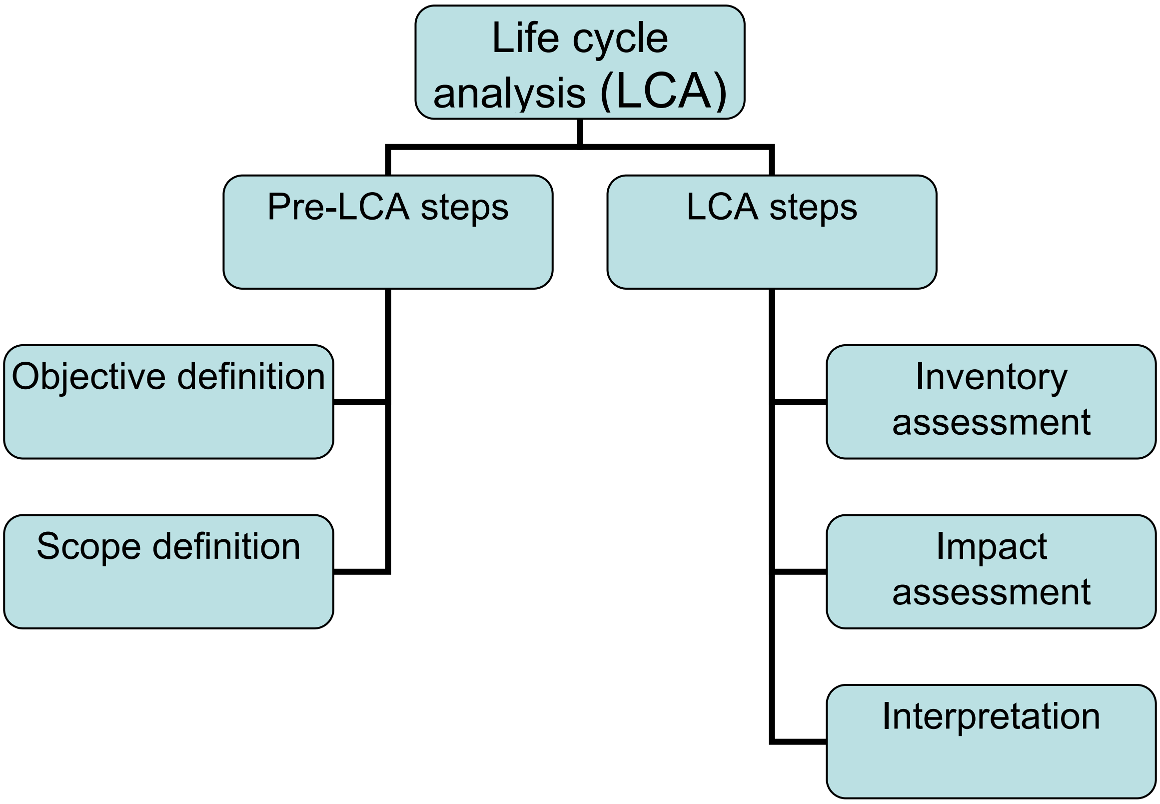


LCA generally involves three main steps (see Figure 3):

- Step 1: Inventory assessment. This step entails evaluation of the environmental burdens associated with a product, process or activity by identifying and quantifying the energy and materials used and the wastes released to the environment. This step involves the collection of data and information on the technical and economic flows for the process or product and the environmental resources required.
- Step 2: Impact assessment. This step involves an assessment of the impact of energy and material use and environmental releases, and quantifies the environmental stresses associated with the environmental inputs and outputs identified during the inventory stage of LCA. Numerous environmental impact categories have been developed by such organizations as the U.S. Environmental Protection Agency, the Centre of Environmental Science at Leiden University, The Netherlands, the Nordic Council of Ministers and the United Nations Environment Program [59] .
- Step 3: Interpretation (or improvement assessment). This step identifies and evaluates opportunities for environmental improvements, and identifies and prioritizes environmental improvement options in terms of need and benefit. This step often identifies improvements that enhance sustainability [59].

These steps are usually preceded by definition of LCA objective(s) and scope. The latter establishes the economic-environmental boundaries and limits for the investigation. Note that many interactions occur between the steps in Figure 3, allowing feedback provided by improvements to help shape objectives, scope and inventory analysis for subsequent LCAs.

Figure 3. Principal steps in life cycle assessment. Interpretation is used at all stages.



10. Requirement 5: Fulfillment of Other Aspects of Sustainability

Many other sustainability factors relate to engineering processes, and consequently need to be considered in the quest for engineering sustainability. These factors are sometimes related and often overlap. Some of these follow:

- Economic affordability. To be sustainable, engineering services that are required to provide basic needs must be economically affordable by all societies and people. It is noted that this requirement can be met in some ways today. For instance, some efficiency improvement and environmental mitigation measures can be implemented in ways that save money over time, or are revenue neutral.
- Equity. All societies need to be able to access engineering services, regardless of geographic location, to achieve engineering sustainability. In addition, equity among developed and developing countries must be achieved in terms of engineering services. Also, true engineering sustainability requires that future generations be able to access resources. Equity is somewhat time dependent, and this author expects that short-term differences will diminish in time and engineering opportunities in all countries will converge in the longer term.
- Meeting increasing resource demands. The increasing use of material and energy resources, especially in developing countries as they become more industrialized and as their living standards rise, must be able to be met. This will be a particularly challenging task as populations rise.

- Safety. Engineering must be safe in terms of injury, and cause as few negative health effects as reasonably possible in the short and long terms to be sustainable.
- Community involvement and social acceptability. People and communities must be involved in major engineering-related decisions if engineering sustainability is to be attained, as the support of these groups is critical to success of any initiatives, and such support almost always requires consultation and involvement in decision making.
- Meeting human needs. The human dimensions of the new technologies must be addressed to achieve engineering sustainability. Addressing only engineering facets is often not adequate [60].
- Appropriate land use. The use of land for engineering-related activities needs to be balanced with other needs, such as agriculture and recreation. This is a particularly significant challenge with technologies like biomass energy, which often involves the growth of energy plants on land that could be used for other purposes like food production.
- Aesthetics. Ensuring engineering products are aesthetically appealing is an important aspect of engineering sustainability, given the importance of gaining support of individuals and their communities for sustainability initiatives to succeed. This include cleanliness of the environment, which is an important aesthetic aspect of sustainability in that it affects the well-being of people.
- Lifestyles. Modifying lifestyles and tempering desires that are engineering-driven can help in the quest for engineering sustainability. Given that aspirations of people tend to increase continually, this aspect of engineering sustainability is often very challenging. Transforming behavioural and decision-making patterns requires recognition that current development paths are not sustainable. History suggests that such recognition occurs only when short-term consequences are obvious. For instance, to successfully mobilize the resources needed to reduce the risks associated with energy use, the public must perceive the potential long-term consequences associated with present behaviour patterns. Translating future threats associated with engineering into immediate priorities is and will likely remain one of the most difficult challenges facing policy makers.
- Population. Increasing global population places stresses on the environment and the carrying capacity of the planet. Sustainable engineering need to account for population growth or address it in other ways.

Most of these factors are considered indirectly in the previous four requirements, and in fact in some, but certainly not all, cases are addressed in whole or in part if the other requirements are addressed with a sustainability focus. For instance, the utilization of sustainable resources must take into account such factors as economics, global stability and equity (geographic and intergenerational) if a sustainability focus is implemented. Nonetheless, the non-technical issues presented here must be addressed, and integrated into engineering activity, if engineering sustainability is to be achieved.

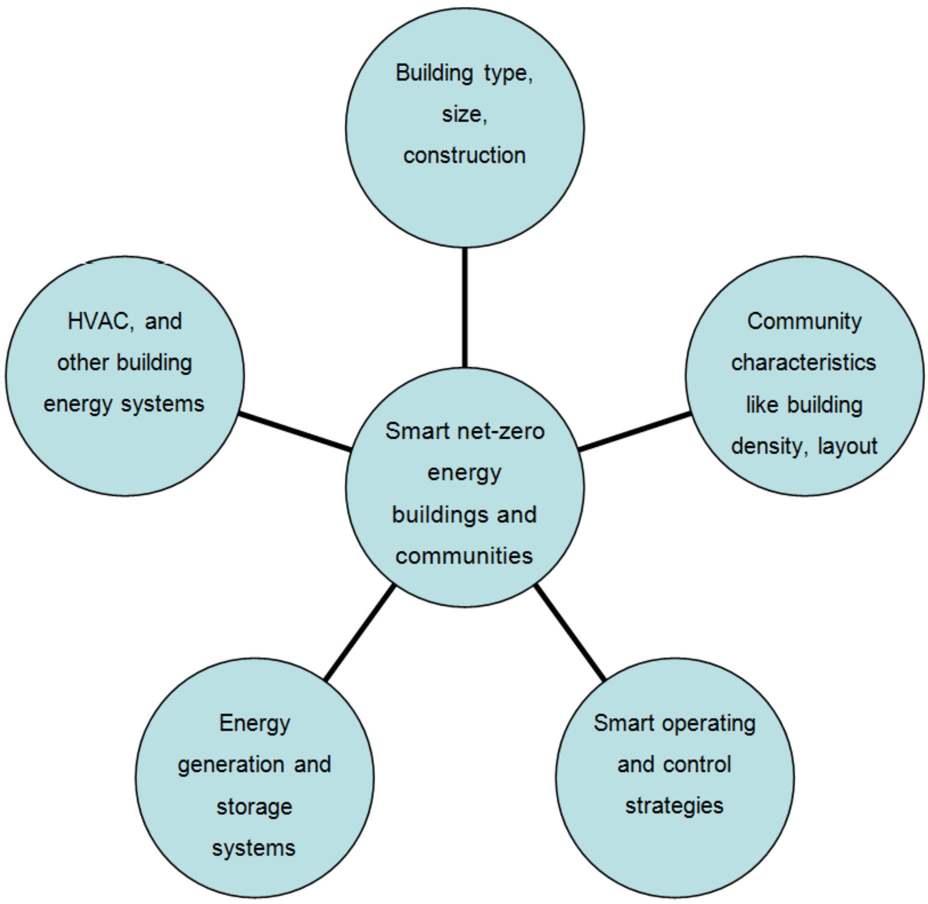
11. Illustration: Smart Net-Zero Energy Buildings and Communities

Buildings are responsible for a significant portion of the resource use and environmental impacts in many countries. In Canada, for instance, approximately one third of GHG emissions and half of electricity consumption are attributed to building energy consumption. Buildings are largely responsible for the peaks in electricity demand associated with space heating, cooling, lighting and appliances. But the manner in which buildings and communities are designed, constructed and operated can be transformed to reduce energy use and emissions, by allow buildings to act as a net energy generators. The development the technologically advanced high performance net-zero energy buildings can contribute significantly to sustainability in the future.

11.1. Net-Zero Energy Buildings and Communities

A net-zero energy building is defined as one that, in an average year, produces as much electrical plus thermal energy from renewable energy sources as it consumes. A net-zero energy community is similar, but applicable to communities. A smart net-zero energy approach requires a whole-building systems and integrated approach, e.g., HVAC, lighting, storage and renewable energy components must be linked, building envelopes must be designed appropriately, and advanced building automation and control systems are needed to ensure the various building services are operated to meet indoor environment needs and, safety and health requirements, while enhancing efficiency. Note that in this context "smart" means more information rich, but it also tends to lead to more intelligent designs. Factors in smart net-zero energy buildings and communities are illustrated in Figure 4.

Figure 4. Factors in smart net-zero energy buildings and communities.



The penetration the net-zero energy concept into the building industry is often difficult because of higher initial costs associated with the technologies, the fragmented nature of the industry, a lack of familiarity with the technologies, and concerns over liabilities arising from malfunctions of new systems. These difficulties can usually be overcome, often with significant benefits. Smart net-zero energy buildings and communities can reduce long-term environmental impacts like those associated with GHG emissions. Also, localized generation strategies, load management, reduction in utility electrical energy demand should mitigate the need to build new fossil fuel power plants, and transportation energy savings via electric or hybrid cars that use electricity from renewable building-integrated energy systems.

11.2. Recent Developments on Net-Zero Energy Buildings and Communities

Work on net-zero energy buildings has been reported. For instance, the International Energy Agency (IEA) SHC/ECBCS Task 40/Annex 52 is entitled "Towards Net-zero Energy Solar Building" (where SHC denotes Solar Heating and Cooling, and ECBCS Energy Conservation in Buildings and Community Systems). Also, a Smart Net-zero Energy Buildings Strategic Research Network, involving over 30 universities, companies and government agencies, was established in Canada in 2011 to focus on smart net-zero energy buildings and communities [61].

11.3. Net-Zero Energy Buildings

Much research has been conducted on the general concept and application of net-zero energy buildings. For instance, the creation of net zero energy buildings was described in a vision paper [62]. Much of the activity on net-zero energy buildings has been related to the incorporation of solar energy in such buildings. Related design, optimization and modeling issues have been investigated [63], as has the relation between net energy use and the urban density of solar buildings [64]. Work has also been reported on near, rather than full, net-zero energy buildings [65–67].

The need to properly integrate net-zero energy buildings into the electrical grid has been shown to be a significant aspect of designing such buildings [68]. Load matching and grid interaction of net zero energy buildings has been discussed [69].

Much of the focus of net-zero energy buildings has been on the residential sector. The feasibility of a low-emission residential energy system has been reported [70], while the integrated design and performance of net-zero energy houses has been considered [71]. An optimization methodology has been proposed for a near net zero energy demonstration home [65]. Design tools and procedures for near net-zero energy house redesign have also been described [66], as have specific technologies in net-zero energy residential buildings, e.g., solar-assisted radiant floor heating [72]. Broader issues beyond energy performance, such as comfort, are also the topic of research on near net-zero energy houses [67].

Despite the emphasis on residential buildings, there have been advances related to buildings in other sectors. For example, the technical potential has been assessed for achieving net zero-energy buildings in the commercial sector [73].

11.4. Net-Zero Energy Communities

Building on the work on net-zero energy buildings, increasing research has been reported in recent years on net-zero energy communities. The design of solar-optimized neighborhoods has been described [74]. Infrastructure interactions in the design of sustainable neighbourhoods have been examined [75]. Further, the electric utility benefits of zero peak communities have been studied [76]. Specific technologies relevant to net-zero energy communities have also been examined, e.g., the benefits of seasonal storage of solar energy for space heat in a new community has been examined by considering the Drake Landing Solar Community in Okotoks, Alberta, Canada [77].

11.5. Contributions of Net-Zero Energy Buildings and Communities to Engineering Sustainability

Following the concepts described earlier, several contributions of smart net-zero energy buildings and communities to engineering sustainability are considered. The first benefit focuses on the use of sustainable resources in such buildings and communities, and the second on the sustainable processes involved in establishing and operating them. The third benefit is the increased efficiency attainable, and the fourth considers environmental benefits. Lastly, the other aspects of sustainability fulfilled through smart net-zero energy buildings and communities are examined.

- **Sustainable resources.** A primary advantage of net-zero energy buildings and communities, averaged over the year, is that they do not utilize non-sustainable energy resources. The energy that they do utilize typically is derived from renewable energy resources (e.g., solar and geothermal energy). Consequently, such buildings and communities contribute significantly to energy sustainability and thus to sustainable resource use. Of course, this advantage must be balanced against the additional material resources usually required to implement net-zero energy buildings and communities and obtain the technologies they require. But the results of numerous investigations of such technologies over many years suggests that there will be a significant positive overall net contribution to the sustainable use of resources through the utilization of smart net-zero energy buildings and communities.
- **Sustainable processes.** By not utilizing energy resources, the process involved and technologies utilized in net-zero energy buildings and communities are indirectly advantageous in terms of sustainability, during their utilization phases. Of course, of the sustainability of the processes used to build net-zero energy buildings and communities must also be sustainable for the overall processes to be sustainable over their full lifetimes (accounting for extraction of resources, manufacturing of technologies, and ultimate disposal). That aspect of sustainable processes is highly dependent on the methods used to build net-zero energy buildings and communities and the technologies they incorporate. Since such buildings and communities are developed with the intent of reducing resource use, and associated environmental emissions, it is likely the sustainable processes will be sought for designing, developing and building net-zero energy buildings and communities.
- **Increased efficiency.** The efficiency of net-zero energy buildings and communities is typically high, because all the energy-derived services required in buildings and communities are delivered with no net use of energy resources. Such buildings and

communities therefore make a significant contribution to the efficiency improvements necessary for engineering, especially compared to more conventional methods for providing the energy services required by buildings and communities. Nonetheless, efforts are still worth putting forward to improve the efficiency of the processes involved in net-zero energy buildings and communities, especially during the development and construction of the technologies and components of the systems. Such efficiency-improvement efforts can also be aided by exergy analysis. For example, some exergy methods allow the return on investment, in terms of material and resource utilization, during construction of systems such as net-zero energy buildings and communities to be appropriately evaluated and contrasted with the resource savings during their operation.

- **Reduced environmental impact.** Given the main advantage of net-zero energy buildings and communities is that they do not utilize non-sustainable energy resources, they have little environmental emissions associated with their operating phase and little impact on energy-resource extraction from the environment. However, there are environmental emissions and resource extractions associated with the full life cycles of the buildings and communities, and these must be evaluated and compared with the environmental benefits during the operating phase. Given the long lifetimes of buildings and communities, often greater than 30 years, the operating environmental benefits tend to greatly exceed the environmental impacts during the non-operating phases of the technologies, which usually occur only once during the lifetime. Thus, the reduced environmental impact associated with net-zero energy buildings and communities likely make a significant contribution towards engineering sustainability.
- **Fulfillment of other aspects of sustainability.** Smart net-zero energy buildings and communities contribute to non-technical aspects of engineering sustainability. For instance, net-zero energy buildings and communities are anticipated to contribute to economic affordability of energy resources now or in the future as energy prices increase. Also, by using little or no energy resources, net-zero energy buildings and communities are expected to help alleviate the continually increasing resource demands on societies, particularly as populations rise and developing countries become more industrialized. Further, given net-zero energy buildings and communities are an integral part of communities, they are likely to be implemented only where they are viewed as socially acceptable by the communities in which they are located. A high degree of community involvement is likely to be involved, contributing to the sustainability of such engineered buildings and communities. Finally, net-zero energy buildings and communities should alleviate some of the stresses on the environment and the carrying capacity of the planet. Of course, significant additional effort must be put forth to ensure the non-technical aspects of sustainability are addressed, if the outcome is to be holistically sustainable.

12. Conclusions

It is demonstrated that several key factors need to be considered and appropriately addressed to achieve engineering sustainability, which itself is a crucial component of overall sustainability for human activity and development. The key factors include appropriate selection of resources accounting for sustainability criteria, the use of sustainable processes, enhancement of the efficiency of resource utilization and engineering processes, environmental stewardship in engineering activities so as to mitigate environmental impacts, and fulfillment of other aspects of sustainability, such as economics and equity. The author believes that options and pathways for engineering sustainability can be achieved by considering these key factors. Furthermore, through engineering sustainability, the author feels that a shift towards overall sustainability can be given great impetus, given the pervasiveness of engineering activities in all societies and their impacts on the environment, as well as the importance of engineering in economic development and living standards. The use of efficiency tools like exergy analysis and environmental tools like life cycle analysis are shown to be essential in achieving engineering sustainability. The concept of smart net-zero energy buildings and communities illustrates the ideas well.

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Conflict of Interest

The author declares no conflict of interest.

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