Towards Energy Sustainability: A Quest of Global Proportions

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Abstract

Sustainability is a critically important goal for human activity and development. Sustainability in the area of energy is of great importance to any plans for overall sustainability given 1) the pervasiveness of energy use, 2) its importance in economic development and living standards, and 3) the significant impacts that energy 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 energy sustainability are examined in this article. These include appropriate selection of energy resources bearing in mind sustainability criteria, facilitation of the use of sustainable energy resources, enhancement of the efficiency of energy-related processes, and a holistic adoption of environmental stewardship in energy 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 options and pathways for energy sustainability and to the broader ultimate objective of sustainability.

Introduction

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 energy is not directly one of the three components of sustainability cited above, it is indirectly linked to each. That is, energy resources drive much if not most of the world’s economic activity, in virtually all economic sectors, e.g., industry, transportation, residential, commercial, etc. Also, energy resources, whether fossil fuels or renewables, are obtained from the environment, and wastes from energy processes (production, transport, storage, utilization) are typically released to the environment. Finally, the services provided by energy allow for good living standards, and often support social stability as well as cultural and social development. Given the intimate ties between energy and the key components of sustainable development, it is evident that the attainment of energy sustainability is a critical aspect of achieving sustainable development, in individual countries and globally.

The fact that all countries utilize energy resources, and that the impacts on the environment of energy processes are both local and global, and given that the world’s economy Is becoming increasingly globalized, it has become increasingly apparent that the quest for energy sustainability is indeed global in extent.

Energy sustainability is taken here not just to be concerned with sustainable energy sources, but rather to be much more comprehensive. That is, energy sustainability is taken to involve the sustainable use of energy in overall energy systems. Such systems include processes and technologies for the harvesting of energy sources, their conversion to useful energy forms, energy transport and storage, and the utilization of energy to provide energy services such as operating a computer, lighting an office or keeping a person warm in winter. Thus, energy sustainability goes beyond the search for sustainable energy sources, and implies sustainable energy systems, i.e., systems that use sustainable energy resources, and that process, store, transport and utilize those resources sustainably.

The objective of this article is to identify and examine the key factors that need to be addressed to achieve energy sustainability in a global context. An engineering perspective is taken to be pragmatic, and an illustration is presented to provide an example of a practical future sustainable energy option.

Approach

The focus of this article is on technical aspects of the quest for energy sustainability. In many ways, it is evident that the author takes an engineering approach, which is likely influenced by his being or having been a professional engineer, an engineering educator and administrator and the head of engineering societies. This approach is taken to be pragmatic, which is often at the centre of engineering activities. Also, this approach focuses on the technical necessities to achieve energy sustainability, and less on the roles of economics, politics and other non-technical factors. Consequently, the present article is not 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 energy 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 energy sustainability.

Some reasons for this viewpoint follow:

- The economics and politics of energy questions vary with time and location, often with profound geopolitical overtones. Yet, the actual issues involved in achieving energy sustainability remain mainly of a technical nature and are not necessarily affected by these other factors. In fact, most aspects of the quest for energy sustainability, when examined based on technical challenges, do not exhibit the spatial and temporal variations of factors like economics and geopolitics.
- Energy prices are in many ways artificial, in that they are greatly affected by political inputs like taxes, rebates, incentives, penalties, limits, etc. This can be observed by examining the large variations in different countries in prices of energy commodities like gasoline. Thus factors like costs and prices are more like levers which can be pulled by politicians and society to achieve desired aims. If the aim is energy sustainability, then economic tools can be applied to foster the objective, but first one needs to determine the most advantageous method for achieving energy sustainability, and this remains primarily a technical problem.
- Without a sound technical basis, issues relating to energy are often confused – sometimes with significant effect. For instance, consider the terms energy conservation and energy crisis. Both of these are commonly used lay terms that make no sense technically. Based on the first law of thermodynamics, energy is a conserved quantity, even though it can be degraded in quality, so the goal of energy conservation is rendered confusing at best and misleading at worst. The actual goal implied by lay people is the conservation of high-quality and useful energy commodities (e.g., oil, natural gas, electricity). Similarly, since energy is

conserved, the concept of an energy crisis has no meaning, in that the energy we utilize to provide energy services eventually exits, in the same quantity as it was supplied, as waste energy. But, this waste energy is typically of low quality and usefulness, so the actual meaning of an energy crisis is a scarcity of useful, high-quality energy commodities. The reason these illustrations are important is that to address energy sustainability rationally, one must have a sound technical basis, and this basis is not necessarily present when non-technical approaches are adopted.

- 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 (Lior, 2008). In fact, some have suggested the need for a science of sustainability, and initial attempts have been made in this direction. Also, the author feels that a discipline of engineering sustainability is needed. The engineering approach taken in addressing energy sustainability in this paper is intended to circumvent the vagueness often associated with the concept of sustainability. The difficulty in addressing energy sustainability without a solid technical approach can be seen in many activities. For instance, the Ontario Power Authority in Canada has included sustainability as a key factor in its development of a plan for the energy future of Ontario (OPA, 2006), Canada's largest province with about one third of its population. The inclusion of sustainability as a key factor is indeed admirable and the impact of its inclusion is evident in the Ontario Power Authority plan. Yet, the lack of clear methodology to approach energy sustainability has forced the approach to sustainability to be non-comprehensive and to be developed during the planning. Clearly, it would be more straightforward if a discipline of engineering or science sustainability were already developed.

Although an engineering approach is taken in this article, that does not mean that a definitive and comprehensive approach to energy sustainability is presented. That task would be immense. Rather, the approach taken is founded on technical and engineering factors, and intended to assist efforts to move society towards energy sustainability in particular and overall sustainability in general.

Energy And Sustainability

To appreciate the concepts underpinning energy sustainability, it is informative to consider the concept and definitions of sustainability and sustainable development.

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 often require increasing energy use and often yield correspondingly increasing emissions.

Energy Sustainability

In some ways, the concept of energy sustainability is simply the application of the general definitions of sustainability to energy. In other ways, energy sustainability is more complex and involved. In discussions of energy sustainability, it is helpful to describe some basic energy terms and principles so as to avoid confusion.

Energy is used in almost all facets of living and in all countries, and makes possible the existence of ecosystems, human civilizations and life itself. Different regions and societies adapt to their environments and determine their own energy resources and energy uses. The standards of life achieved in countries are often a function of energy-related factors.

Energy can exist in many forms, and can be converted from one form to another with energy-conversion technologies. We use energy carriers (often simply referred to as energy), produced from energy sources, in all aspects of living. It is important to distinguish between energy forms, sources and carriers (Rosen, 2007):

- **Energy forms.** Energy comes in a variety of forms, including fossil fuels, fossil fuel-based products (e.g., gasoline, diesel fuel), uranium, electricity, work (such as the mechanical energy in a rotating engine shaft), heat, heated substances (e.g., steam, hot air), light and other electromagnetic radiation.
- **Energy sources.** Energy resources (sometimes called primary energy forms) are found in the natural environment. Some are available in finite quantities (e.g., fossil fuels, fossil fuel-containing substances such as oil sands, peat and uranium). Some energy resources are renewable (or relatively renewable), including sunlight (or solar energy), falling water, wind, tides, geothermal heat and biomass fuels (when the growth rate exceeds or meets the rate of use). Energy resources are often processed from their raw forms prior to use.
- **Energy carriers.** Energy carriers (sometimes called energy currencies) are the energy forms that we transport and use, and include some energy resources (e.g., fossil fuels) and processed energy forms (e.g., gasoline, electricity, work and heat). Processed energy forms are not found in the environment.

The distinction between energy sources and carriers is important. Energy carriers can exist in a variety of forms and can be converted from one form to another, while energy sources are the original resource from which an energy carrier is produced. Confusion sometimes results between energy sources and carriers because some energy sources are also energy carriers. Hydrogen for example is not an energy source, but rather an energy carrier that can be produced from a wide range of resources using various energy-conversion processes (e.g., water electrolysis, reforming of natural gas and coal gasification). Nevertheless, hydrogen is often erroneously referred to as an energy source, especially in discussions of its potential future role as a chemical energy carrier to replace fossil fuels.

Energy is characterized by the laws of thermodynamics. The first law embodies the principle of conservation of energy, while the second law relates to the quality of energy, and often includes the concepts of entropy and exergy.

With the above details, an informed discussion of energy sustainability is possible. Energy sustainability involves the provision of energy services in a sustainable manner, which in turn necessitates that energy 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. Universal agreement on a definition has not yet been achieved, so other definitions and descriptions have been presented (Haberl, 2006; Rosen, 2002; Goldemberg et al., 1988; Niele, 2005; Wall and Gong, 2001; Zvolinschi et al., 2007; Hennicke and Fischedick, 2006; Dunn, 2002; Lior, 2008).

Key Requirements For Energy Sustainability

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

1. Capture/production of sustainable energy sources.
2. Conversion of sustainable energy sources into appropriate energy carriers.
3. Increased efficiency in the provision of energy services.
4. Reduced environmental impact throughout the life cycle of energy processes.
5. Consideration of other facets of sustainability.

In the following sections, each of these aspects of energy sustainability is described and examined.

Requirement 1: Capture/Production Of Sustainabile Energy Sources

Non-fossil fuel energy options reduce or eliminate greenhouse gas emissions and thus often facilitate sustainable energy solutions. Non-fossil fuel energy options are diverse in their characteristics and types, ranging from renewables to nuclear energy.

Many types of energy sources (renewable and non-renewable) are listed in Table 1. Fossil fuels and non-fossil fuel energy sources are clearly seen in that table. Renewable energy includes solar radiation incident on the earth, and energy forms that result from that radiation, as well as energy from such other natural forces as gravitation and the rotation of the earth.

Table 1. Energy Sources

Renewable energy sources	**Non-renewable energy sources**
Solar radiation (direct)	Fossil fuels
Solar-related energy	Coal
Hydraulic energy (large and small)	Oil
Wave energy	Natural gas
Wind energy	Alternatives (oil shales, tar sands, peat)
Ocean thermal energy (from temperature difference between surface and deep waters)	Non-fossil fuels
Biomass (where use rate does not exceed replenishment rate)	Biomass (where use rate exceeds replenishment rate)
Non-solar-related energy	Uranium
Geothermal energy (internal heat of earth and ground-source energy)	Fusion material (e.g., deuterium)
Tidal energy (from gravitational forces of sun and moon and rotation of earth)	Wastes (usable as energy forms or convertible to more useful energy forms)

Non-renewable energy sources include energy resources which are available in limited quantities and not renewable. The most commonly used of these are fossil fuels, which are the basis for most industrialized countries. In addition to the conventional fossil fuels (coal, oil and natural gas), there exist alternative fossil fuels such as oil shales, tar sands and peat. Other non-renewable energy resources include uranium and fusion material (e.g., deuterium).

Waste materials and energy that would otherwise be discarded are also sometimes considered renewable energy. Wastes can be used directly as energy or converted to more useful forms. Waste heat can be recovered to provide heating, offsetting some or all of the need for external energy. For example, waste heat from hot materials (e.g., stack gases and cooling-water discharges) can be recovered, while material wastes can be used in waste-to-energy incineration to provide useful heat and/or generate electricity.

Nuclear energy may not be a renewable resource, but it avoids greenhouse gas emissions and thus contributes to avoiding climate change. The degree to which nuclear fuel lifetimes can be lengthened via breeder reactors and other advanced nuclear technologies remains the subject of investigations, thus leaving unanswered the question of how renewable nuclear energy is.

Some of the main types of renewable energy follow:

- Direct solar radiation, the main type of renewable energy, reaches the earth at a rate of 1.75×10^{17} W, which is about 20,000 times greater than the global energy-use rate. Solar energy can be collected as heat for thermal processes such as space and water heating, or concentrated for high-temperature heating and thermal electricity generation. Also, solar radiation can be converted directly to electricity in photovoltaic devices. Several other renewable energy types stem from solar radiation.
- Hydraulic energy, which includes falling and running water in rivers, waterfalls, etc.
- Biomass energy, which includes wood, plants and other forms of organic matter. Biomass can be used directly as a fuel or converted into more desirable fuels. Several fast-growing trees have been identified as good candidates for biomass energy production. Biomass energy is only a renewable resource when the rate at which it is used does not exceed the rate at which it is replenished.
- Wind energy, which is increasingly used for electricity generation.
- Ocean thermal energy, which arises due to the temperature difference between surface and deep waters of the ocean, and which can drive a heat engine.
- Wave energy, which exploits the motion of waves.
- Tidal energy, which takes advantage of the motion with tides, caused by gravitational forces of the sun and moon and the rotation of the earth.
- Geothermal energy, both as a consequence of the internal heat of the earth, which can be used directly for heating, as well as the natural temperatures of the ground, which can be used in conjunction with heat pumps.

Renewable energy resources are normally free of greenhouse gas emissions, although some like biomass can lead to such emissions if not managed carefully.

Requirement 2: Conversion Of Sustainable Energy Sources Into Appropriate Energy Carriers

The range of energy carriers is diverse (see Table 2). Energy carriers are very much related to the stage of technological development of a society, and influence the evolution of life standards. Energy carriers include secondary chemical fuels, ranging from such conventional ones as oil 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.

Thermal energy can be either heat (or a heated medium such as hot air, steam, exhaust gases) or cold (or a cooled medium such as cold brine, ice). Thermal energy can be transported to users over long distances in district heating and/or cooling systems, which are used in many cities and industrial parks. District heating systems, for instance, use centralized heating facilities to produce a heated medium which is transported to many users connected along a district heating network. Buildings in the cores of many cities are often connected by pipes through which hot water or steam flows to provide space and water heating. Similarly, district cooling involves the central production of a cold medium, which is transported to users through a piping network to provide cooling.

Table 2. Energy Carriers

- Work
- Electricity
- Thermal energy
  - Heat (or a heated medium such as hot air, steam, exhaust gases)
  - Cold (or a cooled medium such as cold brine, ice)
- Fossil fuels
- Secondary chemical fuels
  - Oil products (e.g., gasoline, diesel fuel, naphtha)
  - Synthetic gaseous fuels (e.g., from coal gasification)
  - Coal products (e.g., coke)
  - Hydrogen
  - Methanol
  - Ammonia

Importance of Energy Carriers

Energy carriers are an important consideration in energy sustainability because conventional and non-fossil fuel energy options are not sufficient for avoiding environmental issues such as climate change, in that they are not necessarily readily utilizable in their natural forms. Conversion systems are often needed to render non-fossil energy more conveniently utilizable. Hydrogen energy systems are considered important in this regard as they facilitate the use of non-fossil fuels by allowing them to be converted to two main classes of energy carriers: hydrogen (and select 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 energy sustainability. As hydrogen is not an energy resource, but rather is an energy carrier that must be produced, it complements non-fossil energy sources, which often need to be converted into more convenient forms.

Hydrogen Energy

Hydrogen is presently used extensively as a chemical feedstock, e.g., in fertilizer production and petrochemical processes. Hydrogen demand as an energy carrier is expected to rise dramatically over the next few decades, coinciding with the expected emergence of a hydrogen economy. In such an energy system, hydrogen will likely be used in power generation, transportation and oil sands processing. Development of technologies like fuel cells that facilitate such hydrogen use is expected to continue.

The general concept of a hydrogen economy has been investigated for several decades, and has received increasing attention recently (Hennicke and Fischedick, 2006; Marban and Valdes-Solís, 2007). Pathways to hydrogen as an energy carrier have been investigated, focusing on renewable energy options and identifying obstacles (Sigfusson, 2007).

The main steps involved in implementing a hydrogen economy have been discussed (Penner, 2006). The potential of hydrogen energy in providing a future sustainable energy system has been studied (Dunn, 2002; Hennicke and Fischedick, 2006). Many have focused on the potential contributions of nuclear energy to a hydrogen economy (Marchetti, 2006). The prospects for hydrogen energy, with particular attention on its potential to avoid climate change and related problems, have been described (Scott, 2007). National approaches to a hydrogen economy have been reported for such countries as Canada (Dalcor Consultants Ltd. and Intuit Strategy Inc., 2004), the United States (Lattin and Utgikar, 2007) and Iceland (Arnason and Sigfusson, 2000),

Some assessments of the potential of a hydrogen economy have focused on the issue of hydrogen production, which is crucial to achieving a viable hydrogen economy. Hydrogen can be generated with fossil fuel-based processes, including natural gas reforming and coal gasification. In addition, hydrogen can be produced through processes not potentially based on fossil fuels, including water electrolysis using electricity. Such processes are commercially available. Three primary energy-supply routes that may be used to implement the hydrogen economy have been compared (Penner, 2006): fossil fuels, nuclear energy and renewable energy sources. A long-term global vision of nuclear-produced hydrogen was recently presented (Marchetti, 2006). Alternative processes are under development which may have economic, environmental and other advantages (Yildiz and Kazimi, 2006). Thermochemical water decomposition is one alternative process, which has several advantages over other hydrogen production processes, and which is often viewed as a future competitor to water electrolysis. Like water electrolysis, thermochemical water decomposition splits water into hydrogen and oxygen.

Requirement 3: Increased Efficiency In The Provision Of Energy Services

High efficiency allows the greatest benefits to be attained from energy options, including non-fossil fuel ones, and thus aid efforts to achieve energy sustainability. Efficiency improvements taken broadly efforts include direct measures to increase efficiency as well as

- energy conservation
- improved energy management

- fuel substitution
- better matching of energy carriers and energy demands
- more efficient utilization of both energy quantity and quality

The latter two concepts are best considered via the use of exergy analysis, a tool based primarily on the second law of thermodynamics. As an alternative to the more conventional energy analysis, exergy analysis often reveals insights not identified with energy analysis (Dincer and Rosen, 2007).

Exergy Analysis

Exergy is similar to energy in some aspects, but different in others. The exergy of an energy form or a substance is a measure of its usefulness or quality, and is determined using the conservation of energy and non-conservation of entropy principles. Two key features are that exergy is:

- the maximum work which can be produced by a flow of matter or energy as it comes to equilibrium with a reference environment. Many models for the reference environment exist, and one that simulates the natural environment is shown in Fig. 1.
- a measure of the potential of a flow to cause change, as a consequence of being in disequilibrium with the reference environment.

Exergy analysis identifies meaningful efficiencies and thermodynamic losses in an overall process and its steps and is consequently beneficial in the analysis, design and improvement of energy systems and processes. Exergy analysis is similar but advantageous to energy analysis. Exergy analysis can reveal whether or not, and by how much, it is possible to design more efficient energy systems by reducing the inefficiencies in existing systems. The exergy method thus greatly assists efforts to achieve energy sustainability. Exergy is not conserved, but instead is consumed or destroyed due to the irreversibilities in any process. Exergy losses occur through both waste exergy emissions and internal exergy destructions. Process performance is assessed by examining exergy balances, losses and efficiencies. 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
- enables the locations, types, magnitudes and causes of inefficiencies (both wastes and internal losses) to be determined

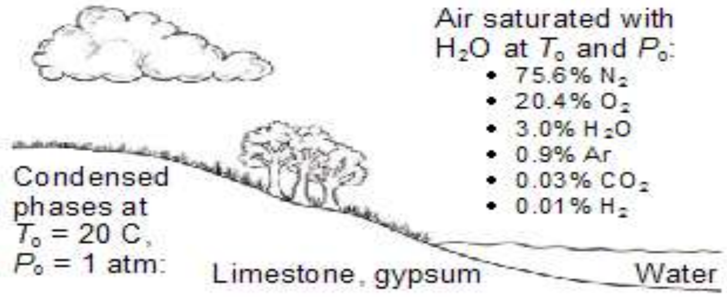

Fig. 1. Illustrative representation of a reference-environment model based on the natural environment.

The contributions that exergy can make to energy sustainability are broader than efficiency improvements because exergy concepts can also be used outside thermodynamics, e.g., in economics (Rosen and Dincer, 2003; Sciubba, 2004) and in environmental and ecological assessment (Dincer and Rosen, 2007; Wall and Gong, 2001; Jorgensen and Svirezhev, 2004). The aim of the latter 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 (Zvolinschi et al., 2007).

Extensive information on exergy and exergy analysis is available elsewhere (Szargut, 2005; Dincer and Rosen, 2007; Rosen et al., 2008). Numerous applications have been reported (Dincer and Rosen, 2007), including electricity generation (Rosen and Dincer, 2003), cogeneration (Rosen et al., 2005), chemical processing (Rosen and Scott, 1998), thermal storage (Dincer and Rosen, 2002), fuel cells and hydrogen engines (Barclay, 2006), and hydrogen production (Rosen, 1990; Rosen and Scott, 1998; Abanades et al., 2006; Sakurai et al., 1996; Orhan et al., 2008).

Requirement 4: Reduced Environmental Impact Throughout The Life Cycle Of Energy Processes

Numerous environmental impacts associated with energy processes are of concern and must be addressed in efforts to attain energy sustainability, including:

- global warming (usually attributable mainly to greenhouse gas emissions and considered to be a key element of global climate change)
- ozone depletion potential (concerned with destruction of the atmospheric ozone layer and subsequent increases in ultraviolet reaching the earth's surface)
- acidification potential (concerned with the impact on soil and water of acidic emissions)
- radiological potential (relates to the probability of radiogenic cancer mortality or morbidity due to internal or external radiation exposure)
- abiotic resource depletion potential (concerned with the extraction of non-renewable raw materials)
- ecotoxicity aquatic (concerned with exposure to toxic substances that lead to health problems)

Global warming is viewed by many as the most urgent environmental impact facing humanity. 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. This gas is the principal greenhouse gas, and is an inherent product of the combustion of carbon-containing hydrocarbons. 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 (Rosen et al., 2008).

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

Given the importance in the author's view of global warming and environmental life cycle assessments, they are discussed in greater detail below.

Energy and Global Warming

An increasingly significant environmental concern, strongly related to energy use, is global warming. In discussing global warming, it is helpful to note that most of the energy entering the earth's atmosphere eventually exits back to space, a concept seen via the earth-sun-space energy balance (see Fig. 2):

Energy input − Energy output = Energy accumulation

Here, energy input is the short-wave solar radiation entering the atmosphere, energy output is the long-wave radiation exiting the atmosphere to space, and energy accumulation is the increase in energy of the earth and its atmosphere. The main implication of this balance is that, since the average temperature of the earth is relatively constant (excluding global warming), the energy accumulation term is zero. Therefore, the energy output is equal to the energy input for the planet.

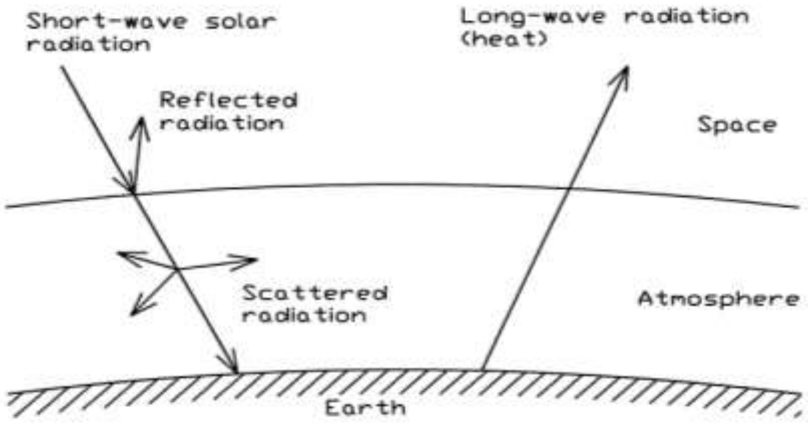

Fig. 2. Earth-sun-space energy balance.

Global warming, generally agreed to be attributable to increased releases of atmospheric "greenhouse gases" that absorb radiation in the 8 to 20 micrometer region, disrupts the earth-sun-space energy balance. When greenhouse-gas concentrations increase in the atmosphere, energy output from the earth and its atmosphere (Fig. 2) is reduced while energy input remains constant. Thus, the energy accumulation term becomes positive, 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.

The main greenhouse gas is carbon dioxide, and the main reason cause of increased emissions of carbon dioxide is the combustion of fossil fuels, in furnaces, power plants, vehicles, etc. A fossil fuel can be modelled as a hydrocarbon, and a qualitative chemical expression for its combustion reveals the main link between fossil fuels and global warming:

Hydrocarbon fuel + Air (mainly O_2 and N_2) $\rightarrow CO_2 + H_2O + N_2$ + Other substances

where the other substances are leftover reactants and other reaction products. Carbon dioxide is clearly seen to be an inherent product of the combustion of any carbon-containing fuel. Generally, the only way to avoid carbon dioxide emissions is to eliminate the use of carbon-based fuels (e.g., by using hydrogen as a fuel). Otherwise, the only way to avoid such emissions to the atmosphere is to capture them and sequester or find alternative uses for them.

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. 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) (Graedel and Allenby, 2003).

LCA considers a product, process or activity from “cradle to grave”, i.e., the entire life cycle of a product, process or activity, from extraction of materials to final disposal (see Fig. 3). This approach 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 of desired energy forms, transportation and distribution of the energy to users and, where relevant, energy storage); operation (use of the energy to provide services and tasks); and post-operation steps (recovery and re-use of output energy that would otherwise be wasted, recycling of wastes and disposal of final wastes).

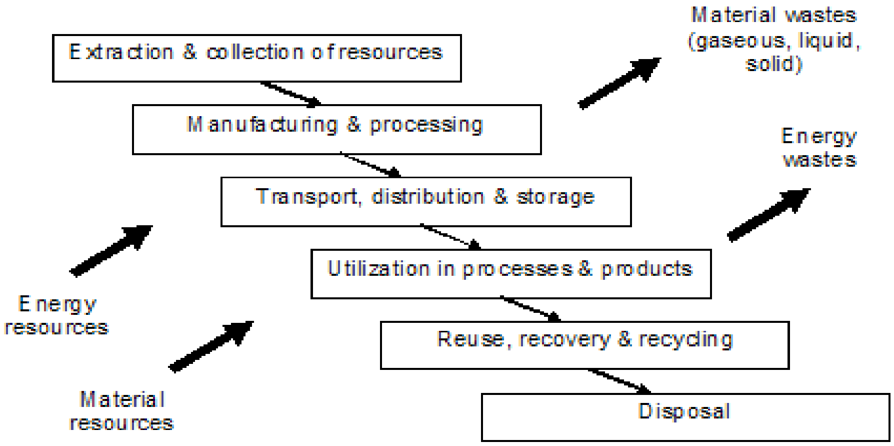

Fig. 3. Scope of life cycle assessment of a product or process.

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 Life Cycle Assessment - Principles and Guidelines, ISO 14041 Life Cycle Assessment - Life Cycle Inventory Analysis, ISO 14042 Life Cycle Assessment - Impact Assessment, ISO 14043 Life Cycle Assessment – Interpretation, ISO 14048 Life Cycle Assessment - Data Documentation Format, ISO 14049 Life Cycle Assessment - Examples for the application of ISO 14041). LCA generally involves three main steps (see Fig. 4):

- 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 is accomplished via 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 US Environmental Protection Agency, the Centre of Environmental Science at Leiden University, The Netherlands, the Nordic Council of Ministers and the United Nations Environment Program (Heijungs et al., 1992).
- Step 3: 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 (Heijungs et al., 1992).

These three steps are usually preceded by definition of LCA objective(s) and definition of the scope of the LCA. The latter establishes the economic-environmental boundaries and limits for the investigation. Note that many interactions occur between the steps in Fig. 4, allowing feedback provided by improvements to help shape objectives, scope and inventory analysis for subsequent LCAs.

LCAs have been performed for various processes, including hydrogen production from natural gas, solar energy and wind energy (Granovskii et al., 2007). Utgikar and Thiesen (2006) conducted an LCA of hydrogen production via nuclear-driven electrolysis, while Solli et al. (2006) compared using LCA the environmental impacts of hydrogen production from nuclear energy and natural gas. Those studies demonstrated that hydrogen represents a potential long-term solution to many environmental concerns.

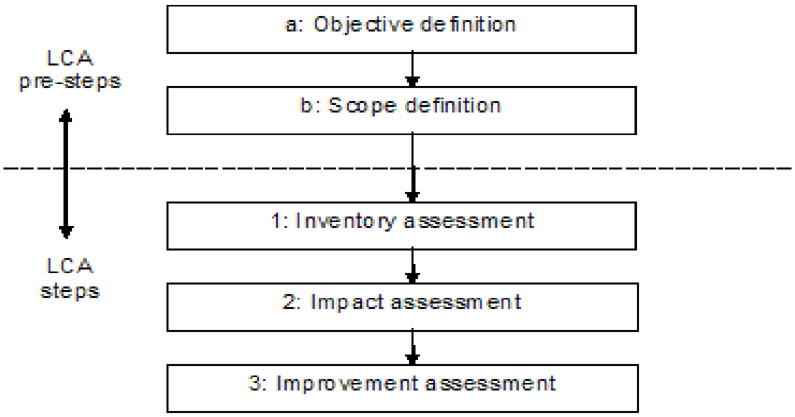

Fig. 4. Main steps in life cycle assessment.

Requirement 5: Consideration Of Other Facets Of Sustainability

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

- Economic affordability. To be sustainable, energy 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 energy resources, regardless of geographic location, to achieve energy sustainability. In addition, equity among developed and developing countries must be achieved in terms of energy opportunities. Also, true energy sustainability requires that future generations be able to access energy resources. Equity in terms of energy is somewhat time dependent, and this author expects that short-term differences will diminish in time and energy opportunities in all countries will converge in the longer term.
- Meeting increasing energy demands. The increasing use of 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. Energy options must be safe in terms of injury, and cause no negative health effects in the short and long terms to be sustainable.
- Community involvement and social acceptability. People and communities must be involved in energy-related decisions if energy 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.
- Appropriate land use. The use of land for energy-related activities needs to be balanced with other needs, such as agriculture and recreation. This is a particularly significant challenge with technologies like hydraulic energy, which often involves flooding large tracts of land, electricity transmission, which often traverses sensitive ecosystems, and bioenergy, which often involves the growth of energy plants on land that could be used for other purposes.

- Aesthetics. The cleanliness of the environment in terms of aesthetics is an important aspect of sustainability, in that it affects the well-being of people. Energy sustainability needs to avoid harming the aesthetics of the environment. This can be challenging even for renewable energy technologies, e.g., wind power systems can involve large wind turbines across the landscape.
- Lifestyles. Modifying lifestyles and tempering desires that are energy-driven can help in the quest for energy sustainability. Given that aspirations of people tend to increase continually, this aspect of energy 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, as in the case of an "oil-price shock" or a disaster such as a drought. 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 energy use 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 energy options 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 usually are addressed if the other requirements are addressed with a sustainability focus. For instance, the capture or production of sustainable energy sources must take into account such factors as economics, global stability and geographic and intergenerational equity if a sustainability focus is implemented.

Illustration: Thermochemical Hydrogen Production

Hydrogen production using thermochemical water decomposition via sustainable routes (i.e. processes avoiding fossil fuels) is used to illustrate the concepts discussed in this article (capture/production of sustainable energy sources, their conversion into appropriate energy carriers, increased efficiency and reduced environmental impact, and other facets of sustainability).

Thermochemical water decomposition (Rosen, 1990; Abanades et al., 2006; Sakurai et al., 1996; Orhan et al., 2008), which is still undergoing development, is anticipated to be capable of large-scale hydrogen production. Thermochemical cycles for hydrogen production are driven by thermal energy and use a series of reactions to split water: $H_2O \rightarrow H_2 + 1/2O_2$. Most preliminary designs of thermochemical hydrogen production are based on nuclear or solar energy, thus providing different sustainable options. Research on thermochemical production of hydrogen began in the 1970s but has increased notably attention in recent years (Funk, 2001; OECD, 2006).

Nuclear and Solar Thermochemical Water Decomposition

In the near term, thermochemical hydrogen production processes are likely to be based on nuclear energy, allowing them to use a non-fossil fuel energy source. Nuclear reactors operating at various temperatures are being considered, including many new reactor concepts (OECD, 2006; Schultz et al., 2005; Le Duigou et al., 2007; Forsberg, 2003). A review of more than 100 thermochemical cycles identified the most promising cycles for efficient, cost-effective, large-scale production of hydrogen utilizing high-temperature heat from an advanced nuclear power station.

Thermochemical hydrogen production studies from nuclear energy are ongoing in many countries, including Japan, Korea, Canada, the U.S. and France (OECD, 2006). Research on the potential coupling with Canada's future nuclear reactors is ongoing, while Sandia National Laboratory in the U.S. and the Atomic Energy Commission (CEA) in France are developing a hydrogen pilot plant with a sulphur-iodine (S-I) cycle. The Korea Atomic Energy Research Institute (KAERI) is collaborating with China to produce hydrogen with the HTR-10 reactor. The Japan Atomic Energy Agency plans for 2020 a sulphur-iodine plant to produce 60,000 m3/hr of hydrogen, which can drive about one million fuel cell vehicles. Several countries are participating through multilateral collaborations in the Generation IV International Forum to develop technologies for cogeneration of hydrogen by high-temperature thermochemical cycles and electrolysis. Bench-scale tests of the sulphur-iodine cycle have been carried out in Japan.

In the longer term, thermochemical hydrogen production is likely to be based on solar energy. Advances in thermochemical hydrogen production using concentrated solar radiation as the source of high-temperature heat have been reviewed and screened recently (Steinfeld, 2005; Abanades et al., 2006), and thermochemical cycles for large-scale hydrogen production using solar energy have been investigated (Le Duigou et al., 2007). For example, thermochemical hydrogen production from water has been considered, based on Zn/ZnO redox reactions using solar energy (Steinfeld, 2002), and on the S-I cycle and hybrid S cycle (the Westinghouse cycle) with solar and nuclear energy (Le Duigou et al., 2007). More generally, exergy efficiencies have been considered in solar thermochemical production of hydrogen (Steinfeld, 2005).

Contributions of Thermochemical Hydrogen Production to Energy Sustainability

Following the concepts described earlier, four contributions of thermochemical hydrogen production to energy sustainability are considered. The first benefit focuses on the use of sustainable energy resources, and the second on the beneficial energy carriers yielded by the process. The third benefit is the increased efficiency attainable, and the fourth considers environmental benefits.

- **Improved energy resource selection flexibility.** The primary advantage of thermochemical cycles is that they split water with lower temperatures than required to split water directly through heating. The advantages of a cycle increase as its required peak temperatures are reduced, as a greater range of heat sources can then be considered and energy sustainability objectives can better be achieved. Research has been carried out to lower the peak temperatures required, and cycles have been investigated that require lower peak temperatures, like the copper-chlorine (Cu-Cl) thermochemical cycle (Suppiah et al., 2006; Arif Khan and Chen, 2006). This cycle, which requires heat at approximately 550°C, has been identified by Atomic Energy of Canada Ltd. as highly promising. The process is illustrated in simplified form in Fig. 5 (Lewis et al., 2003).

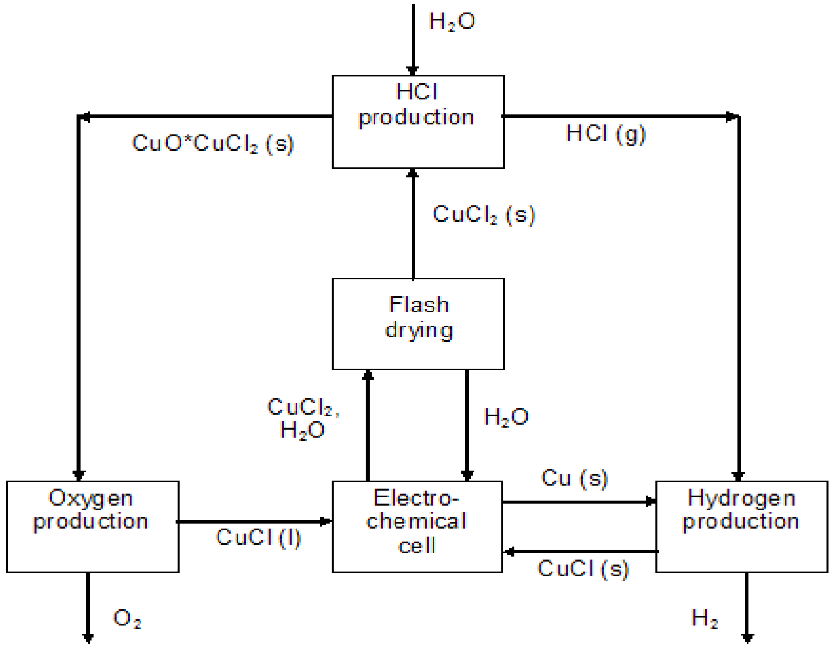

Fig. 5. Simplified diagram of a copper-chlorine thermochemical water decomposition cycle for hydrogen. High-temperature heat is input to the oxygen production, hydrogen production and HCl production steps.

- **Beneficial energy carriers.** By producing hydrogen energy, the process yields a useful chemical fuel that complements electricity and can be used to produce hydrogen-derived fuels (e.g., ammonia, methanol).

- **Improved efficiency.** The efficiency of producing hydrogen by thermochemical water decomposition is suggested by many to exceed the efficiency of other hydrogen production processes that have similar sustainability characteristics. Efforts to improve the efficiency of the process, and to integrate the process more efficiently into society's energy systems, can also be aided by exergy analysis. For example, an exergy analysis was carried out (Rosen, 1990) of the Ispra Mark-10 thermochemical water decomposition cycle for hydrogen production. In that study, it is observed that the hydrogen product has high energy and exergy contents, the by-product oxygen low energy and high exergy contents, and the wastes (spent cooling water and waste gas) high energy and low exergy contents (Table 3). Also, to reduce losses, energy analysis indicates that quantities of waste effluents should be reduced, while exergy analysis indicates that internal exergy consumptions should be reduced. Research to improve the efficiency of this thermochemical water decomposition cycle should be guided, at least in part, by the exergy results which indicate the need to concentrate on subprocesses having large exergy losses.

- **Improved environmental performance.** Thermochemical water decomposition allows for reduced environmental impact, for the reasons described in the previous three bullets. Also, to ascertain the overall environmental impacts of thermochemical hydrogen production, LCA can be used. For example, LCAs have been reported for nuclear-driven versions of the copper-chlorine thermochemical cycle (Lubis et al., 2008) and the Ispra Mark 9 thermochemical cycle (Utgikar and Ward, 2006).

Table 3. Energy and Exergy Balances for Ispra Mark-10 Thermochemical Hydrogen Production Process

Flow	Energy (% of total input energy)	Exergy (% of total input exergy)
Inputs (high-temperature heat and water)	100	100
Products		
Hydrogen	20.5	25
Oxygen*	0	0.5
Total products	20.5	25.5
Losses		
Waste outputs	79.5	4.5
Internal consumptions	-	70
Total losses	79.5	74.5

* Oxygen is treated as a by-product and grouped with products.

Conclusions

It is demonstrated with an engineering approach that several key factors need to be considered and appropriately addressed to achieve energy sustainability, which itself is a crucial component of overall sustainability for human activity and development. The key factors include appropriate selection of energy resources accounting for sustainability criteria, facilitation of the use of sustainable energy resources, enhancement of the efficiency of energy-related processes, environmental stewardship in energy activities, and consideration of other key sustainability measures, such as economics and equity. The author believes that options and pathways for energy sustainability can be achieved by considering these key factors. Furthermore, through energy sustainability, the author feels that a shift towards overall sustainability can be given great impetus, given the pervasiveness of energy use and its impacts on the environment, as well as the importance of energy 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 energy sustainability. The production of hydrogen from sustainable energy sources via thermochemical water decomposition illustrates the concepts well.

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Published by the Forum on Public Policy