

# Bulletin of Science, Technology & Society

<http://bst.sagepub.com/>

---

## **Integrated System Approach to Sustainability Bio-Fuels and Bio-Refineries**

Said S. E. H. Elnashaie, Seif-Eddeen Fateen, Ahmed El-Ahwany and Tarek M. Moustafa

*Bulletin of Science Technology & Society* 2008 28: 510

DOI: 10.1177/0270467608317218

The online version of this article can be found at:

<http://bst.sagepub.com/content/28/6/510>

---

Published by:



<http://www.sagepublications.com>

On behalf of:

National Association for Science, Technology & Society

**Additional services and information for *Bulletin of Science, Technology & Society* can be found at:**

**Email Alerts:** <http://bst.sagepub.com/cgi/alerts>

**Subscriptions:** <http://bst.sagepub.com/subscriptions>

**Reprints:** <http://www.sagepub.com/journalsReprints.nav>

**Permissions:** <http://www.sagepub.com/journalsPermissions.nav>

**Citations:** <http://bst.sagepub.com/content/28/6/510.refs.html>

# Integrated System Approach to Sustainability

## Bio-Fuels and Bio-Refineries

Said S. E. H. Elnashaie  
*Penn State University*

Seif-Eddeen Fateen  
Ahmed El-Ahwany  
Tarek M. Moustafa  
*Cairo University*

The ISA, based on system theory, is the best way to organize knowledge and exchange it. It depends on defining every system through its boundary, main processes within this boundary, and exchange with the environment through this boundary. It relies upon thermodynamics and information theory and is, therefore, applicable to all kinds of systems, which makes it most suitable for cross-disciplinary investigations and innovation. SD is complex and cross-disciplinary by its very nature and, therefore, the ISA is the best way to investigate its different subsystems. Among the most important subsystems of SD are integrated bio-refineries and bio-fuels, both of which are investigated in this article.

**Keywords:** *system theory; integrated system approach, sustainability; sustainable development; bio-fuels; bio-refineries; bio-fuel cells; bio-electrolysis; auto-thermal housing*

### Introduction

System theory is the basis of the ISA (see the appendix for list of abbreviations), which is the most efficient methodology for knowledge classification, organization, transfer, and exchange (Elnashaie & Grace, 2007). The ISA is very valuable in both research and education. In research, it is one of the most important tools for the development of new knowledge and novel processes, especially in areas where cross-disciplinary research and development is a must for innovative solutions. SD is one of those areas that are cross-disciplinary by their very nature (Fiksel, 2006).

SD is formed by a number of subsystems, each of which is formed by its own elements. Subsystems of SD include both technical and non-technical categories, for example, technology, socioeconomic, political, ethical/moral, and so on. Focusing on any one of the SD subsystems can only be successful within a framework that has the other subsystems as a background. Within the technological subsystem of SD, a structural hierarchy of subsystems down to the elements (which depend upon the level of analysis) gives the structure and boundaries of this important subsystem, especially from an engineering point of view. It is useful in this regard to use terminologies and classifications of system theory

coupled with terminology of non-linear dynamics and stability theorem. As an example, we can consider efficient engineering as a subsystem of EE, representing a necessary but not sufficient condition for clean/green technology. This is due to the simple fact that applying efficient engineering without taking environmental constraints into consideration can achieve maximum productivity that would not necessarily be environmentally clean. Clean/green technology will need efficient engineering as a prerequisite. Also, we can consider EE as a subsystem of SE, representing a necessary but not sufficient condition for sustainability. This is due to the simple fact that EE without using RRs can achieve clean/green and maximum productivity but is not necessarily sustainable. SE will have both efficient and environmental engineering as prerequisites. The utilization of RRs is at the heart of sustainability; this leads to the crucial importance of bio-fuels at one level and IBRs at higher levels, as discussed in this article, using the ISA as an efficient tool.

### System Theory and the Integrated System Approach

The theme of this article is to stress the importance of the system theory when dealing with the issue of

sustainability, bio-fuels, and IBRs. System theory is a basic tool for dealing with sustainability and SD and it should be more widely used in engineering education and research. Definitions of some important terms are essential (Elnashaie & Garhyan, 2003; Elnashaie & Uhlig, 2007).

## System Theory

### *What Is a System?*

The word *system* derives from the Greek word *systema* and means an assemblage of objects united by some form of regular interaction or interdependence. A simpler, more pragmatic description regarding systems includes the following:

- A system is a whole composed of parts (elements or subsystems).
- The concepts of a system, subsystem, and element are relative and depend upon the degree of analysis.
- The parts of the system can be parts in the physical sense or they can be processes. A system can be formed of both (i.e., different parts of the system; a reactor and a regenerator combined to form an FCC unit; Elnashaie & Elshishini, 1996), each part having a number of processes taking place within its boundaries.
- The properties of the system are not necessarily the sum of the properties of its components (elements or subsystems), although they are, of course, affected by those components. Instead, the properties of the system result from non-linear interaction (synergy) between elements or subsystems (Elnashaie & Garhyan, 2003; Elnashaie & Uhlig, 2007).

### *The State of the System and State Variables*

The term *state of the system*, rigorously defined through the state variables of the system, is used extensively in discussing and modeling/simulation of systems. These state variables are chosen according to the nature of the system.

### *Input Variables (parameters)*

Input variables are not state variables. Instead, they are external to the system but affect the system (i.e., work on the system). For example, the feed temperature and composition of the feed stream to a distillation tower or a chemical reactor or the feed temperature to a heat exchanger are input variables.

### *Design Variables (parameters)*

Design variables are associated with the design of the system and are usually fixed. Examples are the diameter and height of a CSTR or of a tubular reactor.

## *Boundaries of System*

A system has boundaries distinguishing it from the surroundings or environment. The relation between the system and its environment leads to one of the most important classifications of systems:

1. Isolated systems: They do not exchange matter nor energy with the environment (surroundings). They tend to the state of thermodynamic equilibrium (maximum entropy). An example is a batch adiabatic reactor.
2. Closed systems: They do not exchange matter with the environment (surroundings), but they do exchange energy. Such systems, again, tend to thermodynamic equilibrium (maximum entropy). A batch non-adiabatic reactor is an example.
3. Open systems: They exchange matter and energy with the environment (surroundings). They do not tend to thermodynamic equilibrium but to steady state or what should better be called a stationary non-equilibrium state, characterized by minimum entropy generation. A CSTR is an example.

The above shows that the term *steady state* commonly used in chemical/biological engineering and other disciplines is not precise enough. A more accurate term should be *stationary non-equilibrium state*, which is a characteristic of open systems, distinguishing it from *stationary equilibrium state*, associated with isolated and closed systems.

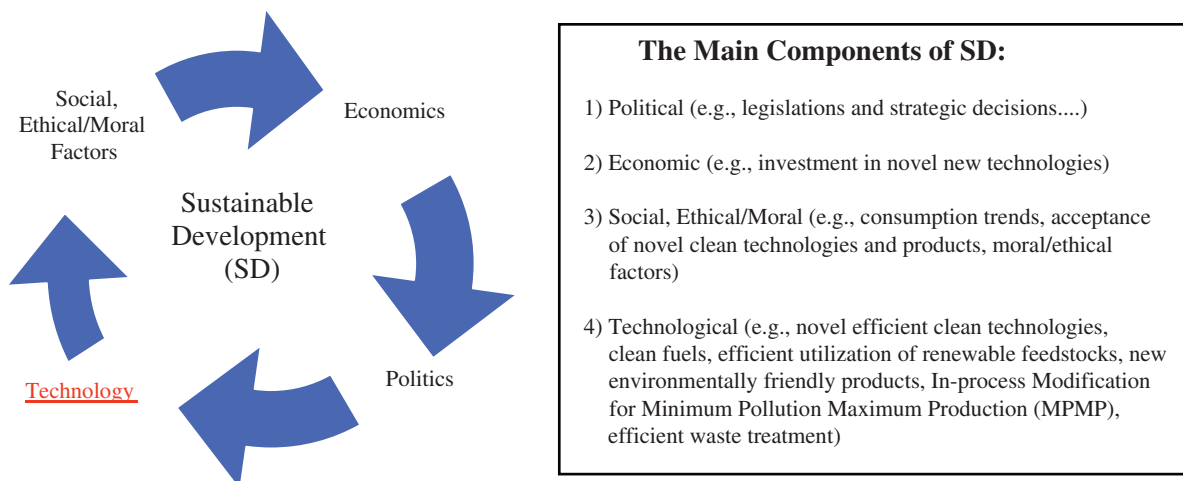
## *Steady and Unsteady States and Thermodynamic Equilibrium of Systems*

Steady state occurs when the state of the system does not change with time, but the system is not at thermodynamic equilibrium. This steady state of lumped systems is a point in a space having the same dimensions as the problem (number of components + temperature + pressure, etc.), whereas that for distributed systems is a profile in the space coordinate(s) as additional dimension(s). Unsteady state of an open system starts at an initial condition and tends with time towards a steady state when the system is stable (a point for lumped system and profile for distributed systems).

## Integrated System Approach

The current lack of success in improving industrial sustainability, coupled with the challenges of bio-complexity and resilience, indicates that sustainability is a system's problem requiring collaborative solutions with a cross-disciplinary nature (Delft University of Technology, 2003; Food and Agriculture Organization of the United Nations, 1997; Hramov & Koronovskii, 2005;

**Figure 1**  
**Main Components of Sustainable Development (SD)**



Note: SD is cross-disciplinary by its very nature. Technology is a subsystem of SD.

Rotmans et al., 1994; Subramanian, 2000; von Bertalanffy, 1976; Way & Wilson, 2005).

A number of technical advances will likely improve the usefulness of models, including rigorous methodologies for dealing with missing and uncertain information; improved methods for interpretation of multivariate data sets and for multi-objective decision making involving trade-offs among conflicting goals; and novel modeling methods as alternatives to traditional mathematical models. More generally, there is a great need for operational definitions and metrics for sustainability and resilience in economic, ecological, and societal systems.

SD in a changing global environment will require resilience at many levels, including human communities and economic enterprises. In the face of ever-increasing global complexity and volatility, it is essential to move beyond a simplistic steady state model of sustainability. Instead, we need to develop adaptive policies and strategies that enable societal and industrial institutions to cope with unexpected challenges, balancing their need to be able to achieve an efficient SD.

### **Basic Principles of Sustainable Development and Bio-Fuels**

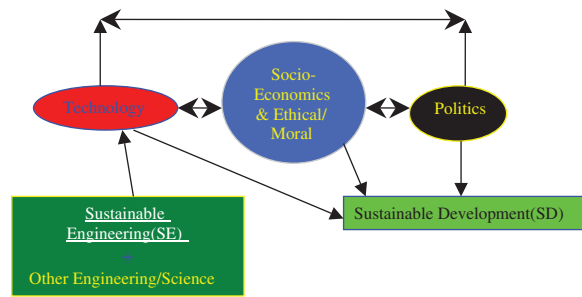
The simple analysis in the introduction and some other components discussed in this article highlight the following basic principles:

1. SD is a system formed of technological and non-technological subsystems as shown in Figure 1 and detailed in this article, with special emphasis on the technological subsystem with the other subsystems in the background.
2. As illustrated in Figure 2, SE is a subsystem of the technological subsystem of SD.
3. SD can also be divided into the following (Hens, 2005; Horbach, 2005; Makower & Fleischer, 2003):
  - a. SD with respect to production, which is the main emphasis of this article
  - b. SD with respect to consumption, which is in the background of this article

SP&C emerged as a key issue on the SD agenda at the UNCED in Rio de Janeiro in 1992. The agenda called on governments, businesses, and others to implement measures to promote efficiencies in production and encourage sustainable patterns of consumption. It went on to say that the developed countries should take the lead in introducing those measures. An international agenda had been introduced by the UNCSO, in cooperation with national governments; the OECD and others responded to this mandate with an international work program and recommendations for action. Proposed action items included the following:

- pricing reforms to internalize environmental costs and remove subsidies that generate unsustainable consumption
- “green” public procurement policies

**Figure 2**  
**Subsystems of Sustainable Development (SD)**



Note: Sustainable engineering is a subsystem of technology, which is a subsystem of SD. An example of technology politics interaction is the U.S. Department of Energy's extensive research for the efficient production of hydrogen and cellulosic bioethanol after the state of the union addresses by President Bush in 2003 and 2006. As engineers, we focus on technology within the framework of other components.

- extending producer responsibility for the lifecycle environmental impacts of goods and services
- eco-labeling programs

The UNCSO has called specifically upon businesses to do the following:

- integrate environmental criteria into their purchasing policies
- design more efficient products and processes
- increase the life-spans for durable goods
- improve their after-sales services, reuse, and recycle
- promote sustainable consumption through advertising, marketing, and product information

4. Efficient engineering is a subsystem of EE, which is a subsystem of SE. In other words, efficient engineering is necessary but not sufficient for EE, which itself is necessary but not sufficient for SE aiming at sustainability.
5. Metrics are necessary for measuring sustainability (ICHEME, 2002; Trazil, Ma, & Beloff, 2003). According to the extensive study by the ICHEME, metrics for sustainability can be divided into three groups: environmental indicators, economic indicators, and social indicators. This emphasizes the fact that EE is necessary but not sufficient for sustainability. However, the three categories do not show explicitly the importance of RRs for sustainability, shown very simply and briefly above.
6. RRs represent a crucial component of SE and, thus, SD. Green technology based on non-renewable raw materials may be satisfactory from an EE point of view but is not sustainable.

7. RCFs is a very important subsystem of RCE, which is a very important subsystem of SE and, thus, SD. Under the Energy Policy Act of 2005, the EPA is responsible for promulgating regulations to ensure that gasoline sold in the United States contains a minimum volume of RCFs. A national renewable fuel standard program (also known as the renewable fuel standard program, or RFS program) will increase the volume of RCFs required to be blended into gasoline, starting with 4.0 billion gallons in calendar year 2006 and nearly doubling to 7.5 billion gallons by 2012. The RFS program was developed in collaboration with refiners, RCFs producers, and many other stakeholders (U.S. Environmental Protection Agency, n.d.; see also <http://www.wbfevent.com/>).

8. Bio-fuels (Ellison, 2007) represent a very important subsystem of RCFs, which is the main emphasis of this article with other subsystems of RCFs in the background. There is a large number of bio-fuels; each one of them can be produced through different routes. Figure 3 shows some of these routes for bio-diesel and bio-hydrogen, while Figure 4 shows the routes to bio-ethanol. All bio-fuels and all technologies will have their positions in the clean fuels matrix of the future.

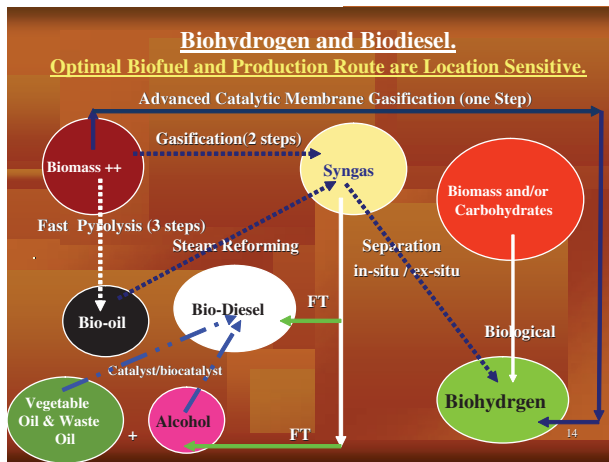
9. Figure 3 shows two types of bio-diesels, the strategic FT bio-diesel and the non-strategic bio-diesel from the trans-esterification of vegetable oils. A third type of bio-diesel, which may prove to be more strategic than both, is the algae bio-diesel (Alvarado, 2007; Briggs, 2004; *Directory: Biodiesel From Algae Oil*, 2007; Sazdanoff, 2006; Sheehan, Dunahay, Benemann, Roessler, & Weissman, 1998). Among the most photo-synthetically efficient plants are various types of algae. Some species of algae are ideally suited to bio-diesel production due to their high oil content (some well over 50% oil) and extremely fast growth rates.

10. Clear definitions for ER and NER (Dewulf & Langenhove, 2006; Rand & Dell, 2004; see also <http://www.energy.gov/>, <http://www.ers.usda.gov/>) should be developed to clear the present confusion regarding ER < 1.0 and NER < 0.0 and QE. A brief review of them can be given in the following few lines:

ER of a fuel is defined as (Energy of Fuel)/(Energy Consumed to Produce the Fuel), while NER of a fuel is (Energy of Fuel - Energy Consumed to Produce the Fuel) (+/-) Energy Consumed to Produce the Fuel/(Energy Consumed to Produce the Fuel) = Y (+/-) X/X.

The (+/-) sign is defined as follows: It is + when Y is positive (ER > 1.0) and - when Y is negative (ER < 1.0).

**Figure 3**  
Some Routes to Bio-Diesel and Bio-Hydrogen



Note: FT = Fisher Tropsch.

## Examples

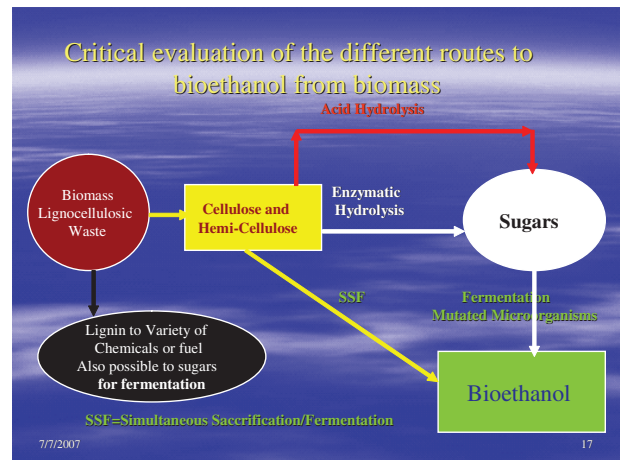
- One researcher gave the following: Total energy use for producing ethanol (A) = 78,081.00 Btu/gal, considered energy of ethanol (B) = 83,961.00 Btu/gal, thus,  $Y = +5,880.0$  and the above sign is + and  $NER = (5,880.0 + 78,081)/78,081 = 1.1$  and  $ER = 1.1$ . Meaning: If we consume 100.0 kJ to produce an amount of ethanol, this ethanol will contain 110 kJ of energy.
- Another researcher gave the following: Total energy use for producing ethanol (A) = 131,017 Btu/gal, considered energy of ethanol (B) = 76,000 Btu/gal, thus,  $Y = -55,017.00$  and the above sign is - and  $NER = (-55,017.00 - 131,017)/131,017 = -1.42$  and  $ER = 76,000/131,017 = 0.58$ . Meaning: If we consume 100.0 kJ to produce an amount of ethanol, this ethanol will contain 58 kJ of energy (but may be of higher QE).

The above examples show how sensitive the calculation of ER and NER is and also how the QE can affect the situation.

The main differences in calculating ER and NER are as follows:

- Energies included: Some researchers include solar energy used in the production of the raw materials for the production of the fuel, which is quite disputable.
- Levels of technologies: Some researchers use older technologies when computing energy consumed to produce the fuel, which is not correct.
- Energy estimation techniques: Different researchers use different estimation techniques, which create

**Figure 4**  
Routes for Cellulosic Bio-Ethanol



artificial differences. These estimation techniques need to be standardized.

- Energy is included/not included in capital cost and estimation techniques.
- Energy credits for by-products are included/not included.

Typical data about ER and NER from the USDA (see <http://www.ers.usda.gov/>) and DOE (see <http://www.energy.gov/>) are given in Table 1.

It is clear that bio-ethanol is the only fuel on the list with  $ER > 1.0$  and  $NER > 0.0$ . Other fuels with  $ER < 1.0$  and  $NER < 0.0$  are valid fuels simply because energy of fuel is of higher QE than energy consumed to produce the fuel, for example, electricity from coal ( $ER = 0.4$ ,  $NER = -1.6$ ).

The cellulosic bio-ethanol will be even better than the present corn bio-ethanol as shown in Table 2.

- The final utilization of energy is a subsystem of the entire SE and SD, for example, utilization of fuel cells and bio-fuel cells as well as integrated electrolysis (bio-electrolysis), fuel cells (bio-fuel cells), and efficient hydrogen/oxygen storage using nanotechnology to efficiently transform intermittent solar energy into a continuous electric supply in auto-thermal housing (Palmore & Whitesides, 1994; Shukla, Suredsh, Berchmans, & Rajendran, 2004; Sisler, 1971; Taniquchi, Tabata, Kusuda, Koga, & Sotomura, 2003; Turner, Aston, Higgins, Davis, & Hill, 1982; see also <http://www3.imperial.ac.uk/fuelcells/reports/1/conference%20reports>). In principle, electrolysis

**Table 1**  
**Energy Ratio (ER) and Net Energy Ratio (NER)**  
**From the U.S. Department of Agriculture,**  
**U.S. Department of Energy, and Other Sources.**  
**Examples From the U.S. Department of**  
**Agriculture (supporting ethanol from corn)**

Fuel	ER	NER
Gasoline	0.8	-1.2
Diesel	0.8	-1.2
Electricity	0.4	-1.6
Bio-ethanol	1.6	+1.6
Natural gas	0.9	-1.1
Liquified petroleum gas	0.95	-1.05
Coal	0.95	-1.05

**Table 2**  
**Corn and Cellulosic Bio-Ethanol**

	ER	NER
Ethanol from corn	1.25–1.35	1.25–1.35
Ethanol from cellulosic waste	1.8	1.8

Note: ER = energy ratio; NER = net energy ratio.

and fuel cells are the opposite of each other. So, producing hydrogen by electrolysis in order to utilize it for the production of electricity in fuel cells is certainly not a good idea from an energy point of view. However, it can be used to turn intermittent solar energy to continuous electric energy for many applications including auto-thermal housing (*Hydrogen and Fuel Cell Educational Equipment*, n.d.).

Bio-electrolysis can be looked upon as electrolysis assisted by microorganism power to break the H<sub>2</sub>O molecules in a suitable electrolyte solution. It can also be looked upon, in the opposite sense, as bio-hydrogen production by a microorganism assisted by the ability of an electric current to break down the H<sub>2</sub>O molecules. The bio-fuel cell can have two sides of its bio-action: at the anode, the microorganisms assisting in the ionization of the hydrogen molecules, and at the cathode, using ferric ions instead of oxygen, and when it is reduced to ferrous ions, it is regenerated to ferric ions using a bioreactor, which does that while utilizing CO<sub>2</sub> for photosynthesis to grow the microorganisms and produce a single-cell protein for animal feed (Nagpal, 1997).

The integral system should also have an optimal design of the bio-electrolyzer (operated on electrical

power from solar energy) to produce hydrogen (*How to Build a Hydrogen Electrolyzer*, 2007; Kamitaka, Tsujimura, & Kano, 2007; Satms et al., 2006) to supply the bio-fuel cell during the morning and excess hydrogen to be stored and used to supply the bio-fuel cell by night. Novel techniques for hydrogen storage using nanotechnology are developed (Kamm, Gruber, & Kamm, 2006; Ratner & Ratner, 2003; U.S. Department of Energy, 2005), for example, carbon nano-tubes (*What Is a Biorefinery?*, n.d.), and a flexible bio-electrolyzer, which operates in the morning for electrolysis and by night as an additional bio-fuel cell, will represent a considerable addition to the productivity of this integral bio-system.

12. Bio-fuels are sensitive to location and size of investment/market. This implies the following:

- no single bio-fuel will dominate the market, that is, the present matrix of dirty, non-renewable fuels will be replaced by a matrix of clean, renewable fuels
- no single technology for the same bio-fuel will dominate; each technology will have its domain of application, for example, SSF vs. hydrolysis (enzymatic or acidic) followed by fermentation, for the production of cellulosic bio-ethanol
- research for different bio-fuels and different technologies should continue so that, in each case, the feasibility study will be based on the optimum of each fuel and technology, avoiding misleading results

13. The present situation of bio-fuel production from agriculture products (e.g., bio-ethanol from corn and bio-diesel from vegetable oils, etc.) is not a strategic, long-term, large-scale solution for the renewable energy problem for SD. It will be replaced by large-scale production of bio-fuels from waste (e.g., cellulosic bio-ethanol, FT bio-diesel, etc.). However, it will still occupy a small part of the matrix of clean, renewable fuels.

## Sustainable Development, Sustainable Engineering, and Environmental Engineering

Many SD definitions are catch phrases and not real ones, reflecting the intimacy of the term; an example is, "It is the form of technological, economical and social strategy for development that provides a mode of development so that future generations will have at least the same opportunities to live and prosper that the present generation enjoys." Does this mean that we are happy with the present situation, locally, state-wise,

national-wise, and international-wise? Of course not. SD definition should be more concrete and specific than that. The definition should be formed of a number of components and not catch phrases.

We would rather, then, have the SD description “definition” cover the following:

- develop novel clean technologies capable of achieving minimum pollution-maximum production
- develop technologies capable of using RRs to achieve sustainability (and maybe growth) of raw materials rather than the present situation associated with the continuous and critical depletion of raw materials
- the use of natural distributed RRs in contradistinction to the present depleting raw materials concentrated in certain parts of the world causing continuous conflicts and wars
- produce environmentally friendly products easy to degrade and/or reuse
- develop clean and environmentally friendly housing, office buildings, and shopping centers
- develop efficient technologies for waste treatment and recycling
- building socio-economic and political frameworks to apply the above (including the necessary nonprofit tendencies and change of consumer habits, etc.)
- developing efficient IBRs

## Bio-Fuels and Integrated Bio-Refineries

An IBR is a complex facility that integrates biomass conversion processes and equipment to produce fuel, power, and chemicals/bio-chemicals from the biomass. It is analogous to today’s petroleum refineries and its integrated petrochemical complexes, which produce multiple fuels and products from petroleum. IBRs have been identified as the most promising route to the creation of a new domestic and distributed bio-based industry.

Sustainability does not depend only on sustainable fuels but also on sustainability of other commodities for modern societies. This important simple fact leads to the important concept of IBRs (*Nanotechnology: Opportunities and Challenges*, n.d.; *Understanding Nanotechnology*, 2002) producing not only sustainable fuels but also other sustainable commodities and energy. The National Renewable Energy Laboratory, which is a part of the DOE, defines *bio-refinery* as “a facility that integrates biomass conversion processes and equipment to produce fuels, power, and chemicals from biomass.” The present view about IBRs is based on two platforms, the sugar platform and syn-gas platform, as discussed later.

Production facilities for sustainable bio-fuels is a sub-system of IBRs. The implications of this are as follows:

- A sustainable bio-fuel facility built today should be planned with its growth into an IBR in mind.
- Sustainable fuels production will almost always be a part of IBRs.
- An advanced definition of IBRs and their subsystems including bio-fuels should be developed together with a clear definition of bio-fuels and bio-products.
- A clear definition of sustainability and quantification of these definitions into suitable metrics should be developed.

Both the National Science Foundation and DOE are putting large research funds into development of IBRs (Bohlmann, 2005; Chen et al., 2005; Christensen & Nielsen, 2005; Clark et al., 2006; “Governmental and Industry Partnerships,” 2004; “Integrated Biorefineries,” n.d.; Kochergin & Kearney, 2006; Realf & Abbas, 2004).

IBRs represent an integral critical subsystem of SD, which is a cross-disciplinary system by its very nature, as discussed earlier. It is best to use the ISA to study this complex cross-disciplinary system and its subsystems. We engineers are most interested in the technology part (subsystem of the SD system) but with a background understanding of other subsystems and collaboration with other disciplines, as discussed earlier. Also discussed earlier, SE is the most important subsystem of the technology part, which is itself a subsystem of the SD system.

As discussed earlier, the efficient utilization of RRs is at the heart of sustainability. RRs should be defined very clearly, for this is strongly related to the cycle of renewability, that is, fossil fuels are renewable, but over a cycle of hundreds of thousands of years. A RR should be renewable over a period of 6 to 18 months. RRs can be any kind of renewable waste, for example, agricultural waste, municipal waste, and so on, or special (energy) crops produced specifically to be used for this purpose, for example, switch-grass cultivated and produced especially for bio-fuels. On the other hand, useful agricultural products used today for bio-fuels, for example, corn for ethanol, vegetable oil for trans-esterification to bio-diesel, and so on, are not strategic solutions as RRs and for sustainability because of the consumption of important edible products at a time of food shortage everywhere, especially in developing nations.

Renewable biomass, the main group of RRs, is a storage tank for solar energy through biosynthesis, CO<sub>2</sub>, and other nutrients. The ultimate aim for bio-fuels is to produce as much CO<sub>2</sub> as consumed in the biosynthesis of the biomass that produced it. This, with maximum

efficiency, may lead to approaching zero net CO<sub>2</sub> emission. We cannot really dispose of any CO<sub>2</sub> resulting from fossil fuel; it only keeps circulating from one form/place to the other, except with sequestration by injection under the bottom of the ocean, which is expensive. Its side effects are not known and can only be practiced by very large companies. All other techniques just move the CO<sub>2</sub> from one location/form to the other without reducing the earth CO<sub>2</sub> added inventory from the carbon source that came from under the ground.

Hydrogen is a good clean fuel and will occupy its part in the clean fuels matrix and is, therefore, one of the potential products of IBRs. However, although the claim that it is 100% clean is locally true, it is actually not globally true if its source is fossil fuel, whether directly through CSR (95% of hydrogen produced in United States is through CSR) or indirectly through production of electricity (90% of electricity in the United States is from coal) followed by electrolysis. It can be globally clean only if the source is bio, wind, hydro, nuclear, and so on.

The range of fermentable sugars is expanding due to the development in microbiology and the discovery of efficient mutated microorganisms capable of fermenting the wide range of sugars produced from cellulose/hemicellulose hydrolysis. A strong challenge with lots of intensive research nowadays is in the field of efficient and clean hydrolysis of cellulose/hemicellulose; important improvements are achieved in the enzymatic hydrolysis of cellulose/hemicellulose. The process of fermentation is improving continuously using novel membrane immobilized fermenters and novel modes of operation. Lignin from ligno-cellulose is used as a cheap fuel to improve the energy efficiency of the IBRs; however, the future potential is to use it as a platform for a wide range of products to replace certain petroleum refining and petrochemical products. Important improvements are introduced to syngas production from biomass through both a one-step process (biomass gasification to syngas) and a two-step process (biomass fast pyrolysis to bio-oil followed by CSR of bio-oil to syngas). The two-step process seems to be better with regard to the percentage of H<sub>2</sub> in the syngas. Certain difficulties associated with CSR of bio-oil are solvable through novel reformers configurations such as CFB reformers. An important challenge in the biomass to FT bio-fuels process is the integration of the endothermic CSR process with the exothermic catalytic FT process into one integrated membrane catalytic auto-thermal process.

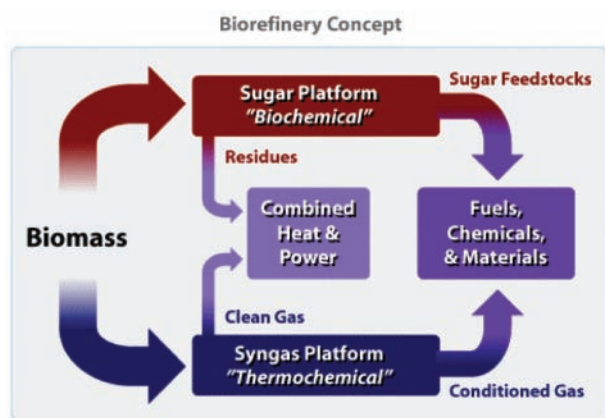
IBRs should be able to contribute towards sustainability and not only renewable bio-fuels. It is important for IBRs to include all that is bio, whether with regard to feedstock, processes, or both, for instance,

- biomass utilizing sequential thermal catalytic processes to produce FT bio-diesel (the processes are not bio, but the feedstock is bio)
- biological treatment of CO and water to produce CO<sub>2</sub> and hydrogen (bio-catalyzed water gas shift [WGS] reaction; the feed is not bio, but the process is bio)
- ligno-cellulose utilizing sequential bio-processes to produce cellulosic bio-ethanol (both feedstock and processes are bio)
- utilization of bio-processes to transfer one form of energy to another, for example, IBE-BFCs to change intermittent solar energy into continuous electric energy, for many applications including auto-thermal housing

IBRs can either grow with time as parts of existing plants (e.g., pulp and paper industry) or start as an IBR based on renewable fuels production and grow into a complete IBR. Other forms of RCE (when suitable, e.g., wind energy) can be integrated with the bio-fuels to generate the total renewable energy profile of an IBR. The central intermediates (platforms) for the bio-fuels part of the IBRs seem to be fermentable sugars suitable for fermentation to bio-ethanol and/or bio-butanol and syngas suitable for both hydrogen extraction and use in the FT process for producing fuels from methanol up to diesel. It is important, also, to notice that it is possible to combine the gasification of biomass (or fast pyrolysis followed by CSR of the product bio-oil) to produce bio-syngas with the fermentation of this bio-syngas to produce bio-ethanol and or bio-butanol (Worden, Grethlein, Jain, & Datta, 1991). Direct utilization of solar energy through different direct techniques (e.g., photocells) without passing through the biosynthesis stage is a possibility, but it has its own bottlenecks and should be integrated with other technologies (e.g., IBE-BFCs) to fully utilize it as a part of auto-thermal housing and IBRs.

From the above, it is clear that neither single bio-fuel nor one technology will dominate for any single one of these bio-fuels. Humanity will move from today's matrix of dirty, non-renewable fuels to a future matrix of clean, renewable fuels, with the sub-matrix of different bio-fuels from different technologies occupying a large portion of the clean fuels matrix, and that sustainability will not be achieved through bio-fuels only but should be extended to IBRs, combining bio-fuels and other bio-products with efficient bio-energy in order to achieve SD.

**Figure 5**  
**Preliminary Bio-Refinery Structure With the**  
**Main Two Sugar and Syngas Platforms**



Source: <http://www.energy.gov/>.

**Figure 6**  
**A Sustainable and Clean Future Town**



Source: <http://www.energy.gov/>.

We can summarize the status of today's IBR concept, as shown in Figure 5, and the future view of a self-sustained clean town, as shown in Figure 6.

### Open Political, Socio-Economical, and Moral/Ethical Questions

In the following, we offer some questions for thinking and discussion. The authors will welcome all views and discussions regarding these and other questions by the readers:

- Is sustainability profitable or is it a moral/ethical obligation?
- Is there a contradiction between sustainability and profitability? And if there is, is it solvable within a profitability-based society? And how?
- Are bio-fuels/IBRs enough to achieve sustainability?
- Will SD affect international relations, decreasing international tensions and wars?
- Is SD compatible or contradictory to globalization?
- What level of public awareness is needed to adopt sustainable policies and what are the best techniques to achieve that? Is this a political or a socio-economical question?
- Do world politics and large incorporated businesses affect adaptation of bio-fuels and IBRs?
- What is the relation between wars and SD?
- Is nuclear energy an option for SD?
- Is there a contradiction between SD and the second law of thermodynamics?

### Conclusions

SD is crucial for the development of human societies and it is cross-disciplinary by its very nature. The ISA based on system theory is the most efficient approach to study and develop the different subsystems of this complex cross-disciplinary system. For engineers, the most important subsystem is the technology one and SE is a subsystem of it. Bio-fuel is one of the most important subsystems of SE, however, their development is not sufficient for sustainability; other bio-products and bio-energy from RRs are essential, leading to the concept of IBRs, which is very important for sustainability. Bio-fuels represent an integral part of BRIs. Well-directed innovative research in all subsystems of BRIs is essential, taking into consideration the other subsystems of SE as well as the non-technical subsystems of SD.

### Appendix

#### Abbreviations Used

- BFCs = bio-fuel cells
- CFB = circulating fluidized bed
- CSR = catalytic steam reforming
- CSTR = continuous stirred tank reactor
- DOE = U.S. Department of Energy
- EE = environmental engineering
- EPA = U.S. Environmental Protection Agency
- ER = energy ratio
- FCC = fluid catalytic cracking
- FT = Fisher Tropsch
- IBE-BFCs = integrated bio-electrolysis coupled to bio-fuel cells

(continued)

## Appendix (continued)

IBRs = integrated bio-refineries  
 IChemE = U.K. Institution of Chemical Engineers  
 ISA = integrated system approach  
 ME = Middle East  
 NER = net energy ratio  
 OECD = Organization for Economic Cooperation and Development  
 QE = quality of energy  
 RCE = renewable clean energy  
 RCFs = renewable clean fuels  
 RFS = renewable fuel standard  
 RRs = renewable resources  
 SD = sustainable development  
 SE = sustainable engineering  
 SP&C = sustainable production and consumption  
 SSF = simultaneous saccharification fermentation  
 ST = states terrorism  
 UNCED = UN Conference on Environment and Development  
 UNCSD = UN Commission on Sustainable Development  
 USDA = U.S. Department of Agriculture

## References

- Alvarado, P. (2007, March 20). *Biodiesel from algae and the biofuels discussion in Argentina*. Retrieved August 2007 from [http://www.treehugger.com/files/2007/03/biodiesel\\_from\\_1.php](http://www.treehugger.com/files/2007/03/biodiesel_from_1.php)
- Bohlmann, G. M. (2005). *Biorefinery process economics*. Paper presented at the World Congress on Industrial Biotechnology and Bioprocessing.
- Briggs, M. (2004). *Widescale biodiesel production from algae*. Retrieved August 2007 from [http://www.unh.edu/p2/biodiesel/article\\_alge.html](http://www.unh.edu/p2/biodiesel/article_alge.html)
- Chen, S., Wen, Z., Liao, W., Liu, C., Kincaid, R. L., Harrison, J. H., et al. (2005). Studies into using manure in a biorefinery concept. *Applied Biochemistry and Biotechnology*, 124(1-3), 999-1016.
- Christensen, B. H., & Nielsen, C. (2005). *Biorefineries with optimal carbon utilization for liquid bio-fuels*. Paper presented at the First International Biorefinery Workshop.
- Clark, J. H., Budarin, V., Deswarte, F. E. I., Hardy, J. J. E., Kerton, F. M., Hunt, A. J., et al. (2006). Green chemistry and the biorefinery: A partnership for a sustainable future. *Green Chemistry*, 8, 853-860.
- Delft University of Technology. (2003). *Annual report of Delft University of Technology (TUDelft)*. Delft, Netherlands: Technol-ogy Assessment Section.
- Dewulf, J., & Langenhove, H. V. (Eds.). (2006). *Renewables-based technology: Sustainability assessment*. Chichester, UK: Wiley.
- Directory: *Biodiesel from algae oil*. (n.d.). Retrieved August 2007 from [http://peswiki.com/index.php/Directory:Biodiesel\\_from\\_Algae\\_Oil](http://peswiki.com/index.php/Directory:Biodiesel_from_Algae_Oil)
- Ellison, K. (2007, September 26). Biodiesel boom heading toward Wall Street. *Business 2.0 Magazine*. Retrieved September 2007 from <http://money.cnn.com/2007/09/25/technology/biodieselboom.biz2/?postversion=07092609>
- Elnashaie, S. S. E. H., & Elshishini, S. S. (1996). *Dynamic modelling, bifurcation and chaotic behaviour of gas-solid catalytic reactors*. Amsterdam: Gordon and Breach.
- Elnashaie, S. S. E. H., & Garhyan, P. (2003). *Conservation equations and modeling of chemical and biochemical processes*. New York: Marcel Dekker.
- Elnashaie, S. S. E. H., & Grace, J. R. (2007). Complexity, bifurcation and chaos in natural and man-made lumped and distributed systems. *Chemical Engineering Science*, 62(13), 3295-3325.
- Elnashaie, S. S. E. H., & Uhlig, F. (2007). *Numerical techniques for chemical and biological engineers using MATLAB*. New York: Springer.
- Fiksel, J. (2006). Sustainability and resilience: Toward a systems approach. *Science, Practice & Policy*, 2(2), 14-21.
- Food and Agriculture Organization of the United Nations. (1997). *A system approach to biogas technology*. Retrieved August 2007 from <http://www.fao.org/sd/EGdirect/EGre0022.htm>
- Governmental and industry partnerships for developing biorefineries. (2004, July). *Biobased Fuels, Power and Products Newsletter*, pp. 1-2.
- Hens, L. (Ed.). (2005). *The World Summit on Sustainable Development: The Johannesburg Conference*. Dordrecht: Springer.
- Horbach, J. (Ed.). (2005). *Indicator systems for sustainable innovation (sustainability and innovation)*. Heidelberg: Physica-Verlag.
- How to build a hydrogen electrolyzer. (n.d.). Retrieved August 2007 from [http://www.geocities.com/hydrogenpower1/experiments/simple\\_electrolyzer.html](http://www.geocities.com/hydrogenpower1/experiments/simple_electrolyzer.html)
- Hramov, A. E., & Koronovskii, A. A. (2005). Generalized synchronization: A modified system approach. *Physics Review E (Statistical Nonlinear and Soft Matter Physics)*, 71(6), 1-4.
- Hydrogen and fuel cell educational equipment. (n.d.). Retrieved August 2007 from <http://www.minihydrogen.dk/catalog/teach-equipment.php>
- Integrated biorefineries. (n.d.). Retrieved August 2007 from [http://www1.eere.energy.gov/biomass/integrated\\_biorefineries.html](http://www1.eere.energy.gov/biomass/integrated_biorefineries.html)
- Kamitaka, Y., Tsujimura, S., & Kano, K. (2007). High current density bioelectrolysis of D-fructose at fructose dehydrogenase-adsorbed and ketjen black-modified electrodes without a mediator. *Chemistry Letters*, 36(2), 218-229.
- Kamm, B., Gruber, P. R., & Kamm, M. (2006). *Bio-refineries—industrial processes and products: Status quo and future directions*. Chichester, UK: Wiley.
- Kochergin, V., & Kearney, M. (2006). Existing biorefinery operations that benefit from fractal-based process intensification. *Applied Biochemistry and Biotechnology*, 130(1-3), 349-360.
- Makower, J., & Fleischer, D. (2003). *Sustainable consumption and production: Strategies for accelerating positive change*. New York: Environmental Grantmakers Association.
- Nagpal, S. (1997). A structured model for thiobacillus ferrooxidans growth on ferrous ions. *Biotechnology and Bioengineering*, 53(3), 310-319.
- Nanotechnology: *Opportunities and challenges*. (n.d.). Retrieved August 2007 from <http://nano.nd.edu/ESTS40403/index.html>
- Palmore, G. T. R., & Whitesides, G. M. (1994). Microbial and enzymatic biofuel cells. In M. E. B. Himmel, J. O. Baker, & R. P. Overend (Eds.), *Enzymatic conversion of biomass for fuels production* (ACS Symposium Series No. 566, pp. 271-290). Washington, DC: American Chemical Society.
- Rand, D. A. J., & Dell, R. M. (Eds.). (2004). *Clean energy*. Cambridge: Royal Society of Chemistry.
- Ratner, M., & Ratner, D. (2003). *Nanotechnology: A gentle introduction to the next big idea*. Upper Saddle River, NJ: Prentice Hall.
- Realf, M. J., & Abbas, C. (2004). Industrial symbiosis, refining the bio-refinery. *Journal of Industrial Ecology*, 7(3-4), 5-9.

- Rotmans, J., van Asselt, M. B. A., de Bruin, A. J., den Elzen, M. G. J., de Greef, J., Hilderink, H. B. M., et al. (1994). *Global change and sustainable development: A modelling perspective for the next decade*. Bilthoven, Netherlands: National Institute for Public Health and the Environment.
- Satms, J. M. A., de Bok, F. A. M., Plugge, C. M., van Eekert, M. H. A., Doling, J., & Dchraa, G. (2006). Exocellular electron transfer in anaerobic microbial communities. *Environmental Microbiology*, 8(3), 371-382.
- Sazdanoff, N. (2006). *Modeling and simulation of the algae to bio-diesel fuel cycle*. Unpublished honors undergraduate thesis, Ohio State University.
- Sheehan, J., Dunahay, T. G., Benemann, J. R., Roessler, P. G., & Weissman, J. C. (1998). *A look back at the U.S. Department of Energy's Aquatic Species Program: Biodiesel from algae*. Golden, CO: National Renewable Energy Laboratory.
- Shukla, A. K., Suresh, P., Berchmans, S., & Rajendran, A. (2004). Biological fuel cells and their applications. *Current Science*, 87(4), 455-468.
- Sisler, F. D. (1971). Biochemical fuel cells. In D.J.D. Hockenull (Ed.), *Progress in industrial microbiology* (Vol. 9, pp. 1-11). London: J. & A. Churchill.
- Subramanian, K. (2000). *The system approach*. Cincinnati, OH: Hanser Gardner.
- Taniquchi, I., Tabata, D., Kusuda, H., Koga, T., & Sotomura, T. (2003). *Construction of bio-fuel cells using catalytic electrodes for oxidation of sugars and reduction of oxygen*. Paper presented at the 204th meeting of the Electro Chemical Society.
- Trazil, D., Ma, G., & Beloff, B. R. (2003). *Sustainability metrics*. Paper presented at the 11th International Conference of Greening of Industry Network, Innovation for Sustainability.
- Turner, A. P. F., Aston, W. J., Higgins, I. J., Davis, G., & Hill, H. A. O. (1982). Applied aspects of bioelectrochemistry: Fuel cells, sensors, and bioorganic synthesis. In C. D. Scott (Ed.), *Fourth symposium on biotechnology in energy production and conservation* (Vol. 12, p. 401). New York: Interscience.
- U.K. Institution of Chemical Engineers. (2002). *The sustainability metrics: Sustainable development progress metrics recommended for use in the process industries*. Rugby, UK: Author.
- Understanding nanotechnology*. (2002). New York: Grand Central.
- U.S. Department of Energy. (2005). *Wood, bioenergy, bioreactors, and biotechnology*. 1st International Biorefinery Workshop. Retrieved August 2007 from <http://smartroad.blogspot.com/2007/11/international-biorefinery-workshop.html>
- U.S. Environmental Protection Agency. (n.d.). *Renewable fuel standard program*. Retrieved August 2007 from <http://www.epa.gov/otaq/renewablefuels/index.htm>
- von Bertalanffy, L. (1976). *General system theory: Foundations, development, applications*. New York: George Braziller.
- Way, L. A., & Wilson, G. (Eds.). (2005). *Managing for tomorrow: Resource-based communities & the environment*. Prince George: University of Northern British Columbia.
- What is a biorefinery?* (n.d.). Retrieved August 2007 from <http://www.nrel.gov/biomass/biorefinery.html>
- Worden, R. M., Grethlein, A. J., Jain, M. K., & Datta, R. (1991). Production of butanol and ethanol from synthesis gas via fermentation. *Fuel*, 70, 615-619.

**Said S.E.H. Elnashaie**, PhD, has been a professor of chemical and biological engineering for 37 years at different universities. He has published more than 300 papers, four books, and one chapter and holds three U.S. and Canadian patents.

**Seif-Eddeen Fateen**, PhD, is an assistant professor in the chemical engineering department at Cairo University. His research interests include air pollution modeling, phase equilibrium calculations, and transport phenomena.

**Ahmed El-Ahwany**, PhD, is an associate professor in the chemical engineering department at Cairo University. He is the executive editor of the Transactions of the Egyptian Society of Chemical Engineers. His research interests are in the areas of catalytic and bio-catalytic reactors with special emphasis on environmental and biomass conversion.

**Tarek M. Moustafa**, PhD, is an associate professor in the chemical engineering department at Cairo University. His research interests include catalytic reaction engineering, modeling and simulation of chemical processes, and kinetic modeling.