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Review

Decentralized chemical processes with supercritical fluid technology for sustainable society

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ABSTRACT

For sustainable society, the design philosophy of chemical processes will need to be changed from large-scale mass production systems to decentralized local-scale production systems so that chemicals and energies can be supplied from diverse biomass and other renewable resources. Supercritical water allows fast reaction rates, high selectivities and high-yield conversions of many biomass and biomass-related feedstocks and allows chemical transformations to occur with compact devices. Supercritical carbon dioxide allows selective separations, efficient transformations, and low-energy processing of many types of materials. In this overview, sustainability is examined with respect to available solar energy, UN Millennium Development Goals, the carbon cycle and competing factors that affect sustainable society. Through a general block diagram for a biomass refinery, material conversions of biomass and biomass-related compounds are discussed along with a proposal for using supercritical water oxidation (SCWO) with biomass boiler to produce energy and a biorefinery on a 100 ha land area. Supercritical fluid technology, especially water and carbon dioxide solvents, can provide the basis for decentralizing chemical processes and for achieving material recycles for sustainable society.

Contents

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1. Introduction

1.1. Sustainability

Sustainability can be thought of as the process of stabilizing the world's population, while reducing hunger and poverty and providing adequate living standards while preserving the Earth's ecosystem [1,2]. From a simple point of view, sustainability is how we decide to manage the solar energy that is absorbed by the Earth (ca. 121,000 TW; Tera = 10^{12} [3]) along with the fixed resources of the Earth to support our environment and cultures for an arbitrary period of time that we think is sufficiently long. Although the amount of solar energy is large compared with present energy consumption, the amount of energy that can be recovered is considerably lower being estimated as 100, 15 and 10 TW in the form of solar including biomass, wind, and ocean thermal gradients, respectively [4].

The subject of sustainability has become recognized as a new science that is appearing in many areas of engineering as well as sociopolitical, medical, and other fields [5,6]. There are many discussions on how society should proceed to achieve sustainability in agriculture [7], world fisheries [8], balance in biodiversity [9] along with analyses that draw relationships between quantitative figures on world population, energy consumption, food, agricultural land and organic materials [10–12]. Kennedy [13] notes that the concept of sustainability is not just about resource use, efficiency of utilization, and conservation, but also contains strong social, economic, and cultural attributes. As that author notes, each culture will develop their own definition of sustainability along with criteria and methods to meet their goals. As part of the thesis of this work, supercritical fluid technology will allow the decentralization of chemical processes so that *just-enough* production is available for local needs, which will promote sustainable society. For a sustainable society, the general welfare of the world's population and trends in population growth and resource and energy consumption are important topics that are discussed below.

1.2. Millennium development goals (MDGs)

The United Nations adopted 8 Millennium Development Goals (MDGs) as part of the Millennium Project to be achieved by 2015 and developed a sophisticated online database tracking system that shows yearly progress by country [14]. Although progress is noted in many countries as of 2007, countries in sub-Saharan Africa are not on track to achieve any of the goals [15] due to the lack of many basic services including energy. The World Energy Assessment [12] provides a matrix that relates the MDGs to energy and notes that access to energy services is a prerequisite for achieving all of the MDGs. In essence, human welfare and sustainable society are intimately linked to energy management and therefore, it is the responsibility of technologists to develop energy systems that not only provide clean energy and but also that encourage resource management.

1.3. The limits to growth

In 1972, the Club of Rome [16] published its first report, entitled, "The Limits to Growth," which described a model of the world in terms of competitive factors: population growth, industrialization, food supply, depletion of resources, and the declining environment. According to the model, food production per person will reach a maximum at around 2020 along with industrial production, and with increasing competition for the dwindling natural resources, environmental pollution will rapidly increase and this will limit population growth and if unchecked will lead to catastrophic consequences to civilization. The work at that time was perhaps overly pessimistic, but still was highly relevant in showing competing factors in world growth. Although the report was made well over 40 years ago, its 30 year update [17] shows remarkable accuracy in tracking factors that affect a sustainable society including population. With world population being 6500 million people in 2005 and being projected to be 7200 million people in 2015 and 8600 million people in 2040, an even greater burden will be placed on food, water, and energy resources in the near future. In the analysis of Okkerse and van Bekkum [10], energy consumption on a per capita basis is expected to increase from 2200 W in 1995, to 3000 W in 2040, which represents almost a 3-fold increase in the expected energy consumption based on increasing the welfare of the general population. To meet this increase, not only new technologies will be needed, but also new philosophies will be needed in daily life.

1.4. Soft landing to sustainable society

A soft landing to sustainable society is one in which an abrupt change does not occur during the transition to a sustainability society. First, to maintain the world population and our high living standards, the supply of energy and resources cannot be cut even for a short while. To postpone the time for the first crisis, the food and water crisis, effective steps must be made to suppress the growing populations in developing countries as soon as possible through the elimination of poverty and promotion of education and birth control as in United Nations MDGs [14]. The developing countries must be given the priority to use energy to improve their infrastructure. Renewable energy is preferred, although use of fossil fuel must be accepted for cases where the infrastructure has not yet been established.

At the same time, to achieve independence from fossil fuel, technical innovation must be taken to create renewable energy sources based on biomass as well as to create CO_2 emission free energy systems. CO_2 levels are expected to rise as high as 550 parts per million (ppm) by 2050 depending from its present value of 370 ppm [18,19] and can be expected to have disastrous consequences for our environment. Hoffert et al. [20] note that present primary energy consumption is 85% fossil-fuel based and amounts to 12 TW. They show the importance of developing 10–30 TW CO_2 emission-free energy systems by 2050. Those authors provide some possible technology paths and point to nuclear energy as a likely candidate, but acknowledge the high technology barriers for achieving such energy systems by 2050 with current initiatives.

To extend the time limit for the environmental crisis caused by uncontrolled CO_2 emissions, many advanced systems for CO_2 separation, storage, utilization and CO_2 emission free energy generation systems will be needed. Compared with the incoming solar energy absorbed by the Earth (121,000 TW), the amount of present primary energy (12 TW) being consumed by our civilization is very small. For sustainability to be achieved, the energy entering into the earth should remain at a steady state condition and methods to provide material circulation with biomass must be developed.

1.5. Earth and carbon cycle

Consider sustainability of a closed system, which is one that has a energy input and energy output from and to its surroundings without material exchange (Fig. 1). The sustainability of a closed system having some internal material conversions, can only be achieved by the existence of material recycle that is limited by the available external energy. One can consider the earth as a closed system, in which the only external energy is solar radiation (Fig. 1). The main mechanism that is responsible for sustainability of the ecosystem is photosynthesis in which water and CO_2 are consumed and organics are produced and converted back to CO_2 and water through living organisms. As humankind is part of the ecosystem, the only way to achieve a sustainable society is to establish material recy-