Catalysis Today 239 (2015) 50–55

Contents lists available at ScienceDirect

Catalysis Today

journal homepage: www.elsevier.com/locate/cattod

Definition and application of ethanol equivalent: Sustainability performance metrics for biomass conversion to carbon-based fuels and chemicals

Edit Cséfalvay [a,b], Geoffrey R. Akien [a,c], Long Qi [a,d], István T. Horváth [a,*]

[a] Department of Biology and Chemistry, City University of Hong Kong, Kowloon, Hong Kong
[b] Department of Chemical and Environmental Process Engineering, Budapest University of Technology and Economics, Budapest, Hungary
[c] Center for Environmentally Beneficial Catalysis, 1501 Wakarusa Drive, Lawrence, KS 66044, United States
[d] Department of Chemistry & Biochemistry, University of California, Santa Barbara, CA 93106-9510, United States

ARTICLE INFO

Article history:
Received 11 October 2013
Received in revised form 30 January 2014
Accepted 8 February 2014
Available online 12 March 2014

Keywords:
Sustainability
Performance metrics
Ethanol equivalent (EE)
Real ethanol equivalent (EE_x)
Fossil resources
Biomass
Biofuels
Chemicals

ABSTRACT

Ethanol equivalent (EE) is defined as the mass of ethanol needed to deliver the equivalent amount of energy from a given feedstock using energy equivalency or produce the equivalent amount of mass of a carbon-based chemical using molar equivalency. The production of ethanol from biomass requires energy, which in a sustainable world could be produced from biomass. Therefore, we also define a real ethanol equivalent (EE_x) indicating that the ethanol equivalent also includes the use of 1 unit of bioethanol to produce x units of bioethanol. Thus, the abbreviation $EE_{2.3}$used in this paper shows a 2.3 output/input bioethanol ratio or efficiency. Calculations of the corresponding mass of corn and size of landwere based on the first generation corn-based bioethanol technology as commercially practiced in the US in 2008. Since the total energy and essential materials requirements of a given process can be calculated, the $EE_{2.3}$ of a production process or even a total technology can be estimated. We show that the $EE_{2.3}$ could be used as a translational tool between fossil- and biomass-based feedstocks, products, processes, and technologies. Since the $EE_{2.3}$ can be readily determined for any given biomass-based technology, the required mass of biomass feedstock, the size of land, and even the volume of water can be calculated. Scenario analyses based on $EE_{2.3}$ could better visualize the demands of competing technologies on the environment both for the experts and to the general public. While differentiating between 1, 1000, and 100,000 BTUs for different options is rather difficult for most people, comparing the amount of the land needed to produce the same amount of energy or mass via different technologies is more straightforward.

1. Introduction

Sustainability is an important concept for all living systems and its meaning has become a great concern for mankind [1]. The most frequently used definition was published in the report entitled "Our Common Future" by the United Nations' World Commission on Environment and Development in 1987. The report stated that "*we should meet the needs of the present without compromising the ability of future generations to meet their own needs*." [2]. This definition seems to guarantee that we would hand over the planet to the next generation in such conditions, for example, 50 years, such that they can live just as well in 2064 or even better than we do now. The key question is: do we know or could we accurately guess today the needs of mankind in 2064? If we don't, we could at least look back in history and ask ourselves if our grandmothers could have imagined in the 1940s that Neil Armstrong would walk on the moon on July 20, 1969 and that only 40 years later a small device such as the iPhone would be as powerful as the computers used to control the flight of Apollo 11 [3]? Could our grandfathers have imagined in the 1940s that we could identify people by their DNA in 1984 [4] or have mapped out bacterial infection routes in hospitals by decoding the bacterial genomes in 2011 [5]? We could ask many similar questions as we have been experiencing continuous acceleration of the generation of knowledge via scientific, technological, and social developments. If the predictions of the distant future have been impossible for generations before us, can we make accurate ones today for the needs of society in 2064 or beyond?

Although we have significantly advanced our prediction capabilities [6], we repeatedly encounter difficulty in envisioning economic changes, good or bad, societal transformations, good or

* Corresponding author. Tel.: +852 3442 7402; fax: +852 3442 0522.
E-mail address: istvan.t.horvath@cityu.edu.hk (I.T. Horváth).

http://dx.doi.org/10.1016/j.cattod.2014.02.006

bad, and even accurate local weather forecasts are problematic beyond a few days not to mention weeks [7]. Our understanding of the "future" can be rather good when the predictions are based on the changes of readily measurable physical properties in a shorter time period within a microscopic environment. The uncertainties increase significantly when we investigate complex and open systems for longer time periods. Accordingly, the current definition of sustainability is too vague to select deliverable objectives for sustainable developments.

2. Results and discussions

2.1. Definition of sustainability

Sustainability of the Earth depends on whether we can supply the increasing population with enough energy, food, water, and chemicals, including carbon-based consumer products, etc., without compromising the long-term health of our planet and her habitats. In order to set deliverable goals for the society, we propose a *sustainable definition of sustainability*, which is based on Nature's two most important evolutionary survival rules: *resources including energy should be used at a rate at which they can be replaced naturally and the generation of waste cannot be faster than the rate of their remediation*. It should be emphasized that sustainability can be increased by using *sustainable refurbishing, remanufacturing, and recycling* processes and/or technologies, provided their resource and energy requirements are also sustainable. Finally, integration of energy and/or materials is another approach to increase the overall sustainability locally and globally. The most important characteristic of the proposed definition is that it addresses the changes in time (or the kinetics to reach sustainable equilibria) and offers the opportunity to calculate the upper limits of sustainability per capita (or the parameters of sustainable equilibria).

2.2. Definition of ethanol equivalent

We know all too well that using the wrong products, processes, or technologies can solve problems only temporarily, but will generate the next nightmares. The replacement of toxic ammonia and sulfur dioxide with chloro-fluoro-carbons (CFCs) was intended to make our refrigerating technologies in kitchens and storage facilities safer, but in the end we began to destroy our protecting ozone layer [8]. Thanks to thousands of environmentalists, scientists, engineers, politicians, governmental and business leaders, CFCs were replaced and the ozone hole started to close by using carefully selected replacement chemicals for refrigerating technologies – of course let's hope that those will remain sustainable too.

The evaluation and comparison of potential options for sustainable development must precede the selection at both the local and global level. A common currency has to be defined, which can be used easily and reliably to calculate "the same currency equivalents" of vastly different components of sustainable development. We propose the use of "*ethanol equivalent*", which is defined as the mass of ethanol (expressed in kilogram, tons or million tons) needed to deliver the equivalent amount of energy from a given feedstock using energy equivalency or produce the equivalent amount of mass of a carbon-based chemical using molar equivalency. Since the energy demand of a given process (including transportation, storage, mixing, heating, cooling, etc.) can be calculated, the "*ethanol equivalent*" of a production process or even a total technology can be estimated. We show that the "*ethanol equivalent*" could be used as a translational tool between fossil- and biomass-based feedstocks, products, processes, and technologies. Since the "*ethanol equivalent*" can be supplied by a given biomass-based technology, the required mass of biomass feedstock, the size of land, and even the volume of water can be calculated.

$$6\,CO_2 + 6\,H_2O \xrightarrow{h\nu} C_6H_{12}O_6 + 6\,O_2 \longrightarrow 2\,CH_3CH_2OH + 2\,CO_2$$

Scheme 1.

We have based our calculations on first generation corn-based bioethanol technology commercially practiced in the US in 2008. Scenario analyses based on ethanol equivalents could visualize better the demand of the competing technologies on the environment both for the experts as well as to the general public – comparing the sizes of the land needed to produce the same amount of energy or mass via different technologies is straightforward.

All our calculations were based on the well-known overall equation for photosynthesis [9] for the production of corn, which is in turn converted to bioethanol by fermentation using established technologies (Scheme 1).

The reason for selecting corn as the biomass, bioethanol as the biomass based reference material, and the year 2008 as the reference year in this study, was to allow the use of reliable data supported by long-term commercial experience [10]. The used and available resources are listed in Table 1.

2.3. The sustainability of first generation bioethanol as primary energy source

The development of a liquid fuel-based transportation system was a key step in the industrial revolution [12]. One need only consider the fuel delivery/distribution and the waste collection/removal problems of a major city of several millions, in which horses are used for transportation [13]. Fortunately, fossil-based transportation fuels such as gasoline, diesel, and kerosene are liquids, which can be easily stored and distributed, and the final products of their combustion, carbon dioxide and water, are readily dispersed in the environment. Similarly, the production of electricity from fossil fuels is convenient, because the system can respond readily to rapidly changing energy demands. In general, fossil fuels have been used either directly, or through the generation of electricity, to improve the quality of our daily life. One of the most challenging impacts of the rapidly growing global population is the depletion of the fossil fuel resources [14] which currently provide 90% of all of our energy needs [15]. While it is difficult to predict the exact date of the depletion of crude oil, natural gas, and coal, the transition to renewable resources should be accelerated [16,17]. One of the reasons for favoring the global use of renewable resources is their potential

Table 1
Used and available resources in the USA in 2008.[a]

	Units	2008
Crude oil consumption	Mtoe[b]	884.5
Natural gas consumption	Mtoe[b]	600.7
Coal consumption	Mtoe[b]	565
Total fossil resource consumption	Mtoe[b]	2050.2
	EJ	86.1
Bioethanol production	Million tons	27.5
Total water due to precipitation[c]	km^3	6549
Annual renewable water[d]	km^3	3070
Corn production	Million tons	308
Total cornfield (planted corn)	Million hectares	78.6
Total planted land	Million hectares	132
Total land	Million hectares	916
Actual irrigated land	Million hectares	22

[a] For details see supplementary material.
[b] Mtoe: million tons oil equivalent.
[c] Calculated value based on average precipitation [11].
[d] 1985.