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Bioenergy and biofuels: History, status, and perspective

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ABSTRACT

The recent energy independence and climate change policies encourage development and utilization of renewable energy such as bioenergy. Biofuels in solid, liquid, and gaseous forms have been intensively researched, produced, and used over the past 15 years. This paper reviews the worldwide history, current status, and predictable future trend of bioenergy and biofuels. Bioenergy has been utilized for cooking, heating, and lighting since the dawn of humans. The energy stored in annually produced biomass by terrestrial plants is 3–4 times greater than the current global energy demand. Solid biofuels include firewood, wood chips, wood pellets, and wood charcoal. The global consumption of firewood and charcoal has been remaining relatively constant, but the use of wood chips and wood pellets for electricity (biopower) generation and residential heating doubled in the past decade and will increase steadily into the future. Liquid biofuels cover bioethanol, biodiesel, pyrolysis bio-oil, and drop-in transportation fuels. Commercial production of bioethanol from lignocellulosic materials has just started, supplementing the annual supply of 22 billion gallons predominantly from food crops. Biodiesel from oil seeds reached the 5670 million gallons/yr production capacity, with further increases depending on new feedstock development. Bio-oil and drop-in biofuels are still in the development stage, facing cost-effective conversion and upgrading challenges. Gaseous biofuels extend to biogas and syngas. Production of biogas from organic wastes by anaerobic digestion has been rapidly increasing in Europe and China, with the potential to displace 25% of the current natural gas consumption. In comparison, production of syngas from gasification of woody biomass is not cost-competitive and therefore, narrowly practiced. Overall, the global development and utilization of bioenergy and biofuels will continue to increase, particularly in the biopower, lignocellulosic bioethanol, and biogas sectors. It is expected that by 2050 bioenergy will provide 30% of the world's demanded energy.
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Abbreviations: ABE, acetone–butanol–ethanol; FAME, fatty acid methyl esters

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1. Introduction

The annual terrestrial primary production adds approximately 120×10^{15} g of dry vegetative biomass [1], storing 2.2×10^{21} J of energy in plant materials [2]. The world energy demand was 5.5×10^{20} J in 2010. It is predicted to increase to 6.6×10^{20} J in 2020 and 8.6×10^{20} J in 2040 [3]. Largely, the bioenergy captured each year by land plants is 3–4 times greater than human energy demands. The bioenergy delivery potential of the world's total land area excluding cropland, infrastructure, wilderness and denser forests is estimated at 190×10^{18} J yr^{-1}, 35% of the current global energy demand [4].

Biofuels refer to plant biomass and the refined products to be combusted for energy (heat and light). Similar to fossil fuels, biofuels exist in solid, liquid, and gaseous forms. Human beings have been utilizing bioenergy and biofuels for domestic purposes since pre-recorded history. Wood was burned for heat and light to cook food, illumine night, warm shelters, and treat clay artifacts. Before the 19th century, wood was the predominant fuel for cooking and heating and plant oil was the chief fuel for lighting worldwide. Today, however, fossil fuels are the dominant energy sources, meeting $>80\%$ of the world's energy demand [5]. Nevertheless, fossil fuels are nonrenewable and their reserves are limited. At the current consumption rates, the supply of petroleum, natural gas, and coal will only be able to last for another 45, 60, and 120 years, respectively [6]. The dwindling supply and the soaring price of fossil fuels, especially petroleum, compel the world to develop renewable energy alternatives. Moreover, tremendous amounts of greenhouse gases have been released from fossil fuel consumption, elevating the atmospheric CO_2 concentration from the pre-industrial level of 280 ppm to the present nearly 400 ppm and causing disastrous climate change effects [7]. The incentives for mitigating global climate change further stimulate international communities to invest in development and utilization of renewable energy. Of the renewable energy sources, bioenergy draws major and particular development endeavors, primarily due to the extensive availability of biomass, already-existence of biomass production technologies and infrastructure, and biomass being the sole feedstock for liquid fuels. Currently, commercial production of electricity and transportation fuels from biomass feedstocks is practiced in most nations. The U.S. bioenergy production reached 4.76×10^{15} J (4.51 quadrillion Btu; 1 Btu = 1054.35 J) in 2011, accounting for 48.8% of the renewable energy and 5.8% of the total energy produced in the year [8]. Approximately 42% of the U.S. corn grains were used to generate 49 billion liters of bioethanol, representing 94% of the liquid biofuels produced in 2012 (52.2 billion liters) and replaced 10% of the nation's demanded gasoline fuel [9]. The U.S. Energy Independence and Security Act of 2007 mandates to increase annual biofuel addition to gasoline from 34 billion liters (9 billion gallons; 1 gal = 3.781 L) in 2008 to 136 billion liters by 2022, with 60 billion liters of the biofuel from lignocellulosic materials. A variety of conversion technologies to produce "drop-in" fuels like butanol and C_3–C_{10} hydrocarbons from wood and grasses are under investigation. The extensive production of biomass feedstock and biofuels, however, will generate significant environmental and socioeconomic impacts on soil, water, land, food, and civil development. This paper is to summarize the history of human utilization of bioenergy, review the present use and development of solid, liquid, and gaseous biofuels, and look into the future of bionenergy and biofuels. It aims to present a whole picture of bioenergy and biofuels and prepare readers to transit into the "after-fossil fuel" life.

2. Development and utilization of solid biofuels

2.1. Firewood

Wood and other plant materials have been directly burned for heating and cooking since the dawn of modern human beings. Before the discovery of fossil fuels, firewood was the primary fuel for domestic purposes. At 220–300 °C or higher temperature, most dry plant materials ignite in air to cause fire (flame), releasing the inherent bioenergy in heat and light. Combustion starts initially with exothermic pyrolysis of wood at around 260 °C to generate solid char and gaseous fume. Subsequently the char burns to ash and the fume to flame. Fire – the combustion of organic matter – is prompt oxidation of bio-carbon compounds by oxygen at high temperature and can be simply described as:

$$C_6H_{10}O_5 + 6O_2 \rightarrow 6CO_2 + 5H_2O + \text{heat} + \text{light} \quad (1)$$

It is not clear when human beings started the controlled use of fire for heat and light. The initial fire must be from lightening and volcanic eruption that ignited wood. Nevertheless, human beings had grasped the "bow-drill fire making" technique six thousand years ago [10]. Archaeologists identified charred animal bones and stone tools in wood ash in Wonderwerk Cave of Kuruman Hills in South Africa, providing evidence of controlled fire use by prehistoric "mankind" creatures one million years ago [11]. Wood, straw, hay, cattle dung, and peat have been intentionally collected, dried, and burned to prepare food and warmth. In the wilderness, bonfires and straw torches are commonly used for heating and lighting. Fire has also been used to clear land, to attack enemy in war, to smelt ores, and to treat clay artifacts for china, bricks, and tiles.

Firewood is normally packed in bundles and traded in volume. In the U.S., firewood is measured in "cord," with one cord equivalent to 128 ft^3 ($4'\times8'\times4'$) or 3.6 m^3. The weight of one cord firewood varies from 1350 to 2600 kg, depending on the wood type and moisture content. Hardwood is generally "heavier" than softwood. Green, unseasoned firewood may contain 150% (commonly 40–100%) moisture on the *dry mass basis* (The same applies in the following if not specified). Seasoned, air-dry firewood usually contains 10–25% moisture. "Wetter" firewood is normally lower in energy content, as certain heat has to be consumed to transform water into steam upon combustion. Therefore, green firewood should be seasoned for at least 6 months in a well-ventilated place to bring its moisture content to below 20% prior to use. The energy content of well-seasoned firewood is $\sim$15 MJ kg^{-1}, one-third to half of that of fossil fuels [12]. The energy would be fully released in heat and light upon complete combustion that produces only CO_2 and water vapor emissions. Unfortunately, combustion of wood and other raw plant materials in conventional furnaces is generally incomplete, resulting in significant smokes (a mixture of water vapor, volatile organic compounds, and carbon black particulates) and creosote (smoke condensate) that

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