Biomass as Renewable Energy for Sustainability

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1. Introduction

Biomass resources are potentially one of the world's largest and most sustainable energy source, which broadly consist of agricultural, forestry and livestock residues, agricultural crops (cereals and sugar crops e.g.) and oil-bearing plants (rapeseed and algae e.g.), and organic municipal and industrial waste. The estimated worldwide annual bioenergy potential is 500 Exa-Joule (~1.4 x 10^{14} KW-hr), of which 230 Exa-Joule can be considered available on a sustainable basis at competitive prices. At present approximately 9.2% of the world energy needs are met by biomass, of which 9% is obtained from "plant biomass" used directly for cooking and heating primarily in the third-world countries and 0.2% is used as biofuel created mainly from agricultural crops. It is forecasted that the share of biomass in the total energy demand by 2030 will be between 15 to 20%. Depending upon the type of biomass, biochemical, thermochemical and other physical/chemical processes can be applied to create transportation fuels (ethanol and biodiesel), biogas, methanol and hydrogen, and solid fuels. However, significant technology development challenges need to be addressed for biomass to become a major source of energy by 2030. The paper addresses the current state of technology in bioenergy production depending upon the biomass type and its usage (for electricity generation or as transportation fuel) and the challenges ahead. The impact of biomass energy on environment (for example on GHG emissions), and food and agriculture is also discussed. The generation of biofuels from food crops has become a hotly debated topic worldwide because of its potential impact on commodity prices and food supply. The paper summarizes the current worldwide efforts towards using biomass as an energy source, the associated technological challenges, environmental implications, economic and political implications (since the current investment in biofuels remains highly dependent on government subsidy in largest ethanol and biodiesel producing countries and there are trade restrictions in the form of import tariffs), issues related to energy security, and outlook for 2030.

2. Key Topics

The Role of Biomass in Global Energy Requirements: The total land area of the earth is 1.3x10^{14} m^2 (~ 13 billion hectares) of which 30.5% is forest and savannah, 34.4% is non-arable, 23.6% is used for pasture and range, and 11.4% is used for crops (4.6% is used for cereal production). In 2005, the world population was 6.44 billion and the total energy consumption rate was 14.5 TW (460 x 10^{18} Joule), of which 9.2 % energy was generated from biomass. It has been forecasted that by 2050, the world population will increase to 9.4 billion and the energy consumption rate will be close to 27.6 TW. This forecast takes into account both the population growth and the economic growth increasing the energy demand [1]. It has been estimated that the 1 TW of energy from biomass requires about 200 million hectares of land; therefore 27.6 TW will require 42.5% of total land area of the earth, which is too large to be available. Under the best scenario, approximately 5 to 7 TW of energy needs can be met by biomass by 2050, which is about 20-25% of total energy needs. Biomass has been a source of energy for many millennia and still is the primary source of energy for poor population in third-world countries. For example, in India in 2005, 25% of all primary energy needs were met by directly burning of the biomass (wood from trees, dung-cakes etc.) by the poor rural population which has adverse impact of deforestation which in turn adversely effects the carbon sequestration due to thinning of crown density and therefore contributes to CO_2 addition in the atmosphere and global warming. Only a negligible fraction (less than 1%) of total biomass is currently converted in India into biogas, biofuel or electricity. Biomass requires the use of land, water, and fertilizers (and sunlight) whose availability varies in different region of the world. Available land and water resources are scarce in many regions of the world because of population and other natural geographical factors. Therefore the use of biomass for biogas, biofuel and electricity generation needs careful planning and coordination among world governments so that it does not adversely impact the other basics of human sustenance, namely food, water and health. There is a lack of consensus as to the impact of using biomass for bioenergy on food prices. In developed economies of the world (especially in U.S. and Europe) there has been a major push in the past decade towards converting biomass into ethanol and biodiesel for use as a transportation fuel. This increased emphasis has been primarily driven by the high oil prices and energy security considerations and to a lesser degree from the concerns for GHG emissions and global warming (although biomass can be essentially considered as carbon neutral and the replacement of gasoline by biofuels can reduce the overall GHG emissions). Furthermore, at present the conversion of biomass into biofuel is not very efficient for a wide variety of biomass; technological breakthroughs are needed to make them competitive.

Types of Biomass and Energy Generation: The definition of biomass includes all organic material which is either a direct product of photosynthesis (e.g. all plant matter including trees, grasses, algae etc.) or an indirect product of photosynthesis (e.g. animal mass and waste resulting from the consumption of plant material). The bioenergy in the form biofuels is considered essentially carbon neutral; CO_2 emitted due to combustion of biomass gets used by the new plants for growth. However, it should be noted that the life-cycle analysis (LCA) of bioenergy will indicate some small emissions due to the use of fossil fuels in cultivation, harvesting and transportation of the biomass. However, these are a small fraction of those associated with replaced fossil fuels. Thus, biomass is considered as a carbon neutral renewable energy source. All the direct photosynthetic biomass can be broadly categorized as: trees (Eucalyptus to Palm oil), plants (corn, wheat, sugarcane, sorghum, soybean, sugar beet etc.), grasses (miscanthus, switch grass, cassava, jatropha etc.) and algae (red marine algae, green algae etc). There are several issues involved in using these types of biomass for bioenergy: (1) value as a food grain for human and animal consumption and (2) time required for replacement, (3) effect on ecosystem, and (4) availability of land and water. Forests should not be used because they play a major role in the balance of the ecosystem and the average replacement rate is 25 years. Many food grain plants on the cultivated land such as corn, wheat, soybean, sorghum etc. can be replaced within a year and half; however there is a contentious debate on their effect on the food prices. Nevertheless many countries including the U.S., Brazil, Japan, and several countries in Europe are marching ahead in using these plants for Ethanol and Biodiesel production. Grasses do make a desirable candidate and are being considered as a source of biofuel by many countries (mentioned before) as well as China and India. Algae are attractive; they are aquatic, their replacement rate is less than a year, and they have high oil content.

Harvesting useful fuels from trees, plants and grasses that grow on dry land requires lots of processing. These plants are composed mainly of three types of large molecules – cellulose, hemi- cellulose and lignin. Each is made of a chain of smaller molecules, and all three are often bound together in a complex called lignocellulose, particularly in the wood. Figure 1 shows the steps involved in turning sunlight into biofuels [2]. Diverse technologies are needed to turn a particular type of biomass into a biofuel. For conversion, bio-chemical, thermochemical and/or other physical/chemical processes may be needed. Some of these processes are currently better developed than others; research efforts are underway in many countries to improve the existing processes as well as to develop the new. For example, currently most of the ethanol in the world (48% in U.S. from corn and 31% in Brazil from sugarcane) is produced by biochemical conversion process wherein yeasts ferment sugar from cornstarch and sugar crops into ethanol. Cellulosic biomass from trees, grasses, and agricultural residues can be used to produce “cellulosic ethanol” by biochemical conversion process. A combination of heat, pressure, chemicals and enzymes unlocks the sugar in the cellulosic biomass which is then fermented into ethanol by using genetically engineered microorganisms. On the other hand, a much simpler process, known as transesterification, is used to produce the biodiesel. The vegetable oils, seed oils, or animal fats are reacted with ethanol or methanol in the presence of a catalyst to produce biodiesel. A thermochemical process, known as pyrolysis, can also be employed to decompose biomass by heating it in the absence of air. This results in oil like liquid which can be burned like fuel oil or refined into chemicals and fuels such as “green gasoline.” This process can also be used to pretreat biomass for conversion to biofuels. As shown in Figure 1, another widely used thermochemical process is gasification. In this process, heat and a limited amount of oxygen are used to convert the biomass into a hot synthesis gas called the “syngas.” Syngas can be combusted to produce electricity using a gas turbine or can be converted into ethanol using microbes (such as *Clostridium*) or catalysts; it can also be used to produce hydrocarbons, alcohols, ethers and other chemical products. Algae on the other hand do not require much processing to become biodiesel. Algae can be grown in large scale open water reservoirs/ponds or in photobioreactors. Algae plants can operate side by side with CO_2 generating plants because they can utilize the flue gas for their growth. The only problem in harvesting oil from algae is that of extracting it from ponds, drying it out and breaking-open its cells. This process can be very tedious. Current research efforts are also focused on genetically modifying the plants and algae for

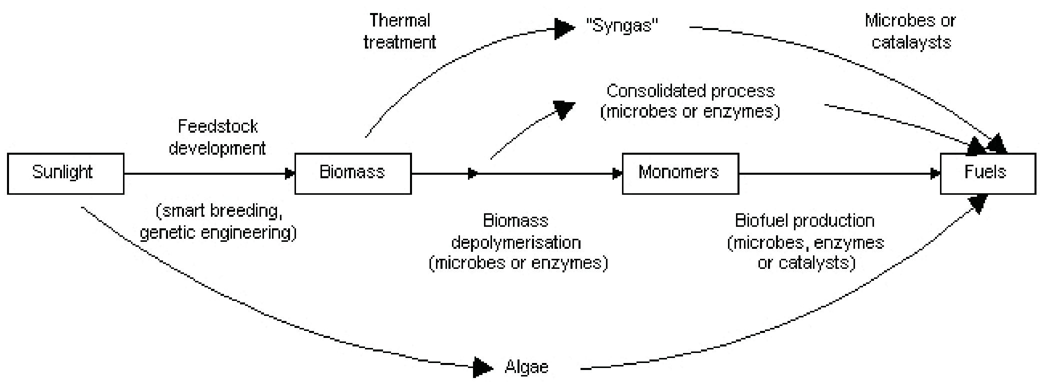

Figure 1. Potential Pathways for Biofuel Production [2].

Table 1. Biofuel type, its biomass source, its benefits and technological maturity [3].

Fuel	Source	Benefits	Maturity
Grain/Sugar Ethanol	Corn, sorghum, and sugarcane	- Produces a high-octane fuel for gasoline blends - Made from a widely available renewable resource	Commercially proven fuel technology
Biodiesel	Vegetable oils, fats, and greases	- Reduces emissions - Increases diesel fuel lubricity	Commercially proven fuel technology
Green Diesel and Gasoline	Oils and fats, blended with crude oil	- Offer a superior feedback for refineries - Are low-sulfur fuels	Commercial trials under way in Europe and Brazil for fuel
Cellulosic Ethanol	Grasses, wood chips, and agricultural residues	- Produces a high-octane fuel for gasoline blends - Is the only viable scenario to replace 30% of U.S. petroleum use	DOE program is focused on commercial demonstration by 2012
Butanol	Corn, sorghum, wheat, and sugarcane	- Offers a low-volatility, high energy-density, water-tolerant alternate fuel	BP and DuPont plan to introduce butanol fuel in 2007
Pyrolysis Liquids	Any lignocellulosic biomass	- Offer refinery feedstocks, fuel oils, and a future source of aromatics or phenols	Several commercial facilities produce energy and chemicals
Syngas Liquids	Various biomass as well as fossil fuel sources	- Can integrate biomass sources with fossil fuel sources - Produce high-quality diesel or gasoline	Demonstrated on a large scale with fossil feedstocks, commercial biomass projects under consideration
Diesel/Jet Fuel From Algae	Microalgae grown in aquaculture systems	- Offers a high yield per acre and an aquaculture source of biofuels - Could be employed for CO_2 capture and reuse	Demonstrated at pilot scale in 1990s
Hydrocarbons From Biomass	Biomass carbohydrates	- Could generate synthetic gasoline, diesel fuel, and other petroleum products	Laboratory-scale research in academic laboratories

higher yield of cellulosic content and oil respectively. Table 1 shows different categories of fuel that can be extracted from various types of biomass using the appropriate bioprocess some of which are relatively mature and some of which require more research and innovations [3]. Research efforts are also devoted, primarily in U.S., towards developing efficient production processes for methanol, butanol, dimethyl ether, propanol, heptanol, pyrolysis oil, and other biofuels that could offer efficiency and cost benefits compared to corn ethanol [4].

Energy Requirements for Generating Bioenergy: It has been argued in the past that more fossil energy is required to produce ethanol than it provides as fuel. However, a recent study by Argonne National Lab in Chicago and General Motors has concluded that the corn growers and ethanol plants in U.S. consume only about 7Btu of fossil fuel energy for every 10Btu of fuel they produce [3]. The benefits are even greater in terms of replacing petroleum. Since most of the energy for producing corn and for ethanol plant is supplied by coal and natural gas, only 1 Btu of petroleum is consumed for every ten units of biofuel produced. Thus every gallon of ethanol produced significantly reduces the use of petroleum. The energy balance is even better for the production of cellulosic ethanol [3].

Land-Use, Water Requirements and Economics of Biofuel Production [4]: Estimates for biomass that can be produced from one acre of land range from five to twenty tons because the yield depends upon the quality of land, type of biomass, cultivation methods, and environmental conditions. Biomass yields in excess of ten dry tons per acre even on non-prime farmland are likely to be feasible in the near future with new bioengineering innovations. For example, switchgrass can sustain itself on lands that would not be considered acceptable for most food crops. Neutered versions of switchgrass, which do not reproduce from seeds, are being developed that can produce ten tons of biomass per acre while requiring much less fertilizer and water than what is used for food crops. Same is true for other grasses like jatropha in India. However large-scale plantings would likely involve land use changes that could impact biodiversity and the availability of land for other purposes. Assuming an average yield of ten tons of biomass per acre, the ethanol yield would be in the range of 800 to 1200 gallons/acre. Therefore a 100-million gallon ethanol refinery would require approximately 100,000 acres to grow its feedstock. In a best case scenario, this would mean transporting material an average of ten miles, adding $0.25 per gallon to the cost. The cost of converting feedstock into sugar and to ferment and distill sugar into ethanol is estimated to be $0.20/gallon. There is an additional cost of distribution which can be significant. Most experts agree that the present pipelines are not suitable for transporting ethanol without expensive upgrades; current cost estimates assume that ethanol will be shipped by trucks or rail to the distribution points. The U.S. Department of Energy (DOE) estimates that the final cost of cellulosic ethanol can be reduced by half of the current price of $2.25/gallon by 2020. These costs are different in different countries, for example the cost of Brazil's cane-sugar-based ethanol is estimated to be $0.75/gallon, not including the distribution cost. The economics and commercialization of biofuels are heavily dependent on the price of oil. If the price of oil remains high (over $40/barrel which has certainly been the case for the past two years and will remain so in the future), ethanol and biodiesel production will grow and become increasingly competitive. In the U.S., there is already a high demand for ethanol for blending in E10 (10% ethanol and 90% gasoline) because of high oil prices as well as to meet clean air regulations. E85 (85% ethanol and 15% gasoline) is also becoming competitive; its use and demand will expand with the availability of Flex-Fuel-Vehicles (FFV) at affordable prices and the development of required infrastructure. In addition, the issues of government subsidies currently provided in largest ethanol (U.S. and Brazil) and biodiesel (European Union) producing countries as well as the trade restrictions in biofuels imposed in the form of import tariffs need to be addressed in order to address the food insecurity for the most vulnerable populations in the developing countries [5].

3. Conclusions

Biofuels offer one of the more sustainable alternatives for replacing fossil fuels for transportation. It is forecasted that about 25 to 30% of petroleum-based transportation fuel can be replaced by biofuels by 2030. However, to achieve this objective, croplands and forests as well as lands not particularly well-suited for food crops should be developed to grow biomass. Cellulosic conversion technologies need to be developed on a commercial scale. Biofuel distribution issues need to be addressed. Until large-scale refineries are completed, the costs and benefits of converting cellulosic biomass into fuels will not be fully understood or optimized.

4. References

1. Lewis, N.S. and Nocera, D.G., “Powering the Planet: Chemical Challenges in Solar Energy Utilization,” Proc. Nat. Ac. Sci., Vol. 103, No. 43 (2006), pp. 15729-15735.
2. “The Power and the Glory,” A Special Report on Energy, Economist, 21-27 June 2008.
3. National Renewable Energy Laboratory, USA Report NREL/BR-510-39426, August 2006.
4. Presidential Commission on Advanced Science & Technology (PCAST) Report titled, “The Energy Imperative: Technology and Role of Emerging Companies,” Nov. 2006.
5. OECD Report titled, “Economic Assesment of Biofuel Support Plocies,” Directorate of Trade and Agriculture, 2008.

Speaker’s Biography

Professor Ramesh K. Agarwal is the William Palm Professor of Engineering and the director of Aerospace Research and Education Center at Washington University in St. Louis. From 1994 to 2001, he was the Sam Bloomfield Distinguished Professor and Executive Director of the National Institute for Aviation Research at Wichita State University in Kansas. From 1978 to 1994, he was the Program Director and McDonnell Douglas Fellow at McDonnell Douglas Research Laboratory in St. Louis. Dr. Agarwal obtained his Ph.D. from Stanford University in 1975. Since then, he has worked primarily in Computational Fluid Dynamics (CFD). Recently, he has been engaged in research in several areas of renewable energy systems which include windmills, photobioreactors and fuel cells. He is the author and co-author of over 300 publications. He is the recipient of many honors and awards. He is a Fellow of ASME, AIAA, APS, IEEE and AAAS.