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Biomass and renewable fuels

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Abstract

Biomass is an important contributor to the world economy. Agriculture and forest products industries provide food, feed, fiber, and a wide range of necessary products like shelter, packaging, clothing, and communications. However, biomass is also a source of a large variety of chemicals and materials, and of electricity and fuels. About 60% of the needed process energy in pulp, paper, and forest products is provided by biomass combustion. These processes could be improved to the point of energy self-sufficiency of these industries. Today's corn refinery industry produces a wide range of products including starch-based ethanol fuels for transportation. The biomass industry can produce additional ethanol by fermenting some by-product sugar streams. Lignocellulosic biomass is a potential source for ethanol that is not directly linked to food production. Also, through gasification biomass can lead to methanol, mixed alcohols, and Fischer–Tropsch liquids. The life science revolution we are witnessing has the potential to radically change the green plants and products we obtain from them. Green plants developed to produce desired products and energy could be possible in the future. Biological systems can already be tailored to produce fuels such as hydrogen. Policy drivers for increased use of biomass for energy and biobased products are reviewed for their potential contributions for a carbon constrained world. © 2001 Published by Elsevier Science B.V.

Keywords: Biomass; Fuels from biomass; Biological hydrogen production; Sustainable energy systems; Carbon constrained world

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1. Introduction

In the future, our energy systems will need to be renewable and sustainable, efficient and cost-effective, convenient and safe. Can the integrated development and use of our nation's biologically derived renewable resources contribute significantly to our energy

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independence, increased energy diversity, and reduced carbon emissions while at the same time fostering rural development, technological innovation and commercialization?

We address biomass, derived fuels and energy, and biological hydrogen production.

2. Today's biomass economy from an energy viewpoint

The United States consumes about 94.2 quads (1 quad = 1 quadrillion Btu = 1.055 EJ) of all forms of energy self-generated or imported. Of those, 7.1 quads are renewable energy. More than 3 quads provide residential and commercial heat, heat and power in industry, direct electricity production, as part of the energy and environmental services in residue disposal and landfill gas use, and transportation fuels from biomass. These various sources of bioenergy and their relationship with the conventional biomass industries are shown in Fig. 1 [1].

As a primary energy source, biomass (43%) is just behind hydropower (51%) among the renewable resources. The Public Utilities Regulatory Policy Act (PURPA) of 1978 provided the incentive for industry to invest US$15 billion, establish 66,000 jobs and create a biomass power industry worth US$1.8 billion/year (see Fig. 2a). A total of 0.75

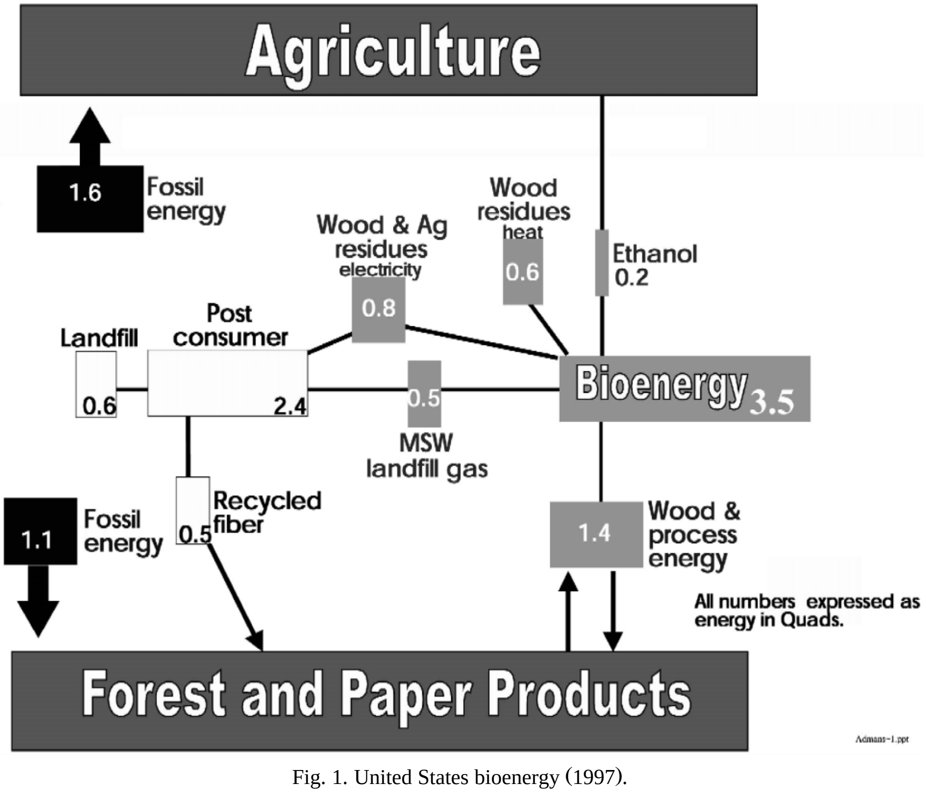

Fig. 1. United States bioenergy (1997).

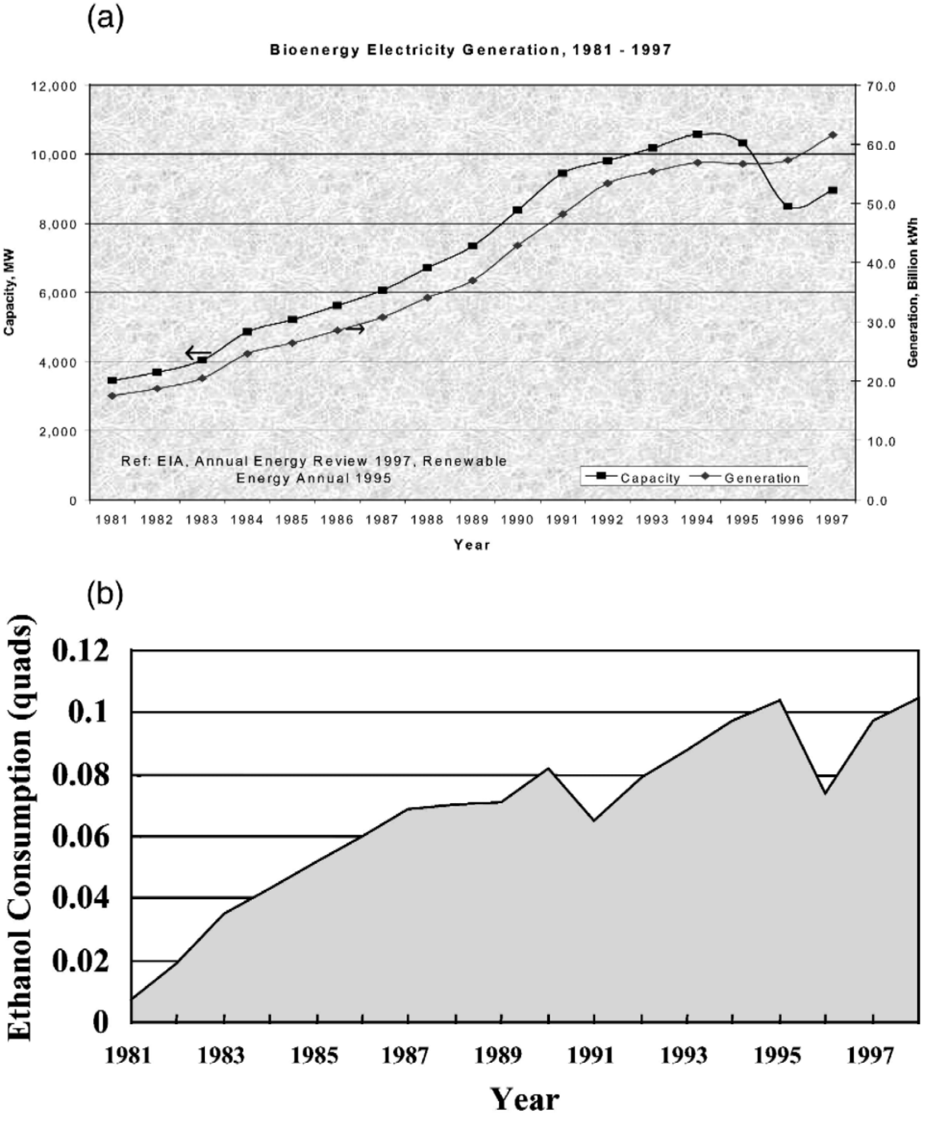

Fig. 2. (a) Electricity from biomass in the United States. (b) Ethanol market evolution.

quads or 1% of U.S. electricity is from biomass power, and more than twice that amount of energy is generated and used within the forest products industry. Waste to energy represents another 0.5 quads. More than a thousand biomass facilities generate electricity or cogenerate for their own use [2]. Utility restructuring is challenging many of these operations because of competition with facilities in which capital costs have already been amortized and can produce electricity at lower costs. Some added bioenergy capacity cannot compete on cost alone because natural gas-fired combined cycle plants have lower capital cost and moderate fuel costs and are predicted to be stable. One way in which bioenergy can be helped is by finding ways to pay for the environmental service it can provide, such as landfill avoidance. Another way is the renewable portfolio standard, which ensures a minimum level of renewables in the electricity portfolios of power suppliers in implementing jurisdictions.

Today's bioenergy industry also produces liquid fuels, primarily ethanol, using approximately 6% of the corn grain produced each year (see Fig. 2b) [3]. Production started in the late 1970s and capacity has increased steadily due to the Federal tax incentive and various state and local tax credits. Bioethanol production from lignocellulosic biomass is beginning to emerge due to recent advances in conversion technology. The same biotechnology revolution that is driving near-term commercialization will drive down the cost of bioethanol manufacture over the next 10 years. A point of cost competitiveness with the wholesale gasoline price of today will be reached based on the use of inexpensive residues [4].

3. Policy drivers to increase bioenergy and biobased products

The President issued Executive Order 13134 on August 12, 1999 to coordinate Federal efforts to accelerate the development of 21st century bio-based industries that use trees, crops, and agricultural and forestry wastes to make fuels, chemicals, and electricity. The Order is titled "Developing and Promoting Biobased Products and Bioenergy". The Order and related Executive Memoranda [5] were based on extensive literature and findings [4,6] from which the following can be concluded.

- There is a sufficient supply of biomass materials to provide food, feed, fiber and some level of energy, fuels and materials. The precise level and impact of energy production varies but a tripling of biobased products and bioenergy by 2010 is a Presidential goal. By 2020, the goal is a 10-fold increase.
- Several drivers provide impetus to a bioenergy and biobased products effort. These include emerging market opportunities, increased rural development needs, reducing environmental impacts, increasing energy security and diversity, reduce fossil carbon emissions, and meeting the growing need for energy and materials with sustainable technologies.
- Many companies developing bioenergy and biobased products are emerging and others are large and generally more mature (corn refining and pulp and paper). Because of the nascent nature of the "business", a large emphasis on research, development and deployment is needed.
- There is no single agency, industry, or sector that can meet the challenges and needs to accomplish these aggressive goals on their own. All of these studies call for integrated efforts across federal agencies, current industrial sectors, academia, national laboratories, non-profit organizations, professional societies, public interest groups, etc.

Several Congressional bills have emerged with strong bipartisan support. These have aligned objectives with the Executive Order and Federal Agency actions. From these congressional actions, the Agricultural Risk Protection Act of 2000 was passed (Public

Law 106-639, June 2000). It includes Title III, Biomass Research and Development Act of 2000, which implements much of the research and development activities described in the Executive Order. It provides significant guidance on areas of research and development that should be explored by a concerted U.S. federal program under the leadership of the Departments of Agriculture and Energy with participation of other relevant agencies.

4. Near-term increased biomass use

Current industrial biomass use is primarily of residues of agriculture, forest products operations or urban and industrial residues. Additional crop residues could be collected for product or energy purposes. Additional increases in supply would have to come from crops specially planted for these purposes. Fig. 3 shows an example of a supply curve considering the residues and at what point some dedicated feedstock supply is needed. Life cycle analysis of a dedicated poplar plantation and electricity production through an

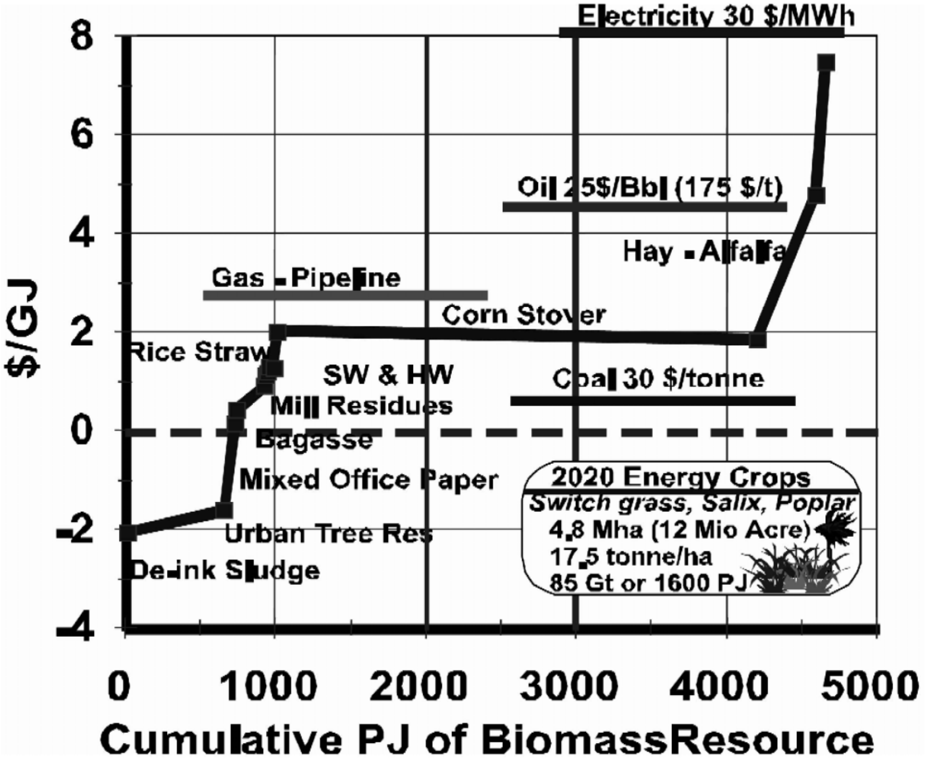

Fig. 3. Supply curve of various biomass residues and dedicated feedstock plantations, for instance, of switchgrass, salix, and poplars.

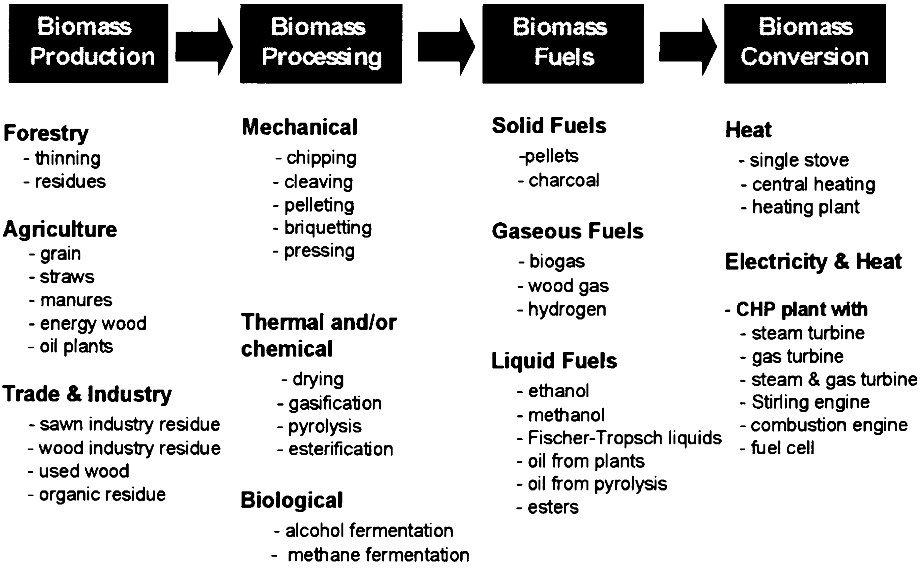

Fig. 4. From multiple biomass resources to a variety of fuels and energy products.

integrated gasification combined cycle shows that there are almost no net carbon emissions [7]. The current conventional energy values are also included.

5. Multiple energy options from biomass

Biomass is a complex resource that can be processed in many ways leading to a variety of products. Biological routes can convert the carbohydrate portion of the lignocellulosic feedstock into ethanol, an oxygenate that can also be used as a fuel additive. The lignin component cannot be used this way and is combusted to generate heat and electricity. Gasification provides a way to generate syn-gas and from it the clean conventional fuels: Fischer–Tropsch liquids, methanol, and others (see Fig. 4).

A proxy for how well some of these various processes perform is the overall process efficiency starting with lignocellulosic biomass [8].

Fuels from biomass	Efficiency (HHV)	Comment
Methanol	54	> From gasification
Hydrogen	60	From gasification
Fischer–Tropsch liquids (FTL)	49	From gasification
FTL (single pass) + electricity	26.5 (FTL); 17.2 electricity	> From gasification, lower capital costs
Ethanol	50% (1999); 63% (2015)	From hydrolysis and fermentation

6. Long-term renewable hydrogen production technologies

The use of solar energy to split water into oxygen and hydrogen is an attractive means to directly convert solar energy to chemical energy. Biological systems are reviewed below. There are also chemical and electrochemical systems that have long-term ($>$ 10 years), high-risk, high-payoff technologies for the sustainable production of hydrogen. These systems have been summarized by Gregoire Padro [9].

The biological processes include the following.

(1) Algal hydrogenases that evolve hydrogen at a rate that is four times that of the wild type, and are three to four times more oxygen tolerant [10].

(2) Photosynthetic organisms with light harvesting, chlorophyll–protein complexes that effectively concentrate light and funnel energy for photosynthesis. These cells showed photosynthetic productivity (on a per chlorophyll basis) that was six to seven times greater than the normally pigmented cells [11], a phenomenon that could lead to significant improvements in the efficiency of hydrogen production on a surface-area basis. Various reactor designs are under development for photobiological hydrogen production processes (single-stage vs. two-stage, single organism vs. dual organism) [12].

(3) Systems to convert CO (found in synthesis gas) to hydrogen via the so-called water–gas shift reaction ($CO + H_2O = CO_2 + H_2$) at ambient temperatures. Microorganisms isolated from nature are used to reduce the level of CO to below detectable levels (0.1 ppm) at temperatures of around 25–50°C in a single reactor [13,14]. This process has significant potential to improve the economics of hydrogen production when combined with the thermal processing of biomass or other carbon-containing feeds.

7. The role of renewable fuels in a carbon-constrained world

Decarbonization of fossil fuels is a way to increase energy consumption without increasing carbon consumption in a carbon-constrained world. Removal of carbon from fossil fuels prior to use in energy production is likely to be far less costly than attempting to remove CO_2 from dispersed sources. If fossil fuels are converted to hydrogen in a central facility, the collection of CO_2 (or elemental carbon, depending on the process) is relatively simple compared to collecting CO_2 from every fossil fuel-consuming vehicle on the road. Carbon neutral biomass-derived transportation fuels offer solutions to this.

8. Conclusions

For renewable processing of biomass or direct biological hydrogen production, the cost of the technologies still needs to be decreased through research, development, demonstrations, and diffusion of commercialized new technologies. Valuing the environmental and social contributions that biomass inherently makes can also help increase its use. Broad societal consensus on land and water use issues is needed. Each route still requires significant integrated efforts across federal agencies, multiple industrial sectors, academia, national laboratories, non-profit organizations, professional societies, public interest groups, etc. The challenge to make renewable resources a major commercial reality is equated to putting man on the moon. The versatility of biomass and conversion technologies makes it suitable to either adapt to today's fuel and vehicle infrastructure or to be a part of a new infrastructure for hydrogen fuels and super efficient vehicles of the future.

References

[1] Energy Information Administration, Renewable Energy Annual 1998, data for 1997, DOE/EIA_0603(98)/1 and National Renewable Energy Laboratory additional data including the generation of electricity from independent power producers and non-utility generators that is not included in the Energy Information Administration data.

[2] R.P. Overend, C.M. Kinoshita, M.J. Antal Jr., Bioenergy in transition. J. Energy Eng. (1996) 78–92, December;
in: R.P. Overend, E. Chornet (Eds.), Biomass: A Growth Opportunity in Green Energy and Value Added Products, in two volumes. Proceedings of the 4th Biomass Conference of the Americas, Pergamon, 1999, 1783 pp.

[3] Energy Information Administration, http://www.eia.doe.gov/pub/energy.overview/aer98/txt/aer1003.txt.

[4] National Research Council, Board on Biology, Commission on Life Sciences, "Biobased Industrial Products: Priorities for Research and Commercialization", National Academic Press, Washington, DC, 1999. In particular, this document performs an analysis in Appendix A of the Case study of lignocellulosic ethanol processing on pp. 115–120.

[5] See http://www.bioproducts-bioenergy.gov/ for the Executive Order text and also Memoranda and for the actions of the combined Interagency Council on Biobased Products and Bioenergy.

[6] See, for instance, vision and technology roadmap documents produced by trade and professional societies in partnership with government: Technology Vision 2020: The U.S. Chemical Industry (1996), www.ccrhq.org/vision/index.html; Plant/Crop-Based Renewable Resources 2020: A vision to enhance U.S. economic security through renewable plant/crop-based renewable resource use (1998), http://ncga.com/05newmarkets/main/index.html; The Technology Roadmap for Plant/Crop-Based Renewable Resources 2020: Research priorities for fulfilling a vision to enhance U.S. economic security through renewable plant/crop-based renewable resource use (1999), www.oit.doe.gov/agriculture/; Agenda 2020: A Technology Vision and Research Agenda for America's Forest, Wood, and Paper Industry (1994), http://www.afandpa.org/Environmental/Agenda2020/; Agenda 2020: The Path Forward—An Implementation Plan (1999), http://www.oit.doe.gov/forest/; Powerful Partnerships—The Federal Role in International Cooperation on Energy Innovation, June 1999, http://www.whitehouse.gov/WH/EOP/OSTP/html/OSTP_Home.html.

[7] M.K. Mann, P.L. Spath, 1997, Life Cycle Assessment of a Biomass Gasification Combined-Cycle Power System, NREL/TP-430-23076.

[8] From multiple papers and discussions with Eric Larson, Princeton and NREL assessments.

[9] C.E. Gregoire Padro, Back to the future: hydrogen production now and then. Division of Fuel Chemistry, 217th American Chemical Society National Meeting, Anaheim, CA, March 21–25, vol. 44, 1999, pp. 235–239, No. 2;
in: C.E. Gregoire Padro (Ed.), Advances in Hydrogen Energy. Kluwer Academic–Plenum Publishers, New York, 2000.

[10] M.L. Ghirardi, R.K. Togasaki, M. Seibert, Oxygen sensitivity of algal hydrogen production. Appl. Biochem. Biotechnol. 63–65 (1997) 141–151;

M. Seibert, T. Flynn, D. Benson, E. Tracy, M. Ghirardi, Development of selection/screening procedures for rapid identification of hydrogen-producing algal mutants with increased oxygen tolerance. International Conference on Biological Hydrogen Production. Plenum, NY, 1998, in press.

[11] A. Melis, J. Neidhardt, I. Baroli, J.R. Benemann, Maximizing photosynthetic productivity and light utilization in microalgal by minimizing the light-harvesting chlorophyll antenna size of the photosystems. International Conference on Biological Hydrogen Production. Plenum, NY, 1998, in press.

[12] J.P. Szyper, B.A. Yoza, J.R. Benemann, M.R. Tredici, O.R. Zaborsky, Internal gas exchange photobioreactor: development and testing in Hawaii. International Conference on Biological Hydrogen Production. Plenum, NY, 1998, in press.

[13] P.-C. Maness, P.F. Weaver, Variant O_2-resistant hydrogenase from photosynthetic bacteria oxidizing CO. Proceedings of the Fifth International Conference on the Molecular Biology of Hydrogenase, Albertville, France 1997.

[14] P.F. Weaver, P.-C. Maness, S. Markov, Anaerobic dark conversion of CO into H_2 by photosynthetic bacteria. International Conference on Biological Hydrogen Production. Plenum, NY, 1998, in press.