

material contributors to primary energy supply, whereas cost-related constraints dominate the ultimate commercial potential of PV-derived solar energy conversion and storage systems.

One approach to storing electrical energy in chemical bonds is through electrolysis, in which water is split into H<sub>2</sub> and O<sub>2</sub> in an electrolyzer. However, Pt-based electrolysis in acidic or neutral media is expensive and unlikely to be scalable to the levels that would be required for this process to be material in global primary energy production. Ni-based electrolysis in basic aqueous solutions is cheaper but requires scrubbing the input stream to remove the CO<sub>2</sub> (13); additionally, even the best fuel cells are only 50 to 60% energy-efficient and the best electrolysis units are 50 to 70% energy-efficient (13), so the full-cycle energy storage/discharge efficiency of such a system is currently only 25 to 30%. Clearly, better catalysts for the multielectron transformations involved in fuel formation are needed. Nature provides the existence proof for such catalysts, with the hydrogenase enzymes operating at the thermodynamic potential for production of H<sub>2</sub> from H<sub>2</sub>O, and with the oxygen-evolving complex of

photosystem II producing O<sub>2</sub> from H<sub>2</sub>O in an energy-efficient fashion. However, no human-made catalyst systems, either molecular or heterogeneous, have yet been identified that show performance even close to that of the natural enzymatic systems. Development of such catalysts would provide a key enabling technology for a full solar energy conversion and storage system.

Whether the fuel-forming system is separate, as in a PV-electrolysis combination, or integrated, as in a fully artificial photosynthetic system that uses the incipient charge-separated electron-hole pairs to directly produce fuels with no wires and with only water and sunlight as the inputs, is an interesting point of discussion from both cost and engineering perspectives. However, the key components needed to enable the whole system remain the same in either case: cost-effective and efficient capture, conversion, and storage of sunlight. Each of these functions has its own challenges, and integration of them into a fully functioning, synergistic, globally scalable system will require further advances in both basic science and engineering. Such advances, together with advances in existing technologies,

will be required if the full potential of solar energy is to be realized.

#### References and Notes

1. *World Energy Assessment Overview, 2004 Update*, J. Goldemberg, T. B. Johansson, Eds. (United Nations Development Programme, New York, 2004) ([www.undp.org/energy/weaover2004.htm](http://www.undp.org/energy/weaover2004.htm)).
2. *Basic Research Needs for Solar Energy Utilization* (U.S. Department of Energy, Washington, DC, 2005) ([www.er.doe.gov/bes/reports/abstracts.html#SEU](http://www.er.doe.gov/bes/reports/abstracts.html#SEU)).
3. M. I. Hoffert *et al.*, *Science* **298**, 981 (2002).
4. M. A. Green, *Third Generation Photovoltaics: Advanced Solar Energy Conversion* (Springer-Verlag, Berlin, 2004).
5. R. D. Schaller, M. A. Petruska, V. I. Klimov, *Appl. Phys. Lett.* **87**, 253102 (2005).
6. M. A. Green, *Prog. Photovolt.* **9**, 137 (2001).
7. B. M. Kayes, H. A. Atwater III, N. S. Lewis, *J. Appl. Phys.* **97**, 114302 (2005).
8. D. J. Milliron, I. Gur, A. P. Alivisatos, *MRS Bull.* **30**, 41 (2005).
9. G. Yu *et al.*, *Science* **270**, 1789 (1995).
10. N. S. Lewis, *Inorg. Chem.* **44**, 6900 (2005).
11. M. Gratzel, *Nature* **414**, 338 (2001).
12. R. Smalley, *Bull. Mater. Res. Soc.* **30**, 412 (2005).
13. J. Ivy, *Summary of Electrolytic Hydrogen Production* (National Renewable Energy Laboratory, Golden, CO, 2004) ([www.nrel.gov/docs/fy04osti/36734.pdf](http://www.nrel.gov/docs/fy04osti/36734.pdf)).
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#### PERSPECTIVES

## Challenges in Engineering Microbes for Biofuels Production

Gregory Stephanopoulos

Economic and geopolitical factors (high oil prices, environmental concerns, and supply instability) have been prompting policy-makers to put added emphasis on renewable energy sources. For the scientific community, recent advances, embodied in new insights into basic biology and technology that can be applied to metabolic engineering, are generating considerable excitement. There is justified optimism that the full potential of biofuel production from cellulosic biomass will be obtainable in the next 10 to 15 years.

The idea of converting biomass-derived sugars to transportation biofuels was first proposed in the 1970s. Once again, the idea is being seriously contemplated as a possible substitute for petroleum-based liquid fuels. Economic and geopolitical factors (high oil prices, environmental concerns, and supply instability) have certainly played a role in reviving interest in renewable resources. However, an additional impetus is now provided by scientific and technological advances in biosciences and bioengineering that support increased optimism about realizing the full potential of biomass in the liquid fuels area within the next

10 to 15 years. New approaches to biology are being shaped by the genomics revolution; unprecedented ability to transfer genes, modulate gene expression, and engineer proteins; and a new mind-set for studying biological systems in a holistic manner [systems biology (1)]. We are also seeing advances in metabolic engineering (2–4), with the goal of overproducing useful compounds by rationally and combinatorially engineering cells and their metabolic pathways (5). Combination of concepts and methods from these fields will create a platform of technologies that are critical for overcoming remaining obstacles in cost-efficient biofuel production from cellulosic biomass.

Figure 1 shows the basic features of a biomass-to-biofuels (B2B) process (6). After harvest, biomass is reduced in size and then

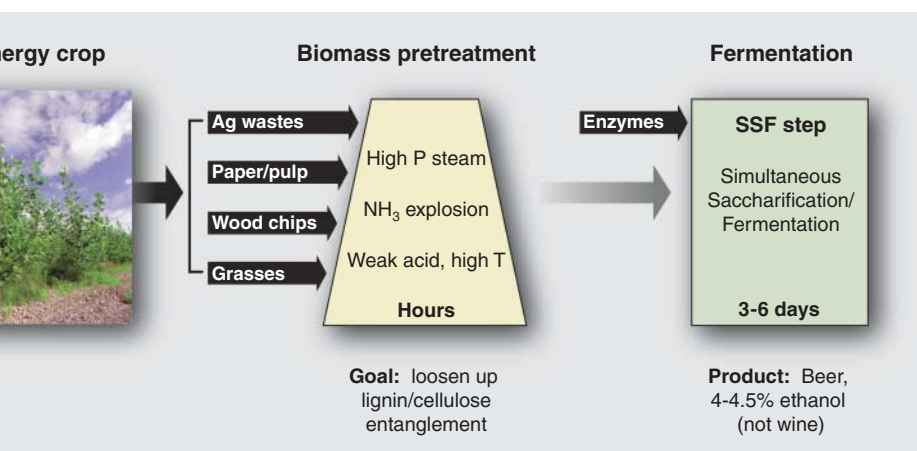
treated to loosen up the lignin-cellulose fiber entanglement in a step that can take from a few minutes to many hours. Several methods have been used for this purpose, such as biomass treatment with saturated steam at 200°C, explosion with ammonia, and cooking with warm dilute acid (6). Dilute acid pretreatments are fast (minutes), whereas steam-based treatments can take up to a day. After pretreatment, the solid suspension is exposed to cellulolytic enzymes that digest the cellulosic and hemicellulosic biomass components to release the hydrolysis products, primarily six- and five-carbon sugars, respectively (along with acetic acid and lignin-derived phenolic by-products). The type of pretreatment defines the optimal enzyme mixture to be used and the composition of the hydrolysis products. The latter are fermented by ethanol-producing microorganisms such as genetically engineered yeasts, *Zymomonas mobilis* (Fig. 2), *Escherichia coli*, or *Pichia stipitis* (Fig. 3). Presently, cellulose hydrolysis and fermentation are combined in a single unit, termed the simultaneous saccharification fermentation (SSF) stage. The rationale of combining saccharification (the breaking up of complex carbohydrates into monosaccharides) and fermentation (the conversion of a carbohydrate to carbon dioxide and alcohol) in a single unit was to prevent inhibition of the hydrolytic enzymes by the reaction products (7). The SSF step typically lasts 3 to 6 days, with cellulose hydrolysis being the slow, limiting step. The product of SSF is a rather dilute ethanol stream of 4 to 4.5% from which ethanol is separated by distillation.

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# Sustainability and Energy

Biomass pretreatment and hydrolysis are areas in need of drastic improvement. Despite substantial reduction in the cost of cellulolytic enzymes (8), sugar release from biomass still remains an expensive and slow step, perhaps the most critical in the overall process. Intensive research and development in all areas of enzyme production reduced the cost of cellulolytic enzymes by a factor of 10 to 30, down to 20 to 30 cents per gallon of ethanol produced (8, 9). Although this is certainly an important advance, it is estimated that the enzyme cost will have to be further reduced to a level comparable to that of current approaches that produce ethanol from the starch in corn kernels at a cost of 3 to 4 cents per gallon of ethanol. Expression of cellulases in fermenting organisms or transfer of the biofuel-synthesizing pathway into a cellulase-producing organism are being pursued in a process termed the consolidated bioprocess (CBP) (10). CBP, however, is presently hampered by the relative inability of yeast to process recombinant cellulases at high rates through their endoplasmic reticulum and secretory pathways, and the relative (with regard to *E. coli* and yeast) lag in development of molecular biological methods to manipulate organisms (such as *Trichoderma*) that secrete cellulases naturally. The fact that glucose suppresses respiration in *Saccharomyces cerevisiae* reduces the amount of adenosine triphosphate available for protein biosynthesis, which may also render it difficult for enzyme production in yeast to be competitive with enzyme production by aerobic fungi such as *Trichoderma* or *Aspergillus*. When realized, CBP will enjoy the benefit of completely eliminating the cost of purifying cellulase and of higher activity of the cell-associated cellulase enzyme. To accomplish this goal, the hydrolysis and fermentation steps will have to be coordinated well inside a single cell, such that neither one limits the overall conversion process to proceed at maximum capacity. Although attainable over a longer time scale, in the near term B2B will benefit from the availability of large amounts of inexpensive and more active cellulases. This opportunity should be pursued by coordinated approaches from protein engineering, fungal overexpression, and bioprocess engineering to take advantage of economies of scale in enzyme production.

In engineering better microorganisms for biofuels production, combinatorial searches for promising target genes and other lab-scale experiments should be conducted with synthetic media. In terms of identified target genes or cell phenotypes, results obtained with the more convenient complex media (Luria broth or yeast

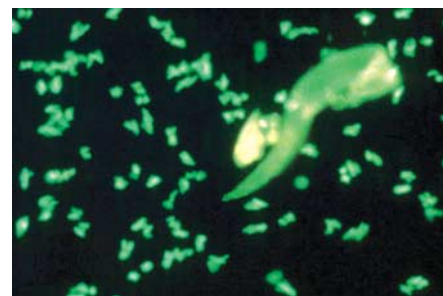


**Fig. 1.** Schematic of the overall conversion process of an energy crop to ethanol.

extract) do not usually translate well to industrial conditions that use synthetic media.

Nonenzymatic, physicochemical hydrolytic methods (such as high-temperature pretreatments and hot-acid hydrolysis) are much faster than enzymatic approaches, albeit at the cost of reduced sugar yields due to undesirable side reactions. This is a problem that can be potentially solved by novel bioreactor designs operating at optimal contact times so as to minimize the rate of sugar-degrading side reactions without impairing biomass hydrolysis in the first place. The presence of lignin that effectively accumulates in the solids fraction as the carbohydrates are hydrolyzed away can interfere mechanically with filtration and recycling operations and complicate efforts to optimize the performance of the hydrolysis step. Advanced material-handling methods and new filtration devices specifically addressing the peculiarities of lignin consistency, or sequence-reversing schemes (whereby lignin removal precedes the hydrolysis step) are some possibilities that could exploit the fast rates of physicochemical hydrolysis while minimizing adverse side reactions. Finally, use of novel types of solvents such as those derived from ionic liquids are promising alternatives that should be further evaluated.

The cost competitiveness of a process such as that depicted in Fig. 1 depends on product titer, yield, and productivity. Final product titer is an important cost determinant not only because it affects the downstream purification cost but because it defines the size of the footprint of the entire processing plant. Low product titer is caused by various factors, including the total amount of substrate solids fed to the fermentor, the presence of inhibitory compounds as by-products of biomass hydrolysis (such as aromatics, furfurals, furan derivatives, and phenolics), and, of course, the toxicity of the final product itself. If, as seems likely, we can increase the solids loading into the SSF unit, then we may be able to increase substantially the final ethanol concentrations. This makes the engineering of ethanol-tolerant strains,



**Fig. 2.** *Zymomonas mobilis*, a metabolically engineered bacteria used for fermenting both glucose and xylose to ethanol. [Credit: Zhang, Min; DOE/NREL]

which can tolerate the adverse environment in which the process takes place, of the utmost importance. Not much progress has been made on this front, perhaps because of the preconception that a complex phenotype such as ethanol tolerance could be modulated by a single gene, or at most a handful of genes. There is now accumulating evidence that no single gene can endow microbes with tolerance to ethanol and other toxic compounds. On the contrary, tolerance is a multigenic trait that must be elicited by drastically different approaches, such as global transcription machinery engineering (11). This method and its extensions should be systematically explored to identify transcription factor mutants that can increase the tolerance of industrial strains to the final fuel product, as well as other relevant toxic compounds.

Because the cost of a biomass-derived fuel depends critically on the yield of sugar conversion to the final product, much attention has been focused on the engineering of strains to use all sugars released from biomass hydrolysis, in particular the pentose sugars that are products of hemicellulose hydrolysis. Such sugars may constitute 5 to 30% of the total carbohydrates; hence, various strategies have been used to attempt either to introduce the ethanol pathway in natural xylose consumers (12) or to engineer the



**Fig. 3.** An 8000-liter fermentation tank used to start the process of turning cellulosic material into ethanol. [Credit: New Energy Company of Indiana; DOE/NREL]

xylose-catabolizing pathway in natural ethanol producers (13, 14). The state of the art is rather well advanced as far as the engineering of various pathways (including pentose phosphate, glycolytic, ethanologenic, and redox balancing) is concerned. An area that has received relatively limited attention is that of sugar transporters and their regulation. There is evidence that a multitude of such transporters may be in operation (15) and that their activity may depend on signaling defined by the sugar composition of the fermentation medium (16). Elucidation of sugar transport at the molecular level and better characterization of kinetic and regulatory properties, including quorum-sensing mechanisms, should be given high priority because they may provide the basis for the simultaneous use of the sugar mixtures released from biomass hydrolysis as opposed to the slower and suboptimal sequential use characterizing most present operations (sugars are consumed simultaneously in, for example, fermentations by recombinant *Z. mobilis*, albeit at low rates). It is important to remember that one mole of CO<sub>2</sub> is produced for each mole of ethanol, for a total yield of 0.51 g of ethanol per gram of glucose consumed. As carbon oxidation to CO<sub>2</sub> is essential for generating the energy and redox equivalents needed to sustain cellular functions and the ethanol pathway itself, an interesting long-term idea is the capture and conversion to liquid fuels of this CO<sub>2</sub> by means of hydrogen

supplied from carbon-free sources (such as nuclear or solar). This could be accomplished by conventional Fischer-Tropsch processes.

Process productivity is a principal determinant of capital cost. For cellulosic ethanol, the capital cost is estimated at ~\$4 per gallon, contributing 20 to 25% of the ethanol manufacturing cost (17). However, these figures, as well as the ones quoted in the following paragraph, vary considerably from source to source and are also time dependent. They should be viewed only as preliminary estimates that need to be validated by detailed empirical and analytic work. Furthermore, costs contributed by the process units are interrelated and cannot be assessed in isolation. Overall system analysis is critical for assessing the relative importance of the various process units and their interactions. Thus, reliable simulation packages for the integrated system operation must be developed for overall system analysis, optimization, and sensitivity studies (18).

The capital cost must be reduced by more than half for an economical process (along with a similar reduction in the feedstock cost, which will come primarily from yield improvements of an energy crop, and a 15 to 25 cents per gallon reduction in cellulosic enzyme costs). Achieving the above goal or, equivalently, doubling process productivity, requires a coordinated approach for improving all units of the process and, in particular, the biomass pretreatment-hydrolysis steps mentioned earlier, because these are apparently the process rate-limiting steps. After that, the volumetric productivity of fermentation must be improved (presently between 1.5 and 2.0 grams of ethanol produced per hour and fermentor volume), which is the product of the specific productivity (grams of product produced per gram of cells per hour) and the total cell concentration that can be sustained in the fermentor. The latter, again, is limited by the presence of the same inhibitory compounds; hence, use of more tolerant strains will affect the total process productivity as well. Additionally, specific productivity must be increased.

Various approaches have been suggested for increasing the specific ethanol productivity, such as increasing the amount of "rate-limiting" enzymes, enzyme deregulation, cofactor replenishment, and increase of precursor supply. Although some of these approaches are valid, some others are grossly misguided. A rather obvious approach to increase the flux through a pathway is by increasing the activity of every single enzyme in the

pathway. Although this is acceptable for modest flux enhancements, it has not been attempted for large, order-of-magnitude scale flux increases on the grounds that it will cause large perturbations in the metabolites and, hence, the physiology of the organism. Yet, this will not happen if all enzymes in the pathway are similarly amplified, because the same steady state with respect to metabolite levels will be preserved. Simultaneous increase of the activity of all enzymes by a factor  $f$  will not affect metabolite levels, while allowing pathway flux to increase by the same factor  $f$ . The only limitation in such a scheme is the cell volume, which may not be able to accommodate drastically increased amounts of all enzymes of a pathway (it is estimated that the enzymes of glycolysis make up 10 to 15% of the total cellular protein). However, this problem can be overcome by engineering more active enzymes. Pathway flux amplification by coordinated activity enhancement of the pathway enzymes (19) has been successfully used in lysine biosynthesis (20), aromatic amino acid production (21), and polyhydroxybutyrate synthesis in *E. coli* (22), among other systems. Determination of flux split ratios at key metabolic branch points (23), guided by flux determination methods (24, 25), can aid this research, along with advanced fermentor feeding strategies that control metabolic activity (26).

Product separation for ethanol, the main biofuel currently produced, is carried out by distillation. Although mature and well optimized, it remains an energy-intensive and overall expensive step contributing 17 to 20 cents per gallon (17, 27). In light of accumulating reports describing configurational changes in materials in response to small environmental changes (pH, temperature, or ionic strength), it may be useful to evaluate such phenomena with respect to their potential to facilitate ethanol separation. One can envision, for example, processes in which ethanol adsorbs preferentially on some material and desorbs when the material changes configuration after a small environmental change. Separation in such schemes would be entropically (as opposed to enthalpically) driven, could be less energy intensive than current operations, and possibly could be consolidated with fermentation in a single step.

As mentioned, ethanol is not the sole or optimal fuel to be produced from cellulosic biomass. Butanol is currently attracting attention because of its potential superior properties with respect to corrosiveness, volatility, energy density, and ease of separation (28). Aside from butanol, other higher alcohols, alkanes, and various types of oils are possible biochemically derived biofuels. It is not clear yet which one(s) will be the ideal biofuel, and the answer to this question may well depend on additional factors, such as the type of biomass available, particular climatic conditions, and composition of engine emissions. The ability to clone, transfer, and control genes from different

organisms, including plants, has reached the point at which researchers will be able to engineer pathways that take advantage of a variety of conditions with a great degree of confidence. Additionally, genome sequences now provide a straightforward supply of genes to be tested in tentative pathway constructs. Nevertheless, it is important to develop technologies for the synthesis and separation of these alternative fuels, because it is yet unclear what additional requirements such technologies will pose in the design of a robust, cost-efficient, commodity-scale process.

In assessing the potential of current and projected technologies to develop cost-efficient B2B processes, it is important to bear in mind that the present state of affairs was reached by minimal investment directly in biofuels research. The major biosciences and bioengineering infrastructure was developed in the process of exploring medical applications of biology and biotechnology. Although this platform is the basis for the present optimism surrounding the use of biosciences for biofuel production from renewable resources, a number of problems still remain in realizing this potential. These problems

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## References and Notes

1. T. Ideker, T. Galitski, L. Hood, *Annu. Rev. Genomics Hum. Genet.* **2**, 343 (2001).
2. J. E. Bailey, *Science* **252**, 1668 (1991).
3. G. Stephanopoulos, J. J. Vallino, *Science* **252**, 1675 (1991).
4. G. Stephanopoulos, A. J. Sinskey, *Trends Biotechnol.* **11**, 392 (1993).
5. G. Stephanopoulos, *AIChE J.* **48**, 920 (2002).
6. B. Hahn-Hagerdal, M. Galbe, M. F. Gorwa-Grauslund, G. Liden, G. Zacchi, *Trends Biotechnol.* **24**, 549 (2006).
7. M. Takagi *et al.*, *Proceedings of the Bioconversion Symposium*, IIT Delhi, p. 551 (1977).
8. Department of Energy, *From Biomass to Biofuels: A Roadmap to the Energy Future*, based on a workshop (Rockville, MD, December 7 to 9, 2005).
9. Data from presentations of K. C. McFarland (Novozymes) and G. Anderl (Genencor International) at the World Congress on Industrial Biotechnology and Bioprocessing, Orlando, FL, July 2006.
10. L. Lynd, *Curr. Opin. Biotechnol.* **16**, 577 (2005).
11. H. Alper, J. Moxley, E. Nevoigt, G. R. Fink, G. Stephanopoulos, *Science* **314**, 1565 (2006).
12. L. O. Ingram *et al.*, *Appl. Environ. Microbiol.* **53**, 2420 (1987).
13. M. Kuyper *et al.*, *FEMS Yeast Res.* **4**, 69 (2003).
14. M. Zhang *et al.*, *Science* **267**, 240 (1995).
15. E. Boles, C. P. Hollenberg, *FEMS Microbiol. Rev.* **21**, 85 (1997).
16. S. Ozcan, M. Johnson, *Microbiol. Mol. Biol. Rev.* **63**, 554 (1999).
17. National Renewable Energy Laboratory, U.S. Department of Energy, "Softwood biomass to ethanol feasibility study," NREL Report SR-580-27310 (2004).
18. I wish to thank J. Deutch for valuable discussions on matters related to the cost of cellulosic ethanol and for pointing out the need to consider the costs of an ethanol process in its entirety and not of isolated units.
19. G. Stephanopoulos, T. W. Simpson, *Chem. Eng. Sci.* **52**, 2607 (1997).
20. M. Koffas *et al.*, *Metab. Eng.* **5**, 32 (2003).
21. R. Patnaik, R. G. Spitzer, J. C. Liao, *Biotechnol. Bioeng.* **46**, 361 (1995).
22. S. J. Sim *et al.*, *Nat. Biotechnol.* **15**, 63 (1997).
23. J. J. Vallino, G. Stephanopoulos, *Biotechnol. Prog.* **10**, 327 (1994).
24. M. I. Klapa *et al.*, *Biotechnol. Bioeng.* **62**, 375 (1999).
25. B. Follstad *et al.*, *Biotechnol. Bioeng.* **63**, 675 (1999).
26. R. D. Kiss, G. Stephanopoulos, *Biotechnol. Prog.* **7**, 501 (1991).
27. USDA, *2002 Ethanol Cost-of-Production Survey*, Agricultural Economic Report No. 841 (USDA, Washington, DC, 2005).
28. A BP-DuPont joint venture announced in June 2006 is focusing on biobutanol.
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## PERSPECTIVE

# Biomass Recalcitrance: Engineering Plants and Enzymes for Biofuels Production

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Lignocellulosic biomass has long been recognized as a potential sustainable source of mixed sugars for fermentation to biofuels and other biomaterials. Several technologies have been developed during the past 80 years that allow this conversion process to occur, and the clear objective now is to make this process cost-competitive in today's markets. Here, we consider the natural resistance of plant cell walls to microbial and enzymatic deconstruction, collectively known as "biomass recalcitrance." It is this property of plants that is largely responsible for the high cost of lignocellulose conversion. To achieve sustainable energy production, it will be necessary to overcome the chemical and structural properties that have evolved in biomass to prevent its disassembly.

High worldwide demand for energy, unstable and uncertain petroleum sources, and concern over global climate change have led to a resurgence in the development of alternative energy that can displace fossil transportation fuel. In response, many countries have initiated extensive research and development

programs in biofuels, a sustainable and renewable energy resource that can provide liquid transportation fuels (1). The U.S. Department of Energy Office of the Biomass Program has developed a scenario for supplying 30% of the 2004 motor gasoline demand with biofuels by the year 2030, which roughly translates to a target of 60 billion gallons per year on a British thermal unit-adjusted basis (2, 3). Similarly, the European Union has developed a vision in which one-fourth of the E.U.'s transportation fuels will be derived from biofuels by 2030 (4). These political timetables result in critical challenges to the scientific community that require cutting-

edge tools in the joint venture of systems and synthetic biology (5).

Starch from corn grain and simple sugars from sugar cane and beets are currently being used directly for ethanol fermentation, but to harness the structural sugars contained in plant fibers, we must first overcome the problems caused by biomass recalcitrance. Cellulose processing cannot commence until we improve (i) the relatively slow kinetics of breaking down pure cellulose into sugars, (ii) the low yields of sugars from other plant polysaccharides, and (iii) the removal of lignin, a relatively intractable polymer of phenylpropanoid subunits. It is clear that technological advances must be realized to make biofuels sustainable and cost effective.

In future biorefineries, biofuels will be produced from biomass resources, including corn grains and lignocellulosic biomass (such as agricultural residues, forestry wastes and thinnings, waste paper, and energy crops). Currently in the United States, approximately 455 million acres are in agricultural production to meet our food, feed, and fiber needs (6). A recent report (7) has suggested that in the near term, more than 1.3 billion tons of biomass could be produced annually in the United States on a sustainable basis, mostly from agricultural and forestry sources. Tilman and co-workers (8) have also described the potential role for low-input, high-diversity grassland perennials for bioconversion. Another study (9) has shown that biomass has the potential to simultaneously meet the nation's needs for liquid transportation fuel and for food, feed, and fiber, provided that we develop more advanced technologies and make certain land-use changes that would not require more net

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3. G. Stephanopoulos, J. J. Vallino, *Science* **252**, 1675 (1991).
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5. G. Stephanopoulos, *AIChE J.* **48**, 920 (2002).
6. B. Hahn-Hagerdal, M. Galbe, M. F. Gorwa-Grauslund, G. Lidén, G. Zacchi, *Trends Biotechnol.* **24**, 549 (2006).
7. M. Takagi *et al.*, *Proceedings of the Bioconversion Symposium*, IIT Delhi, p. 551 (1977).
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11. H. Alper, J. Moxley, E. Nevoigt, G. R. Fink, G. Stephanopoulos, *Science* **314**, 1565 (2006).
12. L. O. Ingram *et al.*, *Appl. Environ. Microbiol.* **53**, 2420 (1987).
13. M. Kuyper *et al.*, *FEMS Yeast Res.* **4**, 69 (2003).
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21. R. Patnaik, R. G. Spitzer, J. C. Liao, *Biotechnol. Bioeng.* **46**, 361 (1995).
22. S. J. Sim *et al.*, *Nat. Biotechnol.* **15**, 63 (1997).
23. J. J. Vallino, G. Stephanopoulos, *Biotechnol. Prog.* **10**, 327 (1994).
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25. B. Follstad *et al.*, *Biotechnol. Bioeng.* **63**, 675 (1999).
26. R. D. Kiss, G. Stephanopoulos, *Biotechnol. Prog.* **7**, 501 (1991).
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# Biomass Recalcitrance: Engineering Plants and Enzymes for Biofuels Production

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Lignocellulosic biomass has long been recognized as a potential sustainable source of mixed sugars for fermentation to biofuels and other biomaterials. Several technologies have been developed during the past 80 years that allow this conversion process to occur, and the clear objective now is to make this process cost-competitive in today's markets. Here, we consider the natural resistance of plant cell walls to microbial and enzymatic deconstruction, collectively known as "biomass recalcitrance." It is this property of plants that is largely responsible for the high cost of lignocellulose conversion. To achieve sustainable energy production, it will be necessary to overcome the chemical and structural properties that have evolved in biomass to prevent its disassembly.

High worldwide demand for energy, unstable and uncertain petroleum sources, and concern over global climate change have led to a resurgence in the development of alternative energy that can displace fossil transportation fuel. In response, many countries have initiated extensive research and development

programs in biofuels, a sustainable and renewable energy resource that can provide liquid transportation fuels (1). The U.S. Department of Energy Office of the Biomass Program has developed a scenario for supplying 30% of the 2004 motor gasoline demand with biofuels by the year 2030, which roughly translates to a target of 60 billion gallons per year on a British thermal unit-adjusted basis (2, 3). Similarly, the European Union has developed a vision in which one-fourth of the E.U.'s transportation fuels will be derived from biofuels by 2030 (4). These political timetables result in critical challenges to the scientific community that require cutting-

edge tools in the fields of systems and synthetic biology (5).

Starch from corn grain and simple sugars from sugar cane and beets are currently being used directly for ethanol fermentation, but to harness the structural sugars contained in plant fibers, we must first overcome the problems caused by biomass recalcitrance. Cellulose processing cannot commence until we improve (i) the relatively slow kinetics of breaking down pure cellulose into sugars, (ii) the low yields of sugars from other plant polysaccharides, and (iii) the removal of lignin, a relatively intractable polymer of phenylpropanoid subunits. It is clear that technological advances must be realized to make biofuels sustainable and cost effective.

In future biorefineries, biofuels will be produced from biomass resources, including corn grains and lignocellulosic biomass (such as agricultural residues, forestry wastes and thinnings, waste paper, and energy crops). Currently in the United States, approximately 455 million acres are in agricultural production to meet our food, feed, and fiber needs (6). A recent report (7) has suggested that in the near term, more than 1.3 billion tons of biomass could be produced annually in the United States on a sustainable basis, mostly from agricultural and forestry sources. Tilman and co-workers (8) have also described the potential role for low-input, high-diversity grassland perennials for bioconversion. Another study (9) has shown that biomass has the potential to simultaneously meet the nation's needs for liquid transportation fuel and for food, feed, and fiber, provided that we develop more advanced technologies and make certain land-use changes that would not require more net

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land. The cost-competitive production of biofuels is currently prevented by the high cost of biomass feedstocks and the processes for converting biomass to sugars—that is, the cost of the thermochemical pretreatment and enzyme hydrolysis unit operations in a biorefinery. Maximizing conversion yield is essential for offsetting feedstock cost.

### Biomass Recalcitrance

Plant biomass has evolved complex structural and chemical mechanisms for resisting assault on its structural sugars from the microbial and animal kingdoms (Fig. 1). Natural factors believed to contribute to the recalcitrance of lignocellulosic feedstock to chemicals or enzymes include (i) the epidermal tissue of the plant body, particularly the cuticle and epicuticular waxes; (ii) the arrangement and density of the vascular bundles; (iii) the relative amount of sclerenchymatous (thick wall) tissue; (iv) the degree of lignification (10); (v) the structural heterogeneity and complexity of cell-wall constituents such as microfibrils and matrix polymers (11); (vi) the challenges for enzymes acting on an insoluble substrate (12); and (vii) the inhibitors to subsequent fermentations that exist naturally in cell walls or are generated during conversion processes (13). In the context of the biorefinery, these chemical and structural features of biomass affect liquid penetration and/or enzyme accessibility and activity and, thus, conversion costs.

At the molecular level (Fig. 2), the crystalline cellulose core of cell-wall microfibrils (14) is highly resistant to chemical and biological hydrolysis because of its structure, in which chains of celldextrins are precisely arranged. The chair conformation of the glucose residues in cellulose forces the hydroxyl groups into radial (equatorial) orientation and the aliphatic hydrogen atoms into axial positions. As a result, there is strong interchain hydrogen bonding between adjacent chains in a cellulose sheet and weaker hydrophobic interactions between cellulose sheets. The hydrophobic face of cellulose sheets makes crystalline cellulose resistant to acid hydrolysis because it contributes to the formation of a dense layer of water near the hydrated cellulose surface (15). The strong interchain hydrogen-bonding network makes crystalline cellulose resistant to enzymatic hydrolysis (14), whereas hemicellulose and amorphous cellulose are readily digestible. Higher-order structures in plants also contribute to biomass recalcitrance. For example, access to the crystalline cellulose cores of microfibrils is restricted by a coating of amorphous cellulose and hemicellulose (16). At a microscopic and macroscopic scale, the complex heterogeneous nature of biomass creates mass-transport limitations for delivery of chemical or biochemical catalysts.

### Current Biomass Conversion Technology

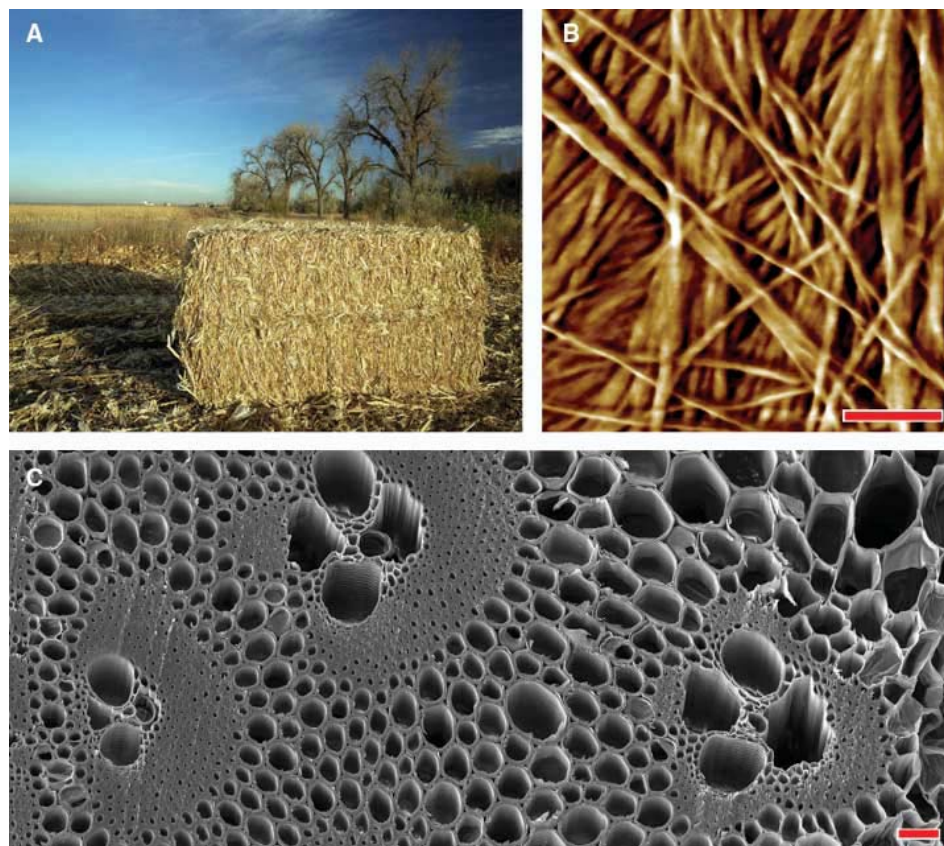
The biorefinery is envisioned to comprise four major sections: feedstock harvest and storage,

thermochemical pretreatment, enzymatic hydrolysis, and sugar fermentation to ethanol or other fuels. Existing biomass conversion schemes typically rely on a combination of chemical and enzymatic treatments. A pretreatment step is usually conducted to reduce recalcitrance by depolymerizing and solubilizing hemicellulose (approximately 20 to 40% weight by weight of biomass). This step converts hemicelluloses to monosaccharides and oligosaccharides, which can be further hydrolyzed or fermented. Removal of hemicellulose from the microfibrils is thought to expose the crystalline cellulose core, which can then be hydrolyzed by cellulase enzymes. In addition, pretreatment typically breaks down the macroscopic rigidity of biomass and decreases the physical barriers to mass transport.

**Pretreatment.** Thermochemical pretreatment of biomass has long been recognized as a critical technology to produce materials with acceptable enzymatic digestibilities. For example, dilute sulfuric acid pretreatment at 140° to 200°C renders the cellulose in cell walls more accessible to saccharifying enzymes. At moderate severities (17), the hemicelluloses are hydrolyzed and the sugars are solubilized as monomers and oligomers; how-

ever, the yields of solubilized sugars are less than quantitative (i.e., 60 to 70%) (18). For the acid treatments, release of mono- and oligomeric sugars from hemicellulose exhibits multimodal kinetics in which a slow component directly relates to the high cost of conversion (19, 20). For example, a number of researchers (20–25) have noted that the solubilization of xylan in hemicellulose appears to be best modeled as a pair of parallel first-order reactions: one that takes place at a fast rate and another that progresses at a much slower rate.

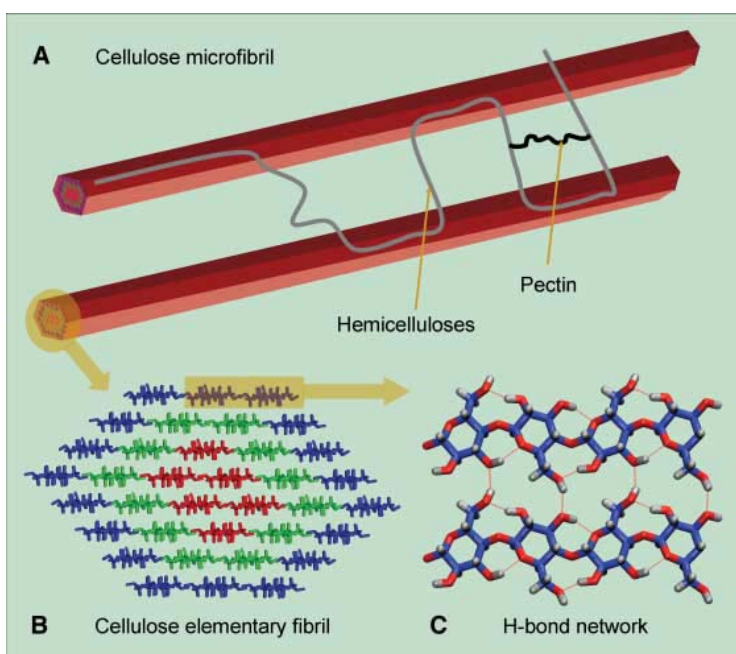
What governs this result is not clear at this time, and it may depend on a number of factors, such as hemicellulose composition; biomass density; the presence of nonsugar components (such as lignin, acid neutralizing ash, and acetyl and other carboxylic acid groups); plant cell structure (including the types of cells or ratios of primary and secondary cell walls); or mass transport. Pretreatment schemes based on alkaline explosive decomposition and organic solvent extractions have been proposed with considerable success (13). The alkaline process, known as ammonia fiber expansion (AFEX), leaves the hemicellulose in place but renders the remaining cell walls considerably more amenable to enzyme hydrolysis (26).



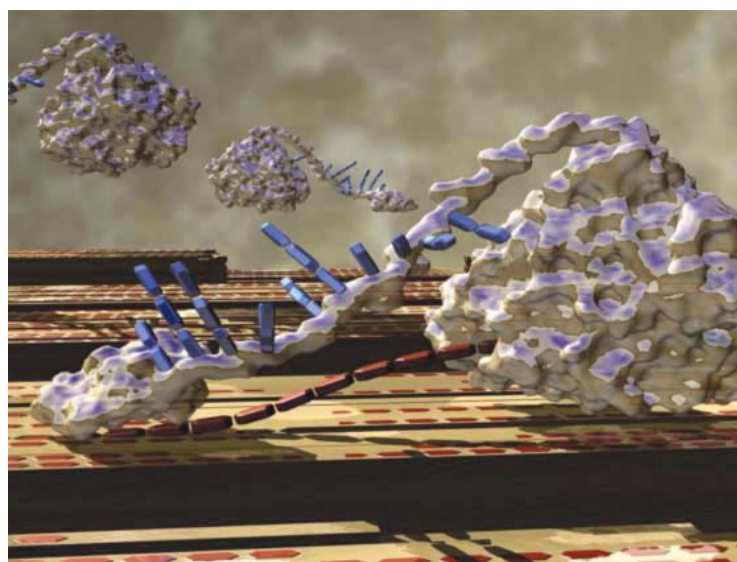
**Fig. 1.** Structural and chemical complexity of cell-wall biomass. (A) Example of high-density bales of corn stover harvested on the eastern plains of northern Colorado. (B) An atomic force micrograph of the maize parenchyma cell-wall surface. The diameter of individual microfibril is only about 3 to 5 nm. Scale bar, 50 nm. (C) A scanning electron micrograph of the cross-section of a maize stem shows vascular bundles and pith tissues, as well as the diverse cell sizes, shapes, and cell-wall thicknesses typical for higher-plant structure. Scale bar, 50  $\mu$ m.

**Enzymatic degradation.** In nature, various cellulolytic microorganisms produce enzymes that function synergistically and associate with the microorganism [such as the cellulosome (27, 28)] or act independently (such as most fungal and many bacterial cellulases) (29). Although it is not fully known how many enzymes are involved in cell-wall deconstruction, three general categories of enzymes are considered necessary to hydrolyze native cell-wall materials: cellulases, hemicellulases, and the accessory enzymes, which include hemicellulose debranching, phenolic acid esterase, and possibly lignin degrading and modifying enzymes (29). Once the hemicellulose barrier associated with cell-wall microfibrils has been compromised by chemical pretreatments, cellulase enzymes can be used to hydrolyze the crystalline cellulose cores of these structures.

Crystalline cellulose is hydrolyzed by the synergistic action of endo-acting (with respect to the cellulose chain) enzymes known as endoglucanases, and exo-acting enzymes, known as exoglucanases. The endoglucanases locate surface sites at locations, probably found at random, along the cellodextrin and insert a water molecule in the  $\beta$ -(1,4) bond, creating a new reducing and non-reducing chain end pair.  $\beta$ -D-glucosidases (cellobiases) act to hydrolyze cellobiose, the product of cellulase action, and thus relieve the system from end-product inhibition. Cellulases and other glycosyl hydrolases (30) are known to proceed through a two-step, Koshland-type mechanism that leaves the terminal C1 carbon hydroxyl in the  $\beta$  configuration (retention of stereochemistry) or a concerted reaction mechanism that leaves the terminal hydroxyl in the  $\alpha$  configuration (inversion of stereochemistry) (31). Water molecules could invade the space under the nonreducing chain end and thus prevent it from reannealing into the cellulose crystal. The removal of cellodextrins from the microfibril core is thought to occur at these new chain ends and this



**Fig. 2.** (A) A simplified model showing the interaction of the major polysaccharides in the cell wall. (Lignin is not shown here because its interactions are not well established.) In this system, hemicelluloses are closely associated to the surface of the rigid cellulose crystallite forming the microfibril network. Pectins are cross-linked polysaccharides forming a hydrated gel that “glues” the cell-wall components together. (B) The 36-chain model of the cellulose elementary fibril. Here, the depiction of the glucan chains is based generally on an x-ray structure of cellulose I $\beta$  (39). It has been proposed (16) that the cellulose elementary fibril may contain three groups of glucan chains: in group C1 (red) are six true crystalline chains; in group C2 (green) are 12 subcrystalline chains with a small degree of disorder; and in group C3 (blue) are 18 surface chains that are subcrystalline with a large degree of disorder. (C) The intra- and interchain hydrogen-bond network in cellulose I $\beta$ .



**Fig. 3.** Artistic concept of an exoglucanase (the *T. reesei* cellobiohydrolase I) acting on crystalline cellulose. In this depiction, the carbohydrate-binding module (left) recognizes and binds to the cellulose surface. By a process not fully understood, a single chain of cellulose is “decrySTALLIZED” and directed into the active-site tunnel of the catalytic domain (right). This enzyme is thought to proceed along a cellulose chain cleaving one cellobiose unit per catalytic event until the chain ends or the enzyme becomes inactivated (40, 41).

process, considered to be the rate-limiting step in cellulase action, is accomplished by exoglucanases also known as the “processive” cellulases.

## Overcoming Biomass Recalcitrance

Current biomass-conversion technologies are primarily developed empirically, based on limited understanding of the biological and chemical properties of biomass. Recent studies of plant development, carbohydrate chemistry, and the ultrastructure of cell walls continue to provide new insights into biomass conversion. To reach the goal of producing cost-competitive biofuels from biomass, these new findings from plant science and carbohydrate chemistry must be translated and integrated into the conversion processes. Further studies will undoubtedly rely on, for example, the development of new techniques for imaging and characterizing the chemical topography of the cell wall at the nanometer scale. The future of research aimed at overcoming biomass recalcitrance will primarily focus on the coengineering of new cell walls to be degraded by newly engineered enzymes designed for this role.

**Plants designed for deconstruction.** Recent studies of plant cell-wall biosynthesis are beginning to provide new understanding about the structure and chemistry of the plant cell wall (10). Although much of our knowledge is anecdotal, the cell walls of higher plants are viewed as an assembly of biopolymers, in some ways mimicking a “liquid crystal,” synthesized by pathways with as-yet undetermined controls (10, 32). For example, cellulose is synthesized and assembled on plasma membrane, whereas hemicelluloses are synthesized in the Golgi apparatus.

Despite our lack of detailed knowledge regarding cell-wall structure, research during the past 20 years, largely reductionist in approach, has led to a body of information regarding treatments of the cell wall that are effective for enhancing enzyme action. Studies have shown that systematic removal of hemicelluloses, by either acidic or enzymatic processes, results in the marked reduction in cellulase loadings required to convert cellulose

to cellobiose or glucose (33, 34). Other studies have shown that a reduction in phenolic esters, such as those characteristic of the linkages between lignins and hemicellulose, also permit a reduction in cellulase loadings (11). It has been theorized, therefore, that engineering plant cell walls by altering the molecular interactions between hemicelluloses, lignin, and cellulose microfibrils could result in more efficient use of costly cellulase enzymes. Finally, of considerably greater potential benefit, and accordingly greater difficulty, is the possibility of changing the nature of cellulose itself. Could the cellulose synthase complex be altered to produce "wounded" (in terms of either degree of crystallization or polymerization) cellulose more amenable to deconstruction? Would such a plant survive and thrive?

Another scale of effective engineering of plant cells and structure may be at the level of the organization of plant tissues. For example, because of the high economic and energetic costs of grinding, biomass-processing biorefineries would ideally be capable of using feedstocks in the 1- to 15-centimeter fragment range (18). This requires that catalyst (chemical and enzyme) penetration throughout the material be optimal. Diffusion of dissolved solids and water throughout plant tissue is controlled by the arrangement of vascular bundles, as well as pits between connecting cell walls. Therefore, another approach, one aimed at enhancing the penetration of pretreatment chemicals and hydrolytic enzymes, could be genetic engineering of the organization of vascular bundles and cell-wall pit density. Again, the concerns regarding plant survivability and vigor can be raised with such an approach.

*Engineering catalysts and bioconversion systems.* In many ways, processive cellulases are "protein machines" (Fig. 3); however, cellulase enzymes function about one to two orders of magnitude more slowly than other polysaccharidases (35). Unfortunately, the enzymatic decrystallization process is both critical and poorly understood, and thus considerable research is needed to enhance the performance of cellulase action. Efforts to improve the performance of cellulases primarily follow two courses: (i) mining diversity to find new enzyme paradigms, and (ii) knowledge-based protein engineering. For the latter approach to be effective, the mechanism of action of these enzymes in the context of the cellulose surface must be understood at the molecular level. Although attempts have been made to adapt directed evolution solutions to the problem of cellulase-specific activity improvement, limitations in effective high-throughput strategies and appropriate expression systems have slowed progress (12).

Future process scenarios have been proposed that combine key process steps, thus reducing overall process complexity and cost. One notable example is the consolidated biomass processing (CBP) technology (36). The CBP concept was probably initiated with the advent of the simulta-

neous saccharification and fermentation (SSF) scheme used by Gauss in a process developed for Gulf Oil (37). More recently, thoughts about combining SSF with enzyme production have resulted in new approaches to CBP, which could either require engineering an ethanologen (such as *Saccharomyces cerevisiae*) to be cellulolytic or engineering a cellulase producer (such as *Clostridium thermocellum*) to be ethanogenic. For the *C. thermocellum* case, the bioenergetic benefits specific to growth on cellulose result from the efficiency of oligosaccharide uptake combined with intracellular phosphorylytic cleavage of  $\beta$ -glucosidic bonds, another pathway not known in fungi. Scientists believe that these benefits exceed the bioenergetic cost of cellulase synthesis, supporting the feasibility of anaerobic processing of cellulosic biomass without added saccharolytic enzymes (38).

### Outlook for an Advanced Biorefinery Industry

Ultimately, biomass conversion processes are attractive because they are in practice today and extension to future scenarios is easy for the public to envision. Although developing the technology for cost-effective motor fuel production by 2030 is challenging, the advances in scientific understanding necessary to achieve this goal appear realizable. The general path forward along the biological fuels production route will generally rely on consolidation of processing steps, both in the engineering and biological sense. Microbial cells will be expected to conduct multiple conversion reactions with high efficiency and to remain robust to process conditions. These improvements require deeper understanding of cellular and metabolic processes. New generations of hydrolytic enzymes will function near their theoretical limits, and energy plants will be modified to serve as improved substrates for these new generation enzymes. Indeed, it is entirely possible that the next generation of energy plants will harbor the genes encoding enzymes necessary for self-deconstruction, activated before harvest or at the normal conclusion of the growth cycle.

### References and Notes

1. A. P. C. Faaij, *Energy Policy* **34**, 322 (2006).
2. U.S. Department of Energy, Office of the Biomass Program, 30 x 30 Workshop, Washington, DC, 1 to 2 August, 2006 ([www.30x30workshop.biomass.govtools.us](http://www.30x30workshop.biomass.govtools.us)).
3. Office of the Biomass Program (OBP), "Multi-Year Program Plan, 2007-2012" (OBP, U.S. Department of Energy, Washington, DC, 2005) (<http://www1.eere.energy.gov/biomass/pdfs/mypp.pdf>).
4. Biofuels Research Advisory Council, "Biofuels in the European Union: A Vision for 2030 and Beyond" (2006); available online ([www.biomatnet.org/publications/1919rep.pdf](http://www.biomatnet.org/publications/1919rep.pdf)).
5. J. Houghton, S. Weatherwax, J. Ferrell, "Breaking the Biological Barriers to Cellulosic Ethanol: A Joint Research Agenda," Biomass to Biofuels, Rockville, MD, 7 to 9 December 2005 (to order the report, see <http://genomicsgtl.energy.gov/biofuels/b2bworkshop.shtml#orderform>).
6. U.S. Department of Agriculture-National Resource Conservation Service, National Resources Inventory: 2001

- Annual NRI (NRCS, USDA, Washington, DC, 2003) ([www.nrcs.usda.gov/technical/land/nri01/nri01lu.html](http://www.nrcs.usda.gov/technical/land/nri01/nri01lu.html)).
7. R. D. Perlack *et al.*, "Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply" (Oak Ridge National Laboratory Report TM-2005, under contract DOE/GO-102005-2135, Oak Ridge, TN, (2005).
8. D. Tilman, J. Hill, C. Lehman, *Science* **314**, 1598 (2006).
9. S. Nonhebel, *Renew. Sustain. Energy Rev.* **9**, 191 (2005).
10. D. J. Cosgrove, *Nat. Rev. Mol. Cell Biol.* **6**, 850 (2005).
11. K. Iiyama, T. B. T. Lam, B. A. Stone, *Plant Physiol.* **104**, 315 (1994).
12. M. E. Himmel, M. F. Ruth, C. E. Wyman, *Curr. Opin. Biotechnol.* **10**, 358 (1999).
13. C. E. Wyman *et al.*, *Bioresour. Technol.* **96**, 1959 (2005).
14. Y. Nishiyama, P. Langan, H. Chanzy, *J. Am. Chem. Soc.* **124**, 9074 (2002).
15. J. F. Matthews *et al.*, *Carbohydr. Res.* **341**, 138 (2006).
16. S. Y. Ding, M. E. Himmel, *J. Agric. Food Chem.* **54**, 597 (2006).
17. Pretreatment severity is defined as the combined effect of temperature, acidity, and duration of treatment. Hot-water pretreatments, which actually use acetic acid liberated from cell-wall hemicellulose, represent the lowest degree of severity.
18. R. Torget, M. E. Himmel, K. Grohmann, *Bioresour. Technol.* **35**, 239 (1991).
19. C. G. Liu, C. E. Wyman, *Ind. Eng. Chem. Res.* **43**, 2781 (2004).
20. A. Esteghlalian, A. G. Hashimoto, J. J. Fenske, M. H. Penner, *Bioresour. Technol.* **59**, 129 (1997).
21. M. Shiang, J. C. Linden, A. Mohagheghi, K. Grohmann, M. E. Himmel, *Biotechnol. Prog.* **7**, 315 (1991).
22. S. B. Kim, Y. Y. Lee, *Biotechnol. Bioeng. Symp.* **17**, 71 (1987).
23. M. T. Maloney, T. W. Chapman, A. J. Baker, *Biotechnol. Bioeng.* **27**, 355 (1985).
24. O. Mayans *et al.*, *Structure* **5**, 677 (1997).
25. Y. Sun *et al.*, *Bioresour. Technol.*, in press.
26. F. Teymouri, L. Laureano-Perez, H. Alizadeh, B. E. Dale, *Bioresour. Technol.* **96**, 2014 (2005).
27. E. A. Bayer, J. P. Belaich, Y. Shoham, R. Lamed, *Annu. Rev. Microbiol.* **58**, 521 (2004).
28. E. A. Bayer, L. J. W. Shimon, Y. Shoham, R. Lamed, *J. Struct. Biol.* **124**, 221 (1998).
29. M. E. Himmel *et al.*, in *Fuels and Chemicals from Biomass*, B. C. Saha, J. Woodward, Eds., vol. 666 of *American Chemical Society Symposium Series* (ACS, Washington, DC, 1997), pp. 2-45.
30. CAZY (Carbohydrate Active Enzymes) is a database for the families of structurally related catalytic and carbohydrate-binding modules of enzymes that degrade, modify, or create glycosidic bonds. The database is available online ([www.cazy.org/CAZY/](http://www.cazy.org/CAZY/)).
31. D. E. Koshland, *Biol. Rev.* **28**, 416 (1953).
32. M. S. Doblin, I. Kurek, D. Jacob-Wilk, D. P. Delmer, *Plant Cell Physiol.* **43**, 1407 (2002).
33. R. Torget, M. Himmel, K. Grohmann, *Appl. Biochem. Biotechnol.* **34/35**, 115 (1992).
34. B. Yang, C. E. Wyman, *Biotechnol. Bioeng.* **86**, 88 (2004).
35. K. Kipper, P. Valjamae, G. Johansson, *Biochem. J.* **385**, 527 (2005).
36. L. R. Lynd, P. J. Weimer, W. H. van Zyl, I. S. Pretorius, *Microbiol. Mol. Biol. Rev.* **66**, 506 (2002).
37. W. Gauss, U.S. Patent 3, 990, 9444 (1976).
38. Y. Lu, Y. H. P. Zhang, L. R. Lynd, *Proc. Natl. Acad. Sci. U.S.A.* **103**, 16165 (2006).
39. Y. Nishiyama, J. Sugiyama, H. Chanzy, P. Langan, *J. Am. Chem. Soc.* **125**, 14300 (2003).
40. J. Rouvinen, T. Bergfors, T. Teeri, J. K. C. Knowles, T. A. Jones, *Science* **249**, 380 (1999).
41. M. Vrsanska, P. Biely, *Carbohydr. Res.* **227**, 19 (1992).
42. We acknowledge the support of the U.S. Department of Energy Office of the Biomass Program. We also thank W. Gretz for providing the picture shown in Fig. 1A, T. Vinzant for providing the image shown in Fig. 1B, and D. Seely at Pixel Kitchen for providing the image shown in Fig. 3.

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## PERSPECTIVE

# Ethanol for a Sustainable Energy Future

José Goldemberg\*

Renewable energy is one of the most efficient ways to achieve sustainable development. Increasing its share in the world matrix will help prolong the existence of fossil fuel reserves, address the threats posed by climate change, and enable better security of the energy supply on a global scale. Most of the “new renewable energy sources” are still undergoing large-scale commercial development, but some technologies are already well established. These include Brazilian sugarcane ethanol, which, after 30 years of production, is a global energy commodity that is fully competitive with motor gasoline and appropriate for replication in many countries.

A sustainable energy future depends on an increased share of renewable energy, especially in developing countries. One of the best ways to achieve such a goal is by replicating the large Brazilian program of sugarcane ethanol, started in the 1970s.

The World Commission on Environment and Development (WCED) in 1987 defined “sustainable development” as development that “meets the needs of the present without compromising the ability of future generations to meet their own needs” (1). The elusiveness of such a definition has led to unending discussions among social scientists regarding the meaning of “future generations.”

However, in the case of energy, exhaustible fossil fuels represent ~80% of the total world energy supply. At constant production and consumption, the presently known reserves of oil will last around 41 years, natural gas 64 years, and coal 155 years (2). Although very simplified, such an analysis illustrates why fossil fuels cannot be considered as the world’s main source of energy for more than one or two generations. Besides the issue of depletion, fossil fuel use presents serious environmental problems, particularly global warming. Also, their production costs will increase as reserves approach exhaustion and as more expensive technologies are used to explore and extract less attractive resources. Finally, there are increasing concerns for the security of the oil supply, originating mainly from politically unstable regions of the world.

Except for nuclear energy, the most likely alternatives to fossil fuels are renewable sources such as hydroelectric, biomass, wind, solar, geothermal, and marine tidal. Figure 1 shows the present world energy use.

Fossil fuels (oil, coal, and gas) represent 80.1% of the total world energy supply, nuclear energy

6.3%, and renewables 13.6%. The largest part is traditional biomass (8.5% of total primary energy), which is used mainly in inefficient ways, such as in highly pollutant primitive cooking stoves used by poor rural populations, leading in many cases to deforestation.

The “new renewable energy sources” amount to 16 exajoules (1 EJ =  $10^{18}$  J), or 3.4% of the total. Table 1 shows a breakdown of the contribution of new renewables, which include small hydropower plants. Many of these technologies are still undergoing large-scale commercial development, including solar, wind, geothermal, and modern biomass. The largest part (1.9% of the total) is modern biomass, which refers to biomass produced in a sustainable way and used for electricity generation, heat production, and transportation of liquid fuels. It includes wood and forest residues from reforestation and/or sustainable management, as well as rural (animal and agricultural) and urban residues (including solid waste and liquid effluents).

From the perspective of sustainable energy development, renewables are widely available, ensuring greater security of the energy supply

and reducing dependence on oil imports from politically unstable regions. Renewables are less polluting, both in terms of local emissions (such as particulates, sulfur, and lead) and greenhouse gases (carbon dioxide and methane) that cause global warming. They are also more labor-intensive, requiring more workforce per unit of energy than conventional fossil fuels (3).

Although technologically mature, some of the renewable sources of energy are more expensive than energy produced from fossil fuels. This is particularly the case for the “new renewables.” Traditional biomass is frequently not the object of commercial transactions and it is difficult to evaluate its costs, except the environmental ones. Cost continues to be the fundamental barrier to widespread adoption of traditional biomass despite its attractiveness from a sustainability perspective.

A number of strategies have been adopted by governments in the industrialized countries and international financial institutions to encourage the use of “new renewables,” and there have been several successes, based on the use of tax breaks, subsidies, and renewable portfolio standards (RPS). Examples are the large growth (of more than 35% per year, “albeit” from a low base value) for wind and solar photovoltaics in industrialized countries such as Denmark, Germany, Spain, and the United States (4). These technologies are slowly spreading to developing countries through several strategies.

In developing countries, the best example of a large growth in the use of renewables is given by the sugarcane ethanol program in Brazil. Today, ethanol production from sugarcane in the country is 16 billion liters (4.2 billion gallons) per year, requiring around 3 million hectares of land. The competition for land use between food and fuel has not been substantial: Sugarcane covers 10% of total cultivated land and 1% of total land available for agriculture in the country. Total sugarcane crop area (for sugar and ethanol) is 5.6 million hectares.

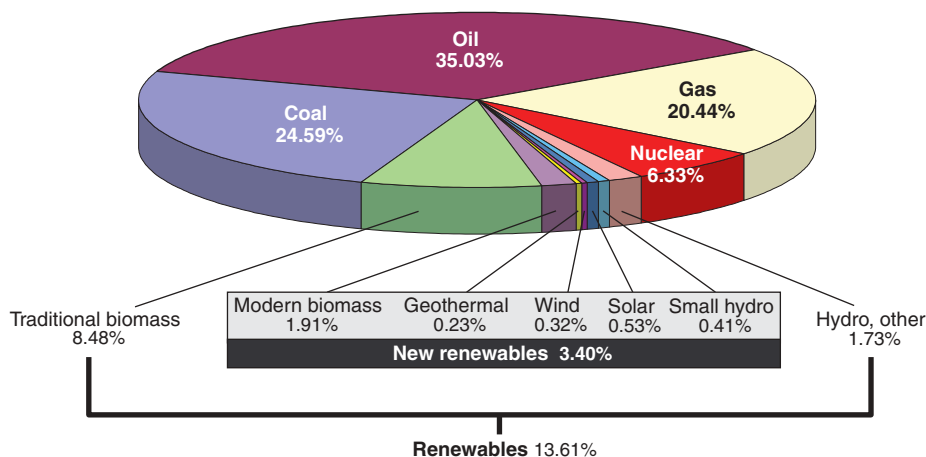


Fig. 1. World total primary energy supply 2004, shares of 11.2 billion tons of oil equivalent, or 470 EJ (15, 16).

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Production of ethanol from sugarcane can be replicated in other countries without serious damage to natural ecosystems. Worldwide, some 20 million hectares are used for growing sugarcane, mostly for sugar production (5). A simple calculation shows that expanding the Brazilian ethanol program by a factor of 10 (i.e., an additional 30 million hectares of sugarcane in Brazil and in other countries) would supply enough ethanol to replace 10% of the gasoline used in the world. This land area is a small fraction of the more than 1 billion hectares of primary crops already harvested on the planet.

What was the process that established firmly the ethanol program in Brazil? In the late 1970s, the Brazilian Federal Government mandated the mixture of anhydrous ethanol in gasoline (blends up to 25%) and encouraged car makers to produce engines running on pure hydrated ethanol (100%). Brazilian adoption of mandatory regulations determining the amount of ethanol to be mixed with gasoline (basically a Renewable Portfolio Standard for fuel) was essential to the success of the program. The motivation was to reduce oil imports that were

consuming one-half of the total amount of hard currency from exports. Although it was a decision made by the federal government during a military regime, it was well accepted by the civil society, agricultural sector, and car manufacturers. Similar policies are being considered by the European Union, Japan, and several states in the United States.

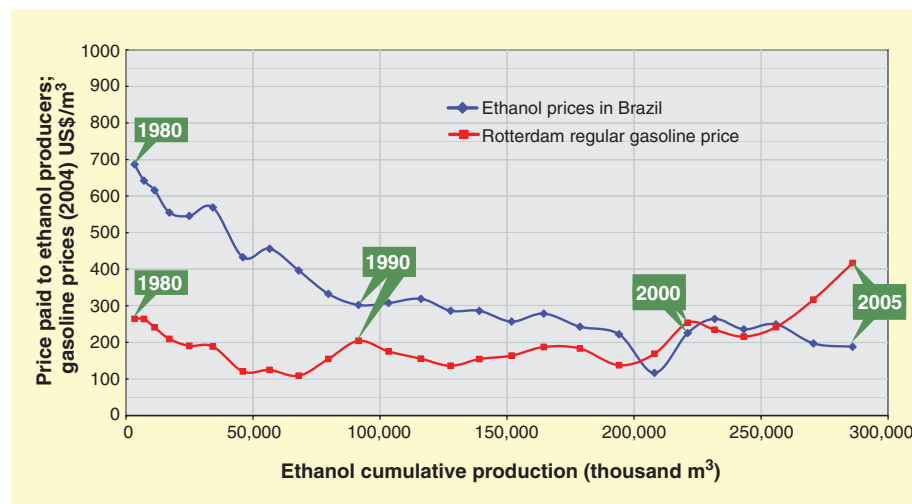
Such a policy decision created a market for ethanol, and production increased rapidly. Ethanol costs declined along a “learning curve” (6) as production increased an average 6% per year, from 0.9 billion gallons in 1980 to 3.0 billion gallons in 1990 and to 4.2 billion gallons in 2006. The cost of ethanol in 1980 was approximately three times the cost of gasoline, but governmental cross-subsidies paid for the price difference at the pump. The subsidies came mostly from taxes on gasoline and were thus paid by automobile drivers. All fuel prices were controlled by the government. Overall subsidies to ethanol are estimated to be around US\$30 billion over 20 years (7), but were more than offset by a US\$50 billion reduction of petroleum imports as of the end of 2006. Since the 1990s subsidies have been progressively removed, and

by 2004 ethanol became fully competitive with gasoline on the international markets without government intervention. Subsidies for ethanol production are a thing of the past in Brazil (Fig. 2), because new ethanol plants benefit from the economies of scale and the modern technology available today, such as the use of high-pressure boilers that allow co-generation of electricity, with surpluses sold to the electric power grid.

The Brazilian ethanol program started as a way to reduce the reliance on oil imports, but it was soon realized that it had important environmental and social benefits (8). Conversion to ethanol allowed the phasing-out of lead additives and MTBE (methyl tertiary butyl ether) and reduced sulfur, particulate matter, and carbon monoxide emissions. It helped mitigate greenhouse gas emissions efficiently, by having a net positive energy balance (renewable energy output versus fossil fuel inputs); also, sugarcane ethanol in Brazil costs less than other present technologies for ethanol production (Table 2) and is competitive with gasoline in the United States, even considering the import duty of US\$0.54 per gallon and energy-efficiency penal-

**Table 1.** “New renewables,” by source in 2004 (15); updated with data from (4, 16). Assumed average conversion efficiency: for biomass heat, 85%; biomass electricity, 22%; biomass combined heat and power (CHP), 80%; geothermal electricity, 10%; all others, 100%.

Source/ technology	2004	
	Exajoules (EJ)	Share in this sector
<i>Modern biomass energy</i>		
Total	9.01	56.19%
Bioethanol	0.67	
Biodiesel	0.07	
Electricity	1.33	
Heat	6.94	
<i>Geothermal energy</i>		
Total	1.09	6.77%
Electricity	0.28	
Heat	0.30	
<i>Small hydropower</i>		
Total	1.92	12.00%
<i>Wind electricity</i>		
Total	1.50	9.35%
<i>Solar</i>		
Total	2.50	15.63%
Hot water	2.37	
Photovoltaic	0.06	
electricity, grid		
Photovoltaic	0.06	
electricity, off-grid		
Thermal electricity	0.01	
<i>Marine energy (tidal)</i>		
Total	0.01	
Total	16.03	100.00%



**Fig. 2.** Ethanol learning curve in volume, comparing the price paid to ethanol producers in Brazil with the price of gasoline in the international market of Rotterdam (6).

**Table 2.** Ethanol costs and energy balances.

Feedstock	Cost (US\$ per gallon)	Energy balance (renewable output to fossil input)
Sugarcane, Brazil		10.2 (18)
2006, without import tax	0.81 (17)	
2006, with U.S. import tax	1.35 (9, 17)	
Sugar beet, Europe, 2003	2.89 (17)	2.1 (19)
Corn, U.S., 2006	1.03 (17)	1.4 (9, 11)
Cellulose ethanol, U.S.		10.0 (11)
Achieved in 2006	2.25 (11)	
Target for 2012	1.07 (11)	

ties (30% or less with modern flexible fuel vehicle technologies) (9). The summer wholesale price of gasoline in the United States is about \$1.9 per gallon; the corn ethanol wholesale price is around US\$2.5 per gallon (10). Cellulose ethanol is a promising option in the long term, but is not being produced on a commercial scale. The longer-term target is as low as 60 cents per gallon, but this will require major advances in producing, collecting, and converting biomass. A more realistic research target is to reduce the cost of production to US\$1.07 per gallon until 2012 (11).

The development of other biomass-derived fuels in Brazil or elsewhere could benefit from such insights. Promising candidates along those lines are the following:

1) The production of ethanol from cellulose materials, which still requires considerable R&D effort before reaching the production stage. If the technology for such conversion is firmly established, it would open enormous opportunities for the use of all kinds of wood and other biomass feedstocks for ethanol production.

2) The enhanced use of biogas produced from microbial conversion in landfills of municipal solid wastes, wastewater, industrial effluents, and manure wastes will abate a considerable share of greenhouse gases that would be released to the atmosphere, replacing also fossil fuels for heat and electricity production.

3) The use of planted forests for the production of electricity either by direct combustion or by gasification and use of highly efficient gas turbines will also replace efficiently coal, natural gas, oil, and even nuclear sources. Reforested wood can also reduce the need for deforested fuel wood, controlling efficiently releases of greenhouse gases through market-friendly initiatives.

The ethanol program in Brazil was based on indigenous technology (both in the industrial and agricultural areas) and, in contrast to wind and solar photovoltaics, does not depend on imports, and the technology can be transferred to other developing countries.

Until breakthrough technologies become commercially viable, an alternative already exists: Many developing countries have suitable conditions to expand and replicate the Brazilian sugarcane program, supplying the world's gasoline motor vehicles with a renewable, efficient fuel.

## References and Notes

1. United Nations, Report of the World Commission on Environment and Development, United Nations General Assembly, 96th plenary meeting, 11 December 1987, Document A/RES/42/187; available at [www.un.org/documents/ga/res/42/ares42-187.htm](http://www.un.org/documents/ga/res/42/ares42-187.htm).
2. British Petroleum, BP Statistical Review of World Energy; available at [www.bp.com/liveassets/bp\\_internet/globalbp/globalbp\\_uk\\_english/publications/energy\\_reviews\\_2006/STAGING/local\\_assets/downloads/spreadsheets/statistical\\_review\\_full\\_report\\_workbook\\_2006.xls](http://www.bp.com/liveassets/bp_internet/globalbp/globalbp_uk_english/publications/energy_reviews_2006/STAGING/local_assets/downloads/spreadsheets/statistical_review_full_report_workbook_2006.xls).
3. J. Goldemberg, "The case for renewable energies" (background paper for the International Conference for Renewable Energies, Bonn 2004); available at [www.renewables2004.de/pdf/tbp/TBP01-rationale.pdf](http://www.renewables2004.de/pdf/tbp/TBP01-rationale.pdf). On jobs see also (12).
4. REN21, Global Status Report 2006 Update (Renewable Energy Policy Network for the 21st Century, 2006); available at [www.ren21.net/pdf/RE\\_GSR\\_2006\\_Update.pdf](http://www.ren21.net/pdf/RE_GSR_2006_Update.pdf).
5. FAO, FAOSTAT (United Nations Food and Agriculture Organization, 2006); available at <http://faostat.fao.org/default.aspx>.
6. J. Goldemberg, S. T. Coelho, O. Lucon, P. M. Nastari, *Biomass Bioenergy* **26**, 301 (2004).
7. J. Goldemberg, S. T. Coelho, O. Lucon, *Energy Policy* **32**, 1141 (2004).
8. J. G. Da Silva, G. E. Serra, J. R. Moreira, J. C. Gonçalves, J. Goldemberg, *Science* **201**, 903 (1978).
9. S. T. Coelho, J. Goldemberg, O. Lucon, P. Guardabassi, *Development* **10**, 26 (2006). On ethanol duties see also (13).

10. J. R. Healey, "Ethanol shortage could up gas prices," *USA Today*, 30 March 2006; available at [www.usatoday.com/money/industries/energy/2006-03-30-ethanol-gas-prices\\_x.htm](http://www.usatoday.com/money/industries/energy/2006-03-30-ethanol-gas-prices_x.htm).
11. M. Pacheco, U.S. Senate Full Committee Hearing—Renewable Fuel Standards (National Renewable Energy Laboratory, National Bioenergy Center, 19 June 2006); available at [http://energy.senate.gov/public/index.cfm?lsPrint=true&FuseAction=Hearings.Testimony&Hearing\\_ID=1565&Witness\\_ID=4427](http://energy.senate.gov/public/index.cfm?lsPrint=true&FuseAction=Hearings.Testimony&Hearing_ID=1565&Witness_ID=4427). On corn ethanol, see also (14).
12. World Bank, "How the World Bank's energy framework sells the climate and poor people short" (World Bank, September 2006); available at [www.nirs.org/climate/background/energyreportfinal91806.pdf](http://www.nirs.org/climate/background/energyreportfinal91806.pdf).
13. A. Elobeid, S. Tokgoz, Removal of U.S. Ethanol Domestic and Trade Distortions: Impact on U.S. and Brazilian Ethanol Markets (Working Paper 06-WP 427 October 2006); available at [www.card.iastate.edu/publications/DBS/PDFFiles/06wp427.pdf](http://www.card.iastate.edu/publications/DBS/PDFFiles/06wp427.pdf).
14. U.S. Department of Agriculture, Estimating the Net Energy Balance of Corn Ethanol, H. Shapouri, J. A. Duffield, M. S. Graboski (U.S. Department of Agriculture, Economic Research Service, Office of Energy, Agricultural Economic Report No. 721); available at [www.ers.usda.gov/publications/aer721/AER721.PDF](http://www.ers.usda.gov/publications/aer721/AER721.PDF).
15. UNDP, UNDESA, WEC, World Energy Assessment Overview 2004 Update (United Nations Development Program, United Nations Department of Economic and Social Affairs, World Energy Council, 2005); available at [www.undp.org/energy/weaover2004.htm](http://www.undp.org/energy/weaover2004.htm).
16. IEA, Key World Energy Statistics (International Energy Agency, 2006); available at [www.iea.org/w/bookshop/add.aspx?id=144..](http://www.iea.org/w/bookshop/add.aspx?id=144..)
17. USDA, *The Economic Feasibility of Ethanol Production from Sugar in the United States* (United States Department of Agriculture, 2006).
18. I. C. Macedo, "Greenhouse gas emissions and energy balances in bio-ethanol production and use in Brazil"; available at [www.unica.com.br/i\\_pages/files/gee3.pdf](http://www.unica.com.br/i_pages/files/gee3.pdf).
19. J. Woods, A. Bauen, "Technology status review and carbon abatement potential of renewable transport fuels in the UK" (United Kingdom Department of Transport and Industry Report B/U2/00785/REP URN 03/982); available at [www.dti.gov.uk/files/file15003.pdf](http://www.dti.gov.uk/files/file15003.pdf).
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## PERSPECTIVE

# Renewable Energy Sources and the Realities of Setting an Energy Agenda

Janez Potočník

The European Commission has been devoting considerable attention to energy issues. This Perspective describes recent progress in Europe toward achieving goals for renewable energy use, and the role that technology can play, as well as the new Strategic Energy Package.

Energy is undoubtedly moving up the political agenda as an issue that needs to be addressed urgently. If last year's threats to European gas supplies during the dispute between Russia and Ukraine did not show the

immediacy of the challenges such as energy supply, then the report toward the end of last year by Sir Nicholas Stern (1) on the economics of climate change must surely have rung a warning bell.

The European Commission has been devoting considerable attention to energy issues for some time now. We were leaders in the process that brought about the Kyoto Protocol and have developed the first large-scale emissions trading scheme in the world. In March 2006, we published a Green Paper on energy (2), which we have now, at the beginning of 2007, followed up with a strategic energy package (3) addressing energy policy in general and also outlining future European policy on various specific elements.

One of these specific elements will be the elaboration at the European level of a Strategic Energy Technology Plan (4). Research and technology will undoubtedly be crucial to cracking the energy and climate change nut. A recent study published by the European Commission (Fig. 1) (5) shows that, if existing trends

European Commission, 1049 Bruxelles, Belgium.

continue, by 2050 CO<sub>2</sub> emissions will be unsustainably high: 900 to 1000 parts per million by volume, that is, well above what is considered an acceptable range for stabilization. Without determined action, energy demand will double and electricity demand will quadruple, resulting in an 80% increase in CO<sub>2</sub> emissions. However, technological development coupled with strong carbon constraint policies can limit this impact, with world emissions stable between 2015 and 2030 and decreasing thereafter. In this “carbon constraint” case, half of the total building stock would be made of low-energy buildings, and more than half of the vehicles would have low or very low emissions, a clear example of how technological development will contribute to our energy and environmental policy objectives.

The strategic energy package sets a target of 20% of Europe's energy coming from renewable sources by 2020. If successful, this would mean that by 2020 the European Union (EU) would use about 13% less energy than today, saving €100 billion and around 780 metric tons of CO<sub>2</sub> each year. For this to be realistic, significant strides need to be made, technologically speaking. Today renewable energy is on the whole costly and intermittent. Even if we are looking to maintain a mix of sources of energy, a cloudy windless day rules out generation from solar and wind power. And yet, on a bright windy day, energy may go unused, because it cannot be stored easily. Reliability and continuity are basic requirements if renewable sources of energy are to be seen as viable alternatives to oil, gas, and coal. Research and technological development are already bringing us closer to solutions in this field, through

improving fuel cells or redesigning electricity grids to deal with more decentralized power generation.

We believe that renewables have the potential to provide around a third of EU electricity by 2020 (3). Current statistics indicate that this is not an unreasonable goal. Wind power currently provides roughly 20% of electricity needs in Denmark, as well as 8% in Spain and 6% in Germany. If other Member States matched the levels that Sweden, Germany, and Austria have attained in geothermal heat pumps and solar heating, the share of renewable energy in heating and cooling would jump by 50%. As for biofuels, Sweden has already achieved a market share of 4% of the petrol market for bioethanol, and Germany is the world leader for biodiesel, with 6% of the diesel market. Biofuels could account for as much as 14% of transport fuels by 2020 (3). The European public is also clearly in favor of advancing renewable sources of energy, with a recent opinion poll (6) showing approval ratings for such energy ranging between 55% and 80%.

The European Commission has certainly taken this on board in its new research funding program, the Seventh Framework Programme (7). Within the energy theme of the cooperation program, which will focus on noncarbon or reduced-carbon sources of energy, emphasis will be given to renewable electricity generation, renewable fuel production, hydrogen and fuel cells, CO<sub>2</sub> capture and storage technologies, smart energy networks, energy efficiency and savings, nuclear fission safety and waste management, the development of fusion energy, and knowledge for energy policy-making. The Seventh Framework Programme increases the annual funding available to energy research at the European level to €886 million a year, compared to €574 million a year in the previous program. But this is not enough: more combined effort is needed. In some areas, we have moved toward common research agendas at the European level through the creation of European technology platforms (8). Several exist in the energy field, including for hydrogen and fuel cells, photovoltaics, zero-emission fossil-fuel power plants, and smart grids. Nonetheless, we have seen investment in energy research being reduced in national budgets over the past 20 years or so. And the research that is carried out is more often than not done in a fragmented, uncoordinated way, leading to duplication in some areas and other important aspects being underfunded or ignored. This is the *raison d'être* of the Strategic Energy Technology Plan, which will, once agreed on, provide a basis for all energy technology efforts in Europe, overcoming the lack of coherence that has unfortunately been present to a greater or lesser extent in the research pro-

grams at the national and European levels up to now.

During the first half of 2007, the Commission will consult intensively with all those that have a role to play in such a strategic plan. On the basis of these consultations, a text will be drawn up toward the middle of the year, upon which the research community, among others, will be invited to give its comments. It is important that the creation of the Strategic Energy Technology Plan is a collaborative bottom-up process if it is to have any chance of achieving its stated objective of being a reference point for future European Union activities in this area.

Since my appointment as European Science and Research Commissioner in November 2004, I have insisted on the importance of science and research as the key to solving many of the challenges that we face. I can think of no better illustration of this approach than the issue of energy. Here, we have various requirements in front of us: finding secure and sustainable sources of energy that support our economic growth and competitiveness without damaging our environment. The answer to reconciling these requirements lies in knowing more and being better. We have a chance to work together to develop solutions to the problems of climate change and energy supply that not only ensure our future economic development, but give European scientists and companies the opportunity to be (or remain) at the cutting edge of technological development. It is crucially important that we take this opportunity and make it work.

#### References and Notes

1. Stern Review on the Economics of Climate Change, 2006, [www.hm-treasury.gov.uk/independent\\_reviews/stern\\_review\\_economics\\_climate\\_change/sternreview\\_index.cfm](http://www.hm-treasury.gov.uk/independent_reviews/stern_review_economics_climate_change/sternreview_index.cfm).
2. Commission of the European Communities, *Green Paper: A European Strategy for Sustainable, Competitive and Secure Energy*, SEC(2006) 317, [http://ec.europa.eu/energy/green-paper-energy/doc/2006\\_03\\_08\\_gp\\_document\\_en.pdf](http://ec.europa.eu/energy/green-paper-energy/doc/2006_03_08_gp_document_en.pdf).
3. Commission of the European Communities, *Communication from the Commission to the European Council and the European Parliament: An Energy Policy for Europe*, COM(2007) 1final, [http://ec.europa.eu/energy/energy\\_policy/doc/01\\_energy\\_policy\\_for\\_europe\\_en.pdf](http://ec.europa.eu/energy/energy_policy/doc/01_energy_policy_for_europe_en.pdf).
4. European Commission, *Toward A Strategic Energy Technology Plan*, COM(2007) 847, [ec.europa.eu/energy/energy-policy/doc/19\\_strategic\\_energy\\_technology\\_plan\\_en.pdf](http://ec.europa.eu/energy/energy-policy/doc/19_strategic_energy_technology_plan_en.pdf).
5. European Commission, *World Energy Technology Outlook - 2050*, 2006, [http://ec.europa.eu/research/energy/pdf/weto-h2\\_en.pdf](http://ec.europa.eu/research/energy/pdf/weto-h2_en.pdf).
6. European Commission, *Energy Technologies: Knowledge-Perception-Measures*, 2006, [http://ec.europa.eu/research/energy/pdf/energy\\_tech\\_eurobarometer\\_en.pdf](http://ec.europa.eu/research/energy/pdf/energy_tech_eurobarometer_en.pdf).
7. European Commission, *Official Journal*, document L412 (2006); <http://eur-lex.europa.eu/LexUriServ.do?uri=OJ:L:2006:412:0001:EN:HTML>.
8. For further information, see [http://cordis.europa.eu/technology-platforms/individual\\_en.html](http://cordis.europa.eu/technology-platforms/individual_en.html).
9. The author is the European Commissioner for Science and Research.

10.1126/science.1139086

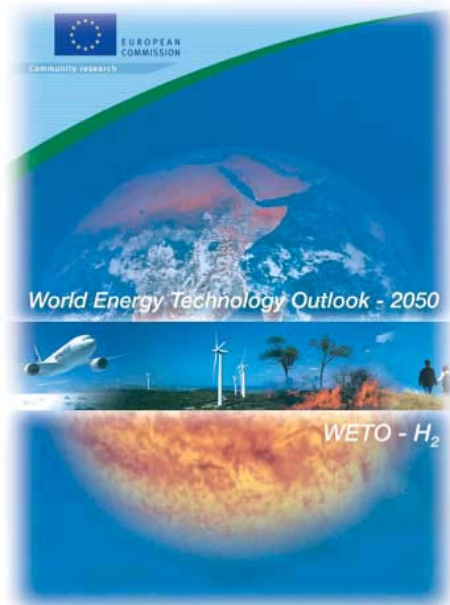


Fig. 1.