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What is (and is not) vital to advancing cellulosic ethanol

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Ethanol made biologically from cellulosic biomass, including agricultural and forestry residues, portions of municipal waste, and herbaceous and woody crops, is finally being widely recognized as a unique transportation fuel with powerful economic, environmental and strategic attributes. Although underfunded, it has been advanced to be competitive with corn ethanol; however, government policies are needed to overcome the perceived risk of first applications if we are to realize its societal benefits soon. Costs below those for fossil sources are foreseeable, with advances in pretreatment, enzyme production, and enzymatic hydrolysis – the steps that overcome the natural resistance of plants to biological breakdown – offering, by far, the greatest economic leverage. We must also build on the wisdom gained from past experience to avoid directing limited funds to projects that offer little new insight, could have marginal impact on commercial outcomes, or could be better improved through the power and wisdom of the learning curve.

Introduction

In his State-of-the-Union address on 31 January, 2006, President George W. Bush acknowledged that cellulosic ethanol could have a vital role in overcoming the 'addiction' of the USA to imported oil. Although his statement might have been a revelation to many, the uniqueness of cellulosic ethanol as a sustainable, liquid transportation fuel, which can be produced in the high volumes and at the low costs essential for appreciable effect, and its many powerful benefits have been known for decades [1–5]. However, controversy about ethanol from other sources, misinformation in the press, public apathy and entrenched political interests have held back its timely development. This new awareness could finally trigger substantial research, development, and deployment programs that bring cellulosic ethanol to commercial reality. But, such efforts must be aggressively funded at much higher levels than to date, well targeted and appropriately led; otherwise this important opportunity will be lost. We must also not dilute its impact through reinventing the wheel, pursuing concepts with limited potential or promoting ill-conceived commercial ventures that taint the technology as not viable or too risky [2]. To complicate matters, the recent prominence of cellulosic ethanol has spawned instant experts, who think that the technology is simple and its needs obvious. Others would unknowingly tackle issues that are either unimportant or have been resolved already. Still others make bold statements about economic competitiveness and performance based on little relevant experience. I offer, here, perspectives gained through almost a lifetime of interest in renewable energy and in excess of 25 years of experience as a leader in cellulosic ethanol, with the hope of helping to clarify the vital needs and to focus funds where they will have the most effect in realizing its amazing benefits.

The unique role of cellulosic ethanol

Petroleum is the largest energy source in the United States, supplying ~40% of its energy. However, it is the only source dominated by growing imports from unstable countries, which hold most of the reserves; furthermore, approximately two-thirds of this oil fuels a transportation sector that is almost totally (>96%) dependent on petroleum and is responsible for approximately one-third of greenhouse gas emissions [6]. A sustainable alternative is vital to overcome this dangerous dependence, and biomass is the only known, large-scale, renewable resource that can be converted into the liquid fuels that are so well suited to transportation [7–10]. Cellulosic ethanol is particularly promising because it can capitalize on the power of biotechnology to dramatically reduce costs, is derived from low cost and plentiful feedstocks, can achieve the high yields vital to success, has high octane and other desirable fuel properties, and is environmentally friendly [5,11–13]. Although we can hope for a miracle cure for our addiction, we cannot count on one; and prudence dictates the rapid development and deployment of cellulosic ethanol.

To provide a context for the thoughts that follow, a simplified process diagram is presented in Figure 1 for the biological conversion of cellulosic biomass to ethanol [1]. A pretreatment step opens up the biomass to enzymes that breakdown the hemicellulose and cellulose, which comprise ~20–30% and 40–50%, respectively, of the material, into sugars that are fermented into ethanol for recovery. Lignin and other components not converted into useful products can be burned to provide the heat and electricity needed to run the process, with the excess sold.

Areas in need of limited attention

Studies

Debate arises regularly about the energy and greenhouse gas consequences of ethanol. However, several qualitative [14], simple quantitative [5,12], and detailed analyses [15],

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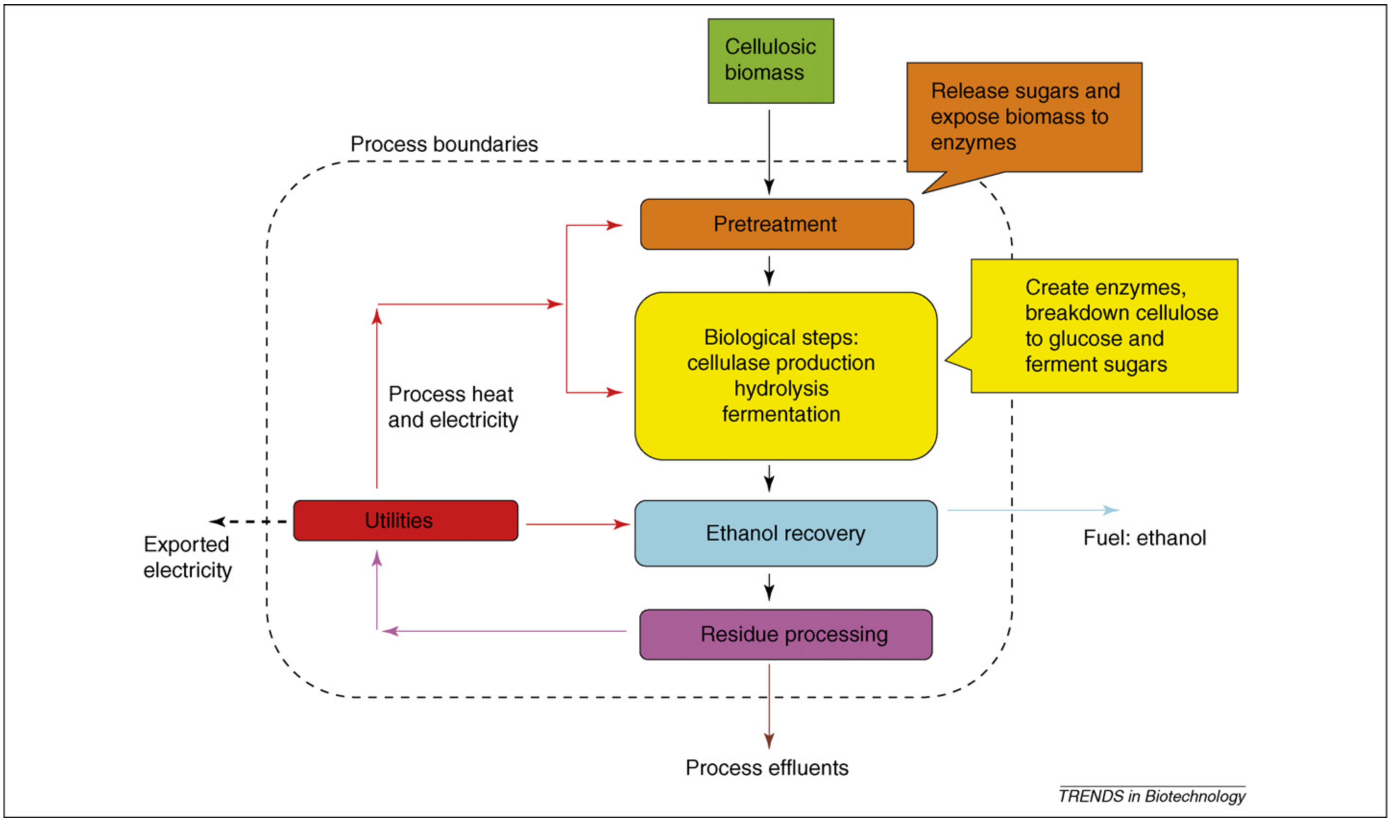

Figure 1. Simplified process flow for biological conversion of cellulosic biomass to ethanol.

which were recently reconfirmed [16], established, years ago, that both are favorable for cellulosic ethanol because of the use of lignin for process heat and power – with one excellent early in-depth study unfortunately not widely available [17]. Regardless, no well-informed audience questions the powerful energy or greenhouse attributes of ethanol [18]. Furthermore, if a portion of the ethanol produced was used instead of fossil fuels to power the vehicles that convey the biomass and transport the ethanol to market, the results would be even more favorable [12]. Because no process is yet commercial, more refined analyses are of marginal value, and further studies are only needed if motivated by notable new insights that could dramatically alter past conclusions or counter new false accusations, which periodically appear.

Process Economics

Cellulosic ethanol cost projections are published or presented regularly [19–22], and some make the bold statement that current costs are too high. However, although thousands of uneconomic approaches can be conceived, only a team with demonstrated experience in the design, construction and operation of commercial biological and biomass-based technologies is likely to design state-of-the-art, commercializable and economical processes. To further complicate matters, many of the best unit operations involve know-how and trade secrets that developers protect from public disclosure. If these substantial obstacles to producing meaningful, publicly available process designs and economic projections are overcome, operating costs can be estimated with good accuracy; but capital cost estimates suffer without competitively bid, vendor quotes based on binding performance guarantees. In addition, although cash costs are low for cellulosic ethanol, capital costs are projected to be high [21], and investor financial arrangements have substantial effects on how the latter are amortized [23]. Thus, although published cost projections can provide valuable benchmarks with which to target technology development, no process cost is ultimately meaningful until it is validated by commercial success, and such projections must be viewed as just that. Comments by amateurs with no record of successfully commercializing processes and/or limited knowledge of biological or biomass processes should be viewed with extreme caution, if not skepticism. Proof-of-competitiveness is best validated by growing private interest in the commercialization of cellulosic ethanol technologies.

Fermentation and product recovery research

Government research funds are not well spent on incremental technical advances because these have little effect on commercialization and would better result from the commercial learning curve. Successful organism development to ferment the five carbon sugars arabinose and xylose with high yields was crucial to making cellulosic ethanol economically viable in the late 20th century [24–27]. However the great success of that time is now applied to achieve excellent yields from all five biomass sugars; thus, further organism genetic modifications will probably have marginal impacts on costs. A topic regularly identified for extensive research is ethanol purification; however, the distillation and/or dehydration operations perfected for the recovery of corn and cane sugar ethanol are inexpensive in comparison with other cellulosic ethanol unit operations [13,21]. Similarly, the ethanol tolerance of organisms that ferment all sugars will not present a problem until processes are devised to handle the associated high solids concentrations in large commercial fermentors, and will provide relatively modest gains even then [20].

High priority challenges

Commercialization

Cellulosic ethanol has tremendous potential for unique and powerful benefits, but none will be realized until it is commercialized. Commercial application will also dramatically reduce the cost of existing technology through the learning curve effect that has substantially lowered ethanol production costs in Brazil and the USA [28]. It cannot be overemphasized that the operation of a process for 24 hours a day, 7 days a week, and close to 365 days per year presents constant opportunities and incentives for improvement, debottlenecking and innovation that cannot be duplicated in the laboratory or through paper studies. Thus, not only is commercialization vital to realizing the tremendous benefits of cellulosic ethanol, it is invaluable to powerful learning curve improvements.

Risk

High capital costs coupled with the high cost of capital stymie the commercialization of cellulosic ethanol. Although cellulosic ethanol technology has low operating costs, its current projected capital costs are high – and driven much higher by the over-design of initial projects to compensate for lack of large-scale experience with the technology [2]. In addition, financial institutions expect high returns on capital for technology that has not been proven, to compensate for perceived risk [23]. To compound these factors, ethanol is a commodity product with tight margins and must compete on price with gasoline and corn ethanol, both of which have substantial learning curves behind them. These aspects present huge obstacles to the initial commercialization of all new technologies and clearly stand in the way of realizing the benefits and learning curve improvements of cellulosic ethanol. It appears that only government policy promoting first-of-a-kind applications can overcome these major impediments for current technologies, just as the petrochemical industry grew, out of necessity, through government support during World War II.

Cost Reductions

Lower capital costs, increased yields and reduced operating costs would make cellulosic ethanol competitive with gasoline if neither is subsidized. However, real technology advances are needed to realize this potential, whereas incremental improvements are best left to the commercial learning curve. Initially, enhancing ethanol yields to >100 gallons per ton of dry cellulosic biomass from the currently published 'anemic' values of ~65–70 gallons per ton would be a major step forward [29]. For these reasons, applying cellulase enzymes to breakdown cellulose into glucose is far more promising than the known routes of acid hydrolysis [20,30–32]. Substantially reducing the use of chemicals, nutrients and other additives would have appreciable effects on operating costs, as would enzymes with much greater specific activity [21]. Technologies that require less heat and/or electricity would leave more lignin available for producing exported electricity or other high value products, enhancing revenues. Capital costs can be reduced by technical leaps that eliminate process steps, simplify operations, substantially speed up reaction rates and reduce energy and chemical inputs [33].

Important cost contributors

Although technoeconomic evaluations show that feedstock is the largest cost contributor, cellulosic biomass is, in fact, inexpensive, with biomass at about $40 per dry ton equivalent to petroleum at about $13 per barrel [8]. Furthermore, although feedstock costs represent ~70–80% of the final product cost for commercial commodity products, feedstock only accounts for approximately one-third of the total for cost estimates of current cellulosic ethanol technologies [20]. Thus, the greatest leverage for cost reductions is in reducing the processing costs, which make up 67% of the total. Further examination reveals that pretreatment is the most expensive single unit operation; next in line are the costs for enzymatic hydrolysis of pretreated cellulose and for making enzymes to carry out this task. In other words, the three most expensive processing operations are for overcoming the natural resistance of plants to the biological breakdown of sugars.

Overcoming the recalcitrance of cellulosic biomass

Just as the three most important considerations in real estate are location, location, location, the three most important factors for commodity products are yield, yield, yield. Thus, the best opportunity for reducing the cost of cellulosic ethanol is, by far, through enhancing sugar yields from cellulose and hemicellulose, while reducing costs to do so. For example, the biomass cost would only be about $0.35 per gallon of ethanol if 100 gallons of ethanol were realized from a feedstock costing $35 per dry ton. Furthermore, if feedstock accounted for more than two-thirds of the final product cost, which is more than typical for mature commodities, cellulosic ethanol could be made for $0.52 per gallon or less. Detailed technology projections confirm the feasibility of advanced technologies with such low costs [33]. Sugar yields are low for the biological processing of native cellulosic biomass because, for survival, the plant has developed a natural resistance to microbial breakdown that locks in sugars. Consequently, pretreatments provide the key to unlocking biological feedstocks for biological conversion, with dilute sulfuric acid, sulfur dioxide, ammonia, neutral pH and lime achieving high sugar yields from corn stover [34]. However, these pretreatments are not universally successful with all types of biomass, and advanced pretreatments with less chemical and energy use are vital [35].

The pervasiveness of pretreatment

The only step more expensive than pretreatment is no pretreatment, because of its impact on virtually all other operations in addition to being expensive in its own right. As summarized in Table 1, pretreatment first and foremost controls sugar yields from both hemicellulose and cellulose,

Table 1. Potential effects of pretreatment on biological processing of cellulosic biomass

Process step	Potential effects
Biomass production	Effectiveness of pretreatment
Harvesting and/or storage	Hardening and drying of feedstock
Size reduction	Heat and mass transfer and energy inputs
Pretreatment	Loss of sugars to degradation, maximum digestion yields
Enzyme production	Choice of enzyme activities
Enzymatic hydrolysis	Enzyme loadings, hydrolysis times, and concentration of sugars
Glucose fermentation	Diauxic effects: preference for glucose rather than other sugars
Hydrolyzate conditioning	Type of conditioning, loss of sugars
Hydrolyzate fermentation	Sugar and ethanol concentrations, diauxic effects
Ethanol recovery	Ethanol concentration, mineral fouling
Residue usage	Heat content of solid residue, mineral concentrations, fouling
Waste treatment	Loading and concentration of dissolved wastes

with high yields vital to the economic viability. In addition, the choice of feedstock influences the selection of pretreatment and vice versa. Size reduction requirements for cellulosic biomass are determined by pretreatment heat and mass transfer considerations. The choices of enzymes to produce and their balance of activities are dictated by the unconverted sugar polymers and oligomers left in the solids after pretreatment. Pretreatment also releases natural inhibitors contained in the biomass and generates inhibitors through degradation, affecting the extent and cost of their removal and the associated yield losses before enzymatic hydrolysis and fermentation. Sugar and ethanol concentrations are influenced strongly by pretreatment water use, which, in turn, has important cost implications for fermentation and product recovery economics. In addition, pretreatment controls whether the proportion of sugars released in each stream presents challenges due to typical fermentative organism preference for glucose at the expense of poor yields from other sugars. Beyond this, pretreatment could shorten the time required for enzymatic hydrolysis of anhydrous sugars left in the solids to a few days. Pretreatment even affects waste treatment loadings as well as the quantity and quality of the lignin-rich solids that can be burned to produce process and exported heat and electricity or used for making other products.

Advanced biological processing

The other major costs in biological processing are for enzymes and their breakdown of polymeric carbohydrates left in the pretreated solids. Despite substantial funds being spent to reduce their costs, cellulases are still expensive to produce and their action is slow. Thus, in addition to making more reactive solids through pretreatment, enzymes with greater specific activity are needed to increase reaction rates and achieve high conversions with much less enzyme. Consolidated bioprocessing (CBP) uses thermophilic microbes to anaerobically produce cellulosome enzymes that have better cellulolytic activity than the typical fungal cellulases and ferment all of the sugars released into ethanol in the same vessel. This would achieve low costs when ethanol selectivity and concentrations for these thermophiles are improved [36,37]. However, development of high-yield fermentative thermophiles that are matched to optimal cellulase operating conditions would be an important step forward. Enzyme cocktails that can effectively release the hemicellulose left in pretreated solids are also important for achieving the high yields needed for large-scale competitiveness [38]. Finally, although many advocate large-scale, continuous enzymatic hydrolysis and fermentation, limited relevant experience, data or design methodologies have been developed for cellulosic ethanol [36]. A better understanding of the factors that control the interactions of substrates and enzymes would be invaluable in identifying pathways to better systems [39].

Better feedstocks

Because the first commercial plants will most probably use existing low-to-near-zero cost feedstocks, such as agricultural and forestry residues or paper sludge, processing costs present the major obstacle to the initial introductions of cellulosic ethanol [2]. Nonetheless, emergence of the industry would be accelerated by reliable data for existing feedstocks, including amounts, locations, compositions, variability, costs and storability. Improved feedstocks will be invaluable in the longer term, once a cellulosic industry is established. In particular, higher productivities will make greater impact possible from a given land area [22]. Plant modifications that facilitate conversion to sugars will also have great payouts, as will such traits as drought tolerance, reduced fertilizer demands, and greater carbohydrate content. Fast growing crops containing recoverable protein would be valuable for producing animal feed as well as, possibly, food and reduce potential conflicts between land use for food versus fuel [40].

Closing thoughts

The message from the above is, simply, that limited funds must be focused where they can have the most impact. The most vital needs to realize the great benefits of cellulosic ethanol are to commercialize the technology now, and to fund aggressively research that targets advances in overcoming the recalcitrance of biomass, to achieve low-cost ethanol production. The diversion of substantial resources into more evaluations of process economics, energy balances, greenhouse gas impacts and other studies are not merited without proper motivation. Nor will market penetration benefit much from spending substantial fractions of the limited funds allocated to cellulosic ethanol research on developing organisms that can ferment all five sugars or for ethanol recovery. Rather, the immediate and most important quests are to develop effective policies to accelerate commercialization, improve our knowledge of cellulosic conversion systems to reduce risk and identify opportunities for advances, and support technology that has the potential for substantial cost reductions for breaking down cellulose and hemicellulose into sugars. Waiting for a miracle from some other still-to-be-discovered technology is an invitation to disaster.

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