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ABE production from corn: a recent economic evaluation

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This article details an economic assessment of butanol production from corn using the newly developed hyper-butanol-producing strain of *Clostridium beijerinckii* BA101. Butanol is produced in batch reactors and recovered by distillation. For a plant with 153,000 metric tons of acetone, butanol, and ethanol (ABE) production capacity, the production equipment cost and total working capital cost is US\$33.47×10^6 and US\$110.46×10^6, respectively. Based on a corn price (C_p) of US\$79.23 ton^{-1} (US\$2.01 bushel^{-1}), an ABE yield of 0.42 (g ABE/g glucose) butanol price is projected to be US\$0.34 kg^{-1}. An improved yield of 0.50 will reduce this price to US\$0.29 kg^{-1}. Assumptions, such as by-product credit for gases and complete conversion of corn steep liquor (CSL) to fermentation by-products, have been taken into consideration. An increased price of corn to US\$197.10 ton^{-1} would result in a butanol price of US\$0.47 kg^{-1}. A grass-rooted plant would result in a butanol price of US\$0.73 kg^{-1} (C_p US\$79.23 ton^{-1}). In a worst case scenario, the price of butanol would increase to US\$1.07 kg^{-1} (C_p 197.10 ton^{-1} for a grass-rooted plant and assuming no credit for gases). This is based on the assumption that corn price would not increase to more than US\$197.10 ton^{-1}. *Journal of Industrial Microbiology & Biotechnology* (2001) **27,** 292–297.

Keywords: corn; *Clostridium beijerinckii* BA101; acetone–butanol–ethanol (ABE); yield; capital cost; plant; corn steep liquor (CSL); fermentation

Introduction

Butanol is an important industrial chemical which is currently produced by either the oxo process starting from propylene (with H_2 and CO over a rhodium catalyst) or the aldol process starting from acetaldehyde [24]. Acetone, a co-product of butanol fermentation, is produced chemically either by the cumene hydroperoxide process or the catalytic dehydrogenation of isopropanol [12]. In either case, these synthetic routes have proven to be economically advantageous in comparison to the fermentation-based processes. For this reason, all butanol/acetone fermentation facilities around the world have ceased. This happened after World War II when rapid development of the petrochemical industry took place.

In 1996, the worldwide annual production of butanol and acetone was 2.49×10^9 and 2.10×10^9 kg, respectively. The total production of acetone and butanol was achieved by chemical process using petroleum-based raw materials. Since 1990, production of butanol has been constant in the United States at 1.17×10^9 kg, while worldwide butanol production has fluctuated slightly. Acetone and butanol production by regions of the world is shown in Table 1 [4].

Butanol has several applications in the chemical industry and as a fuel (Table 2). Butanol contributes to clean air by reducing emissions and unburned hydrocarbons in the tail pipe exhaust. Butanol has research and motor octane numbers of 113 and 94 compared to 111 and 92 for ethanol [6]. Some of the advantages of butanol as a fuel have been reported in the literature [6] including a vapor pressure for pure butanol of 0.63 psi as compared to 2.25 psi for ethanol, and a heat of vaporization of 141.3 kcal kg^{-1} for butanol compared to 204.1 kcal kg^{-1} for ethanol. Additionally, the high boiling point (118°C) and lower vapor pressure for butanol may affect cold starting. It is more miscible with gasoline and diesel fuel, has a lower vapor pressure, and is less miscible with water. It is currently used as a feedstock chemical in the plastic industry and as a food grade extractant in the food and flavor industry (Table 2). Because of the potential for carcinogen carryover, the use of the petroleum-derived butanol is not desirable for food applications [3].

A recent decision of Oil and Petroleum Exporting Countries (OPEC) to reduce oil output has resulted in dramatic fluctuations in oil prices, which have soared to over US\$30 a barrel. Occasional price hikes (since 1973) and instability in the oil supply region have threatened its supply. As a result of a 1973 price increase, research has been focused on developing technology to produce fuels and chemicals from renewable resources. Since then, new microbial cultures, which can produce fuels more efficiently, have been developed. Additionally, various problems associated with the production of fuels and chemicals from natural resources have been solved. New methods of production and separation have been developed. We have reached a time when fermentation-derived chemicals can compete economically with petroleum-based and chemically manufactured fuels and chemicals.

Butanol can be produced from various commercial raw materials including molasses, whey permeate, and corn [5]. *Clostridium acetobutylicum* or *C. beijerinckii* can be used in this fermentation. In a typical butanol fermentation, acetone and ethanol are also produced along with butanol. The typical ratio of acetone, butanol, and ethanol (ABE) is 3:6:1 with maximum concentration of total solvents being 20 g l^{-1} when using traditional strain/s and traditional batch fermentation processes. *C. beijerinckii* BA101, a hyper-butanol-producing strain which is able to produce up to 33 g l^{-1} total solvents, was developed [2]. This culture is unique relative to other cultures in that it can produce and tolerate higher concentration of butanol and its use results in higher ABE yields. Additionally, *C. beijerinckii* BA101 starts producing butanol during

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Table 1 World production of acetone and butanol by region (1996 data)

Region	Butanol (kg)	Acetone (kg)
North America (Total)	1.17×10^9	1.21×10^9
North America (USA only)	1.17×10^9	1.20×10^9
South America	5.12×10^7	8.52×10^7
Asia	4.30×10^8	4.76×10^8
Europe	8.43×10^8	3.31×10^8
Total	2.49×10^9	2.10×10^9

the active growth phase, which results in improved productivity. *C. beijerinckii* BA101 has been studied extensively for its fermentation characteristics and has been used in pilot plant reactors [13].

The raw materials mentioned above may require upstream processing depending upon the process being used for fermentation [22]. Molasses require dilution and removal of sediments in order to remove minerals, whey permeate requires concentration possibly by reverse osmosis, while corn requires de-branning, de-germing/de-oiling, milling, sieving, centrifugation, and saccharification [26]. Our culture, *C. beijerinckii* BA101, is hyper-amylolytic and can hydrolyze starch efficiently to release glucose for fermentation to ABE. Corn contains 13–14% moisture, 4.5% oil, and 75% starch in addition to fiber, protein and ash [10] (Eckhoff and Ping Yang, personal communication).

The objective of the present paper was to report on the cost estimation of butanol production from corn using traditional technology and the hyper-butanol-producing *C. beijerinckii* BA101. Unless stated, the fermentation facility would be annexed to an existing corn milling plant.

Materials and methods

Fermentation, substrate, plant size, and product recovery

Batch fermentation was considered for the present studies. The medium and process used for fermentation have been reported previously [13,14]. The medium contained corn steep liquor (CSL), which is an inexpensive nutrient source. In order to prepare fermentation medium, 1 vol of CSL containing 100 g l^{-1} solids was added to 5 vol of starch solution. The culture, *C. beijerinckii* BA101, and CSL have been tested in our pilot plant reactors. For the purpose of this model, ABE would be recovered by distillation and four distillation columns would be required. It is assumed that recovered water will be recycled to the fermentation plant for medium preparation. After fermentation is complete, cells will be removed from the broth by centrifugation, refrigerated, and sold as cattle feed. It is assumed that fermentation gases will be compressed and sold. Cost for gas compression and storage has not been included. Similarly, cost for the storage of by-products has not been included in this exercise. Figure 1 shows a schematic diagram of butanol fermentation and recovery by distillation. The substrate (corn) would be purchased at US\$79.23 ton^{-1} (US\$2.01 bushel^{-1}) and processed in the milling section of the plant. A plant size of 153,000 metric tons of total ABE is being considered here of which butanol represents 121,596 metric tons. Unless stated otherwise, an ABE yield ($Y_{p/s}$) of 0.42 (based on glucose) has been considered for this exercise.

Financial investment and assumptions

Standard chemical engineering texts were used for design purposes [15,27]. The equipment list has been adapted from a previous publication [16] and cost has been updated to July 2000 per the Chemical Engineering Index. It is assumed that capital is borrowed at an interest rate of 9%, Federal taxes are paid at 35% on profit, and the rate of return on investment is 20%. The fermentors and alkali tank (for pH adjustment) are constructed of stainless steel while the remainder of the plant is composed of carbon steel. The working life of the plant is 15 years with a straight line depreciation. A lang factor (a factor which is multiplied to the equipment cost to get total capital investment) of 3, which is an appropriate factor for an annexed plant, has been used unless stated. ABE productivity on the order of 0.38–0.39 g l^{-1} h^{-1} has been assumed for this exercise. Our typical batch reactors result in reactor productivities of 0.35–0.50 g l^{-1} h^{-1}. The number of working days is considered to be 350 days year^{-1}. Fermentation gases (CO_2 and H_2) will be sold for by-product credit. CSL has been assumed to be a no-cost nutrient source. This plant, being an extension of the existing corn milling plant, would not require site development. All the prices are factory gate prices and do not include transportation costs. It has been assumed that CSL would be utilized completely by the culture. Suspended solids would be removed by centrifugation while dissolved solids would be separated by membrane. The recovered solids would be sold as cattle feed.

Results and discussion

The total equipment cost for batch fermentation and distillative recovery was estimated to be US\$$33.47\times10^6$ (Table 3). A base case price for butanol has been calculated to be US\$0.34 kg^{-1} (Table 4). The current reported price for petrochemically derived butanol is US\$1.21 kg^{-1} [1]. For the present plant, the total annual butanol production was calculated to be 121,596,230 kg for a total

Table 2 Applications of acetone and butanol

Acetone	
Manufacture of:	methyl isobutyl ketone, methacrylates, methyl butanol, bisphenyl A, methyl isobutylcarbinol, isophorone, and diacetone alcohol
Solvent for:	paints, lacquers, resins, nitrocellulose, varnishes, various processing, and cellulose acetate
Butanol	
Manufacture of:	dibutyl phthalate (as a precursor), butyl acetate (as a precursor), butyl acrylate (as a latex), glycol ethers, and amine resins
Other uses:	is an excellent fuel (it is miscible with gasoline and diesel fuel, has high calorific value, has a lower vapor pressure, and is less miscible with water); used in plastic industry as a feedstock chemical; food grade extractant; a solvent in the manufacture of oil, pharmaceuticals, perfumes [25]; and as a solvency enhancer in the formation of nitrocellulose lacquers

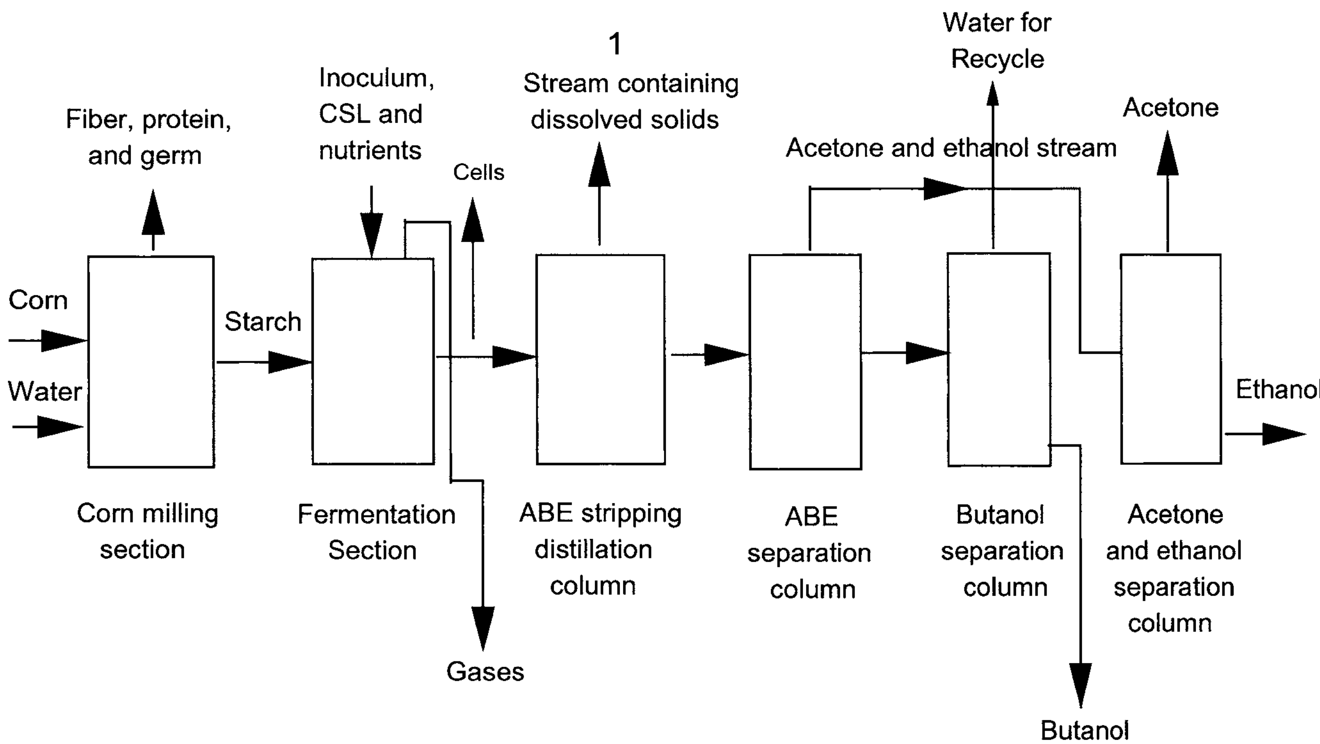

Figure 1 A schematic diagram of butanol production by fermentation of corn (corn starch) and recovery by distillation. Stream (1) containing dissolved solids is directed to membrane section to recover solids and recycle water to the plant.

production cost of US106.1\times$10^6. For the plant, total fixed capital investment was calculated to be US100.42\times$10^6, while the total capital investment would be US110.46\times$10^6. Total direct and indirect expenses were calculated to be US59.35\times$10^6 and US$23.00$\times$10^6, respectively. The general expenses were calculated to be US23.74\times$10^6 which included administration, profit, and federal taxes. At a corn price (C_p) of US$79.23 ton^{-1}, credit for by-products was calculated to be US64.55\times$10^6. After by-product credit, net yearly production expenses were US41.54\times$10^6.

Table 3 Major equipment for ABE fermentation and recovery

	US$
Corn wet milling	
Corn storage	216,762
Steeping tank	352,868
Grinding mill	248,923
Sieving (to remove fiber)	10,082
Centrifuge (to separate gluten)	1,133,513
Starch tank	250,536
Pumps (three)	65,734
ABE fermentation	
Seed vessels (three)	354,280
Medium preparation tank	449,655
Fermentors	2,359,175
Cell centrifuge	1,624,403
Pumps (five)	96,283
ABE recovery	
Reboiler (four)	11,165,755
Heat exchanger (four)	6,212,394
Distillation column (four)	8,116,068
Storage tank (three)	648,975
Pump (12)	166,655
Total	33,472,061

Table 5 shows material input and output for the butanol fermentation plant. For the plant, 5.14$\times$10^8 kg corn containing 14% moisture would be bought at US$79.23 ton^{-1}, unless otherwise stated. This amount of corn would result in the production of 3.65$\times$10^8 kg of glucose following hydrolysis. During processing and fermentation, 5.75$\times$10^8 kg of feed material (including CSL solids) would be fed to the system. The total amount of product (butanol 121,596,230 kg) and by-products (446,707,210 kg) would amount to 5.68$\times$10^8 kg. Approximately 7$\times$10^6 kg of raw material would be lost during processing, which is 1.22% of the total feed material. It should be noted that a significant amount of by-products credit (US64.55\times$10^6) would be received. The amount of by-products is approximately four times that of the product (butanol).

In order to calculate by-products credit, acetone and ethanol prices were obtained from Chemical Marketing Reporter [1]. These prices were US$0.38 and US$0.28 kg^{-1}, respectively. Prices for cell mass, fiber/protein, and recovered polysaccharide were assumed to be US$0.18 kg^{-1} (Ping Yang, personal communication). The credit that would be obtained from the plant is shown in Table 6. The above price of butanol is based on the assumption that US1\times$10^6 would be required for wastewater treatment (W_{wt}) and water recycle [16]. However, if this assumption is increased to US3\times$10^6, butanol price would increase to US$0.36 kg^{-1}. If gases are not recovered, then the butanol price would increase to US$0.53 kg^{-1} ($W_{wt}$ US1\times$10^6).

It has been our prior experience that the cost of substrate has the greatest effect on fuel/butanol price [8,20–22]. Prices of agricultural commodities often fluctuate and it would not be a surprise if the corn price increased in the future. An increased corn price of US$197.10 ton^{-1} (US$5 bushel^{-1}) has also been

Table 4 Total manufacturing expenses and capital investment for a butanol plant (121.6×10^6 kg year^{-1})

Capital investment	US$
Total purchased equipment cost	33,472,061
Fixed capital	100,416,184
Working capital	10,041,618
Total capital investment	110,457,803
Manufacturing expenses	
Direct expenses	
Raw materials	40,724,220
Operating labor	1,500,000
Supervisory and clerical labor	225,000
Utilities	
Steam	6,232,000
Electricity	4,655,000
Water	172,500
Waste water treatment	1,000,000
Maintenance and repair	4,016,647
Operating supplies	602,497
Laboratory charges	225,000
Total direct expenses	59,352,864
Indirect expenses	
Local taxes	1,004,162
Insurance	5,020,809
Depreciation	7,029,133
Interest	9,941,202
Total indirect expenses	22,995,306
General expenses	
Administration	140,000
Research and development	500,000
Annual profit after tax	15,048,517
Federal tax	8,054,279
Total general expenses	23,741,796
Total manufacturing expenses	106,089,966
By-products credit	64,550,206
Net manufacturing expenses	41,539,761
Total butanol production (kg)	121,596,230
Butanol production cost (US$ kg^{-1})	0.34

considered. It has been assumed that the prices of by-products such as fiber and protein, germ/oil, polysaccharide, and cell mass will increase in the same proportion as the price of corn. This approach appears to be more realistic than using the increased price of corn alone. With an increased corn price of US$197.10 ton^{-1}, by-products credit would be US109.71\times 10^6$ resulting in butanol price of US$0.47 kg^{-1} ($W_{wt}$ US1\times 10^6$).

ABE yield and ratio of ABE are the important characteristics of the mutant strain *C. beijerinckii* BA101. We have consistently achieved ABE yields ranging from 0.40 to 0.50 [3], which is much higher than that reported for *C. actobutylicum* [9]. At this stage, we do not know where the alterations have occurred in the metabolic pathways of *C. beijerinckii* BA101. However, it is interesting to note that amounts and ratios of fermentation product and by-products, such as acetone, ethanol, and gases, are different than for other clostridial strains. Assuming a yield of 0.50 together with the typical solvent ratios we observed for this strain, the amount of ABE this culture would produce would be on the order of 182,240 tons year^{-1} (Table 7). In addition to 144,610 tons of butanol per year, 28,470 tons of acetone per year and 9,160 tons of ethanol per year would be produced. The amount of butanol *C. beijerinckii* BA101 produces is much higher than the amount produced by *C. acetobutylicum*. *C. acetobutylicum* produces more gases and less solvents. The amounts of the product and by-products (and by-product credit) which these two cultures would produce are shown in Table 7. It is interesting to note that butanol produced by *C. beijerinckii* BA101 is projected to cost US$0.29 kg^{-1}, while butanol produced by *C. acetobutylicum* is projected to cost US$0.50 kg^{-1} ($C_p$ US$79.23 ton^{-1}, $Y_{p/s}$ 0.42, and W_{wt} US1\times 10^6$).

A grass-rooted plant would be more expensive to start because of expenses involved with development of site, offsite facilities, and auxiliary buildings. For such a plant, the total capital investment would be five times that of the total equipment cost. This would increase the price of butanol dramatically from US$0.34 kg^{-1} to US$0.73 kg^{-1} (C_p US$79.23 ton^{-1}, W_{wt} US1\times 10^6$). A combination of grass-rooted plant and US$197.10 ton^{-1} corn would result in a butanol price of US$0.88 kg^{-1} ($W_{wt}$ US3\times 10^6$). In a worst case scenario, if no credit for gases is taken, then this price would increase to US$1.07 kg^{-1}.

The by-product prices are given in Table 6. Cell mass and corn fiber would be sold as a cattle feed at US$0.18 kg^{-1}. It should be noted that if CO_2 and H_2 are separated economically and sold as pure gases, then the price of butanol would be reduced significantly. A price of US$0.50 lb^{-1} for pure H_2 has been reported in the literature [6]. Moreira [11] discussed the chemical conversion of fermentation offgases to methanol and stated that a discounted cash flow rate of return of 25–30% is likely to be achieved for realistic operating conditions of a methanol synthesis plant co-located next to an acetone–butanol fermentation facility capable of producing 1.00×10^8 kg solvents year^{-1}. The capacity of the plant described herein is 25% larger than suggested by this author.

Another important factor in the ABE fermentation is the economical recovery of solvents. Among several techniques investigated [7], pervaporation is more attractive because it separates ABE selectively from the broth and does not harm the culture. Pervaporation can be used with batch, fed-batch, as well as continuous culture operations. We have studied pervaporation extensively in our reactors in order to separate ABE [17–19]. The impact of using pervaporative recovery on butanol price for a similar capacity plant will be examined in future studies.

Carbon source (substrate) is converted into butanol and a number of by-products such as acetone, ethanol, cell mass, polysaccharide, and gases. For the material balance calculations, it has been assumed (unless otherwise stated) that 42% ($Y_{p/s}$ 0.42) of the carbon is

Table 5 Material balance for the butanol fermentation plant (121.6×10^6 kg year^{-1})

Material balance	
Feed	
Corn	5.14×10^8 kg[a] (moisture 14%) (this amount of corn will result in 3.32×10^8 kg starch or 3.65×10^8 kg glucose)
$FeSO_4 \cdot 7H_2O$	569 kg
NaOH	92,865 kg
Water	5×10^9 l (total fermentation broth volume is 6×10^9 l) (most of the water is recycled water)
Products	
Butanol	121,596,230 kg
By-products[a]	446,707,210 kg

[a]See Table 6

Table 6 Annual by-product credit for a butanol production plant from corn using *C. beijerinckii* BA101

By-products	By-product amount (kg)	Corn price US\$79.23 ton^{-1}		Corn price US\$197.10 ton^{-1}	
		By-product price (US\$ kg^{-1})	Credit (US\$)	By-product price (US\$ kg^{-1})	Credit (US\$)
Acetone	23,938,054	0.38	9,096,461	0.38	9,096,461
Ethanol	7,464,200	0.28	2,089,976	0.28	2,089,976
Gases	232,581,500	0.10	23,258,150	0.10	23,258,150
Fiber and protein	88,408,000	0.18	15,913,440	0.45	39,783,600
Germ/oil	19,891,800	0.40	7,956,720	1.00	19,891,800
Cell mass	42,130,000	0.18	7,583,400	0.45	18,958,500
Polysaccharide	32,293,660	0.18	5,812,859	0.45	14,532,147
Total	446,707,210		64,550,206		109,708,634

converted into ABE, 50% to gases, 5% to cell mass, 1% to maintenance energy, and 2% to other products such as acids and polysaccharides. These assumptions are based on previous findings that the cells require maintenance energy for metabolic activities [23]. It is also well known that the ABE fermentation process is a complicated process and several by-products appear in the fermentation broth which require some carbon for their production.

Production of butanol is a biological process. It should be noted that in a biological process, the concentration of products may vary from batch to batch. This may occur under identical fermentation conditions. The calculations for the present plant are based on a batch fermentation which produced more acetone and ethanol than previously reported [16]; hence, solvents produced in this process are more by 3,000 tons $year^{-1}$. It should be noted that 1×10^9 l of CSL containing 10% (100 g l^{-1}) dry weight solids would be used. The total amount of solids added to the fermentation medium would be 1×10^8 kg, which is a significant amount as compared to corn (5.14×10^8 kg). It has been assumed that all of the CSL solids would be converted into cell mass and by-products (50×10^6 kg gases, 25×10^6 kg cell mass, and 25×10^6 kg polysaccharide). This is in addition to the conversion of corn starch to various products mentioned above. Since CSL contains only limited amounts of sugar, their conversion into ABE has not been considered.

Conclusion

Butanol can be produced at US\$0.34 kg^{-1} from corn at US\$79.23 ton^{-1}. This price is based on a yield of 0.42 and an assumption that gases will be captured, compressed, and sold for by-product credit. For a butanol plant of 121,596,230 kg $year^{-1}$ capacity, by-product credit would be US\$$64.55\times10^6$. The total capital investment for this plant would be US\$$110.46\times10^6$. If gases are not captured, then the butanol price would increase to US\$0.53 kg^{-1}. Increasing the corn price to US\$197.10 ton^{-1} would increase the butanol price to US\$0.47 kg^{-1}. A grass-rooted plant would result in a price of US\$0.73 kg^{-1}. For this exercise, a rate of return and federal taxes have been assumed to be 20% and 35%, respectively. In a worst case scenario, the butanol price would increase to US\$1.07 kg^{-1}. In such a case, gases would not be captured, corn would be purchased at US\$197.10 ton^{-1}, and the plant would be grass-rooted. Throughout this exercise, it has been assumed that the CSL would be fully utilized and would be converted to cell mass, gases, and other by-products.

Table 7 A comparison of amounts of fermentation products derived by *C. beijerinckii* BA101 *versus C. acetobutylicum*

C. beijerinckii BA101, ABE yield 0.50		
Butanol (kg)	144,610,000	
Acetone (kg)	28,470,000	by-product credit US\$63,805,619
Ethanol (kg)	9,160,000	butanol price US\$0.29 kg^{-1}
Gases (kg) (50×10^6 kg from CSL)	203,166,000	
C. acetobutylicum, ABE yield 0.30		
Butanol (kg)	65,640,000	
Acetone (kg)	32,820,000	by-product credit US\$73,254,565
Ethanol (kg)	10,940,000	butanol price US\$0.50 kg^{-1}
Gases (kg) (50×10^6 kg from CSL)	276,103,460	

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