



Short communication

Analysis of historical total production costs of cellulosic ethanol and forecasting for the 2020-decade



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ABSTRACT

This paper presents a comparative analysis of total production costs (TPCs) published between 1995 and 2013 of cellulosic ethanol produced with biochemical platforms. TPC values were first grouped by plant capacity (small, medium and large) and updated (c. 2013) using the US PP Index in order to consider inflation effects. Feedstock and enzymes “per-litre” contributions to each updated TPC value were substituted by the calculated average values thus normalizing the impact of these TPC contributions. Differences in normalized TPC values could, therefore, be associated to other TPC contributions such as capital, operation and financial factors. Based on these data TPC values of cellulosic ethanol–gasoline-equivalent for large capacity plants were calculated for the 2020 decade. The results were compared against average US gasoline TPC forecasts.

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1. Introduction

Total production cost (TPC) estimations of cellulosic ethanol (C-EtOH) and their comparisons with other liquid fuels’ TPC are usually employed by social, private and government sectors as cornerstone information in renewable energy issues. A considerable amount of data from a multiplicity of sources is usually involved for calculating or estimating these values, taking into consideration technological, market, geo-political as well as economic issues. This data heterogeneity, the different nature of the calculation–estimation techniques involved as well as the degree of detail in the calculations and in the reported results make TPC values difficult to compare.

This paper presents an analysis of historical TPC values of cellulosic ethanol (C-EtOH-TPC) produced by biochemical platforms (i.e. using enzymatic saccharification or co-saccharification stages, regardless of the pretreatment, fermentation or separation techniques being employed). Fifteen works [1–15] were identified in the academic literature with enough information as to carry out the comparison. This information includes ethanol yields and feedstock prices as well as a breakdown of “per-litre” contributions of feedstock and enzymes to TPC. These two raw materials usually account for 40–60% of TPC and since both have a proportional impact on TPC (i.e. ethanol yield is proportional to the polysaccharides and enzyme amounts available to the production process),

normalizing these contributions to TPC may help to understand the effect on TPC of other technological or financial factors whose contributions to TPC are included in the calculations but not reported in the works considered.

The next section presents the reference list [1–15] providing 17 TPC values and related data grouped by plant capacity (small, medium and large). All data were first updated (c. 2013) using the annual US PP Index (all commodities) [16] in order to consider the inflation effects. Currency-related information is provided in US dollars. Feedstock and enzymes “per-litre” contributions to each updated TPC value were substituted by the calculated average values thus normalizing the impact of these TPC contributors. Differences in TPC values can, therefore, be associated to other TPC contributions related to capital, operation and financial factors. Normalized values of C-EtOH-TPC for large capacities and their gasoline equivalent (C-EtOH-GE-TPC) were placed in a time-line and values for January 2020 and December 2029 were forecasted. Small and medium capacities TPC values do not exhibit a statistically consistent behavior as to be employed in the same fashion. Section 3 compares current and future C-EtOH-GE-TPC values against average US regular gasoline TPC (US-regas-TPC) forecasts based on historical data (c. May 2013) for January 2001–May 2013. The values obtained are discussed in Section 4 at the light of other works dealing with TPC estimations. Section 5 closes this work emphasizing the magnitude of the possible economic boost required to achieve competitiveness of lignocellulosic ethanol during the 2020 decade.

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2. Cellulosic EtOH TPC normalization and forecast for 2020 decade

Table 1 enlists the 17 TPC values from the 15 publications considered in this work. They were classified into three groups according to plant capacity: small (530–600 ton Dry Basis (tonDB)/day), medium (1050–1250 tonDB/day) and large (1760–2205 tonDB/day). Different types of feedstock are employed, ranging from forestry to agro-residues. The average yield values are (in l EtOH/kg feedstock) 0.26 ± 0.04 , 0.30 ± 0.04 and 0.30 ± 0.03 for small, medium and large capacities respectively. The yield reported by [1] (i.e. 0.19), which incidentally is the oldest work considered in this paper, drives the average yield value down for the small capacity category. Otherwise, average yield values between the three capacity categories would be very similar.

Reported TPC values, feedstock prices as well as feedstock and enzyme contributions to TPC are shown in the left-hand side of Table 2. In order to consider the inflation effects, updated (c. 2013) TPC values by the annual US PP Index (all commodities) are shown in the right-hand side of the same Table. Feedstock and enzymes “per-litre” contributions to each updated TPC value were substituted by the calculated average values (\$0.26/l EtOH, \$0.13/l EtOH for small capacities, \$0.23/l EtOH, \$0.10/l EtOH for medium capacities and \$0.23/l EtOH, \$0.12/l EtOH for large capacities) thus normalizing the impact of these TPC contributions. Differences in TPC values can, therefore, be associated to other TPC contributions such as capital, operation and financial factors, project conditions or even calculation methods employed in the original references. The resulting average TPC values were \$(0.94 \pm 0.11)/l\$ EtOH, \$(0.78 \pm 0.12)/l\$ EtOH and \$(0.69 \pm 0.12)/l\$ EtOH for small, medium and large capacities, respectively.

Table 1

References considered in this study. Plant capacity in ton DB/day; yield in l EtOH/kg feedstock DB; SSF: Simultaneous Saccharification and Fermentation; SHF: Separate Hydrolysis and Fermentation; SHCF: Separate Hydrolysis and Co-Fermentation; SSCF: Simultaneous Saccharification and Co-Fermentation.

Ref.	Calc. date	Plant cap.	Proc. plat.	Yield	Feedstock
<i>Small capacity</i>					
[1]	1995	556	SSF	0.19	Hardwood
[6]	2002	535	SSF	0.32	Softwood
[6]	2002	535	SHF	0.28	Softwood
[7]	2003	547	SSF	0.29	Softwood
[9]	2004	600	SSF	0.28	Lignocel
[13]	2011	542	Softwood	0.25	Softwood
[15]	2012	600	SHCF	0.25	Wheat straw
	Avg.	559.2		0.26	
	σ	28.8		0.04	
	% σ	5.1		16.3	
<i>Medium capacity</i>					
[4]	1999	1050	SHF	0.27	Corn stover
[14]	2010	1245	SSF	0.33	Hardwood
	Avg.	1147.5		0.30	
	σ	137.9		0.04	
	% σ	12.0		13.3	
<i>Large capacity</i>					
[5]	1996	1880	SSF	0.35	Hardwood
[8]	2003	1763	SHF	0.29	Hardwood
[2]	2005	2000	SSF	0.32	Corn stover
[10]	2007	2205	SCF	0.30	Corn stover
[11]	2007	1918	SSCF	0.31	Wood
[12]	2010	2000	SHCF	0.29	Corn stover
[3]	2010	2000	SSCF	0.33	Corn stover
[15]	2012	2100	SHCF	0.25	Wheat straw
	Avg.	1983		0.30	
	σ	135		0.03	
	% σ	6.8		9.6	

After inflation updating, average feedstock costs are similar for all capacities (around \$69/tonDB), despite some works employing very low prices (i.e. [1–3]). Feedstock and enzyme contributions to TPC follow a similar pattern with a 2:1 ratio throughout plant capacities. Average feedstock contributions are \$(0.26 \pm 0.03)/l\$ EtOH, \$(0.23 \pm 0.02)/l\$ EtOH and \$(0.23 \pm 0.08)/l\$ EtOH for small, medium and large capacities, respectively. For enzyme contributions, average values are \$(0.13 \pm 0.02)/l\$ EtOH, \$(0.10 \pm 0.05)/l\$ EtOH and \$(0.12 \pm 0.08)/l\$ EtOH. The large standard deviation in the case of medium and large capacities is due to a very small enzyme contribution value employed by [4,5]. Raw material total contribution to TPC is $41.7 \pm 5.3\%$, $42.3 \pm 6.6\%$ for small and medium capacities whilst for large capacities increases to $51.9 \pm 8.8\%$. Fig. 1 shows (a) the original TPC values, (b) updated by inflation and (c) normalized by the average raw materials (feedstock and enzyme) contribution cost. Average TPC values are depicted by horizontal bars. The effects of both inflation (from (a) to (b)) and raw material normalization (from (b) to (c)) in the reduction of standard deviation are noticeable.

The normalized large-capacity TPC values of C-EtOH (C-EtOH-TPC) and their gasoline equivalent (C-EtOH-GE-TPC) in the time-line are shown in Fig. 2 (pre-2005 values are not shown in the graph). In order to forecast TPC values for the 2020 decade, least-squares regressions were carried out for both C-EtOH-TPC and C-EtOH-GE-TPC considering the complete January 2001–May 2013 period. The largest correlation factor ($R^2 = 0.934$) was obtained for a linear model. The corresponding slopes (m) and intercepts (b) of these tendency lines are included in Table 3. Calculated values for C-EtOH-TPC and C-EtOH-GE-TPC for January 2020 are \$1.15/l EtOH and \$1.72/l EtOH. The corresponding values for December 2029 are \$1.48/l EtOH and \$2.22/l EtOH, respectively.

3. US automotive fuel TPC forecast for 2020 decade and comparison with cellulosic EtOH gasoline-equivalent TPC

C-EtOH-GE-TPC (large-capacity) values for the 2020 decade are compared against US regular gasoline TPC (US-regas-TPC) forecasts based on historical data from December 2008 to May 2013 [17]. Before calculations, US-regas-TPC data were updated using the monthly US PP Index (all commodities). The resultant values are shown in Fig. 2 as red¹ triangles. The effect on US-regas-TPC of oil price recovery after the 2008-food and energy crisis can be observed as a sharp increase after December 2008. After updating for inflation, data were conditioned with a low-pass filter with 0.5 smoothing factor. US-regas-TPC forecast for the 2020 decade were obtained using Holt’s double exponential smoothing method [18]. Level (α) and trend (β) smoothing factors, shown in Table 4, were chosen so as to minimize the Mean Squared Error (MSE). Fig. 2 shows the resulting forecast with its linear section starting at May 2013 (slope 3.89×10^{-5} \$/day) and intercept -0.861 \$. Forecast lines are depicted up to 2015. US-regas-TPC forecasts for January 2020 and December 2029 (not shown in Fig. 2) are \$0.84/l US-regas and \$0.98/l US-regas, respectively. These values are 51.0% and 55.6% lower than their C-EtOH-TPC equivalents.

4. Discussion

The average TPC contributions of feedstock and enzymes (presented in Table 2) exhibit a 2:1 ratio, and most raw material contributions to TPC range between 40% and 60%. This is consistent with anecdotal experience within the biofuels industry. However, all raw material updated costs shown in Table 2 are lower than

¹ For interpretation of color in Fig. 2, the reader is referred to the web version of this article.

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