TECHNOLOGICAL LEARNING IN U.S. ETHANOL PRODUCTION

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ABSTRACT: The Unites States in now the worlds largest ethanol producer, but debates continue on its costs competitiveness and energy balance. Therefore research on the technological development of ethanol production is of high importance. In this study an experience curve approach is applied on production costs of dry grind ethanol production over the timeframe 1980-2005. Cost reduction are allocated to either corn production or ethanol processing. Corn production costs have declined 62% over 30 years, down to 100$$_{2005}$/T in 2005. Corn production has almost doubled since 1975. A progress ratio of 0.55 is calculated; indicating a 45% cost decline over each doubling in cumulative production. Industrial processing costs of ethanol have declined 45% since 1983, to below 130$$_{2005}$/m^3 in 2005 (excluding costs for corn and capital). Plotting an experience curve results in a progress ratio of 0.87. Total ethanol production costs (including capital and net corn costs) have declined approximately 60% from 800$$_{2005}$/m^3 in the early 1980's, to 300$$_{2005}$/m^3 in 2005. Higher ethanol yields, lower energy use and the replacement of beverage alcohol based production technologies, have mostly contributed to this substantial cost decline. In addition, ethanol dry grind ethanol plants have upscaled 235% since 1990. Brazil has shows faster development in industrial processing costs, whereas development in feedstock production is higher in the United States.

Keywords: bio-ethanol, corn, costs

1 INTRODUCTION

Globally, there is a growing demand for and production of biofuels for the transportation sector. However for large scale implementation, the production cost and energy efficiency are not yet optimal and further technical developments are required. Therefore research on the technological development of biofuel production is of high importance.

The United States is now the worlds largest producer of bio-ethanol. Production in 2006 rose to 18 billion litres ethanol, passing Brazil as largest producer. Currently 55 million tonne corn is used for ethanol production, representing a share of nearly 18% of total U.S. corn supply. Future production is likely to exceed the prescribed volumes in the Renewable Fuels Standard by far. Ethanol is now blended in 46% of all U.S. gasoline, mostly in E10 blends (10% ethanol; 90% gasoline), but the market share of E85 (85% ethanol; 15% gasoline) is growing as well. U.S. ethanol production is expanding rapidly, but debates continue on its cost competitiveness and energy balance.

In this study, technological learning in ethanol production from corn in the United States is assessed. The study focuses on the development of production costs and energy use in ethanol production. One of the methods to assess potential future costs is by analysing the historical technological development by means of an experience curve. So far, no effort has been made to quantify reductions in production costs and energy use in the U.S. ethanol production sector over an extended period of time.

The goal of this study is to quantify technological learning in U.S. dry grind corn ethanol production. This will be quantified over the timeframe 1980-2005, in terms of reductions in production costs and energy use. This paper only describes developments in production costs. Underlying reasons will be identified and allocated to either feedstock production or industrial processing. Both insights in cost reductions and improvements of the energy balance are deemed highly important for the successful further development of the U.S. ethanol industry.

2 BACKGROUND

Corn is used as feedstock in over 97% of U.S. ethanol production. Corn production has risen considerably over the past decades; from 170 million tonne in 1980 to 280 million tonne in 2005 (see Figure 1), whereas the amount of hectares has remained fairly constant at around 30 million hectares. Thus, increases in corn production can be mainly attributed to higher corn yield. Average U.S. corn yield rose from 5.7 T/ha to 9.3 T/ha over the same time period.

Ethanol production rose from less than one billion litres in 1980 to 15 billion litres in 2005. One single decrease is observed in 1996, when record high corn prices lead to a shutdown of several ethanol production facilities (see Figure 1). Ethanol now makes up 2.8 percent of U.S. fuel supply (1.9% based on energy content).

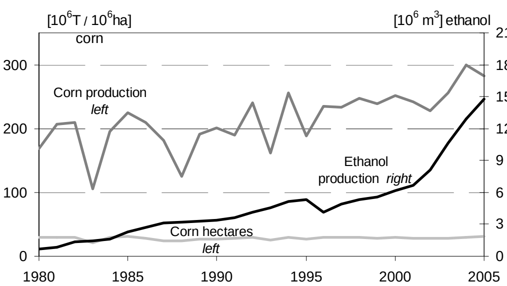

Figure 1: Corn production, amount of corn hectares and ethanol production 1980-2005.

U.S. corn supply almost doubled between 1975 and 2006. In 2006 up to 17 percent of total U.S. corn supply went to ethanol production (equal to at least 7% of world corn production). The increased share for ethanol is mostly compensated by lower stock levels, which are presently historical low. Relative corn exports decreased as well, while the share for animal feed remained constant. In absolute numbers, neither corn for exports, nor for animal feed have been reduced [1]. Recent debates on decreasing corn supply for animal feed, so far seem unfounded. However, recently low stock levels and speculation are among many factors that have caused corn prices to increase. Increased ethanol production is held responsible for increases in e.g. tortilla prices in Mexico and potential higher meat prices in the United States.

First ethanol was produced in large wet milling facilities, that also produced food and feed related products. The major growth in production over the last decade, can be mainly attributed to an increase in (smaller scale) dry grind production processes (see Figure 2). These plants generally have higher ethanol yields (up to 400L/T), and only produce one co-product (Distillers Dried Grains [with Solubles]: DDG[S]).

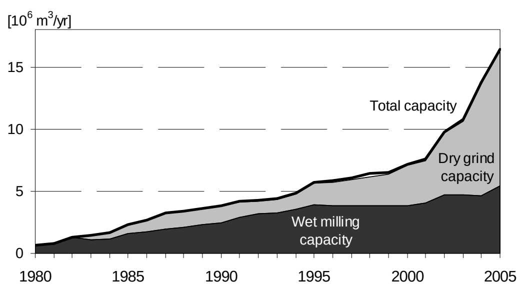

Figure 2: The share of wet milling and dry grind capacity in total ethanol production capacity.

The influence of (smaller scale) farmers cooperatives is significant, in 2005 the half of all ethanol plants were farmer owned or had significant farmer investments, accounting for 38% of total installed capacity. The share of larger corporations is decreasing, while the top five producers in 1990 made up 87% of total ethanol capacity, in 2005 this share dropped to 39%. In addition, average dry grind plants have been upscaled 235%, up to 150 million L/yr in 2005 (see Table I).

Table I: Production structure for dry grind ethanol production 1990-2005 [2].

	1990	1995	2000	2005
No. of dry grind plants	20	26	34	73
Av. plant size [10^6 L/yr]	66	67	94	150
Share dry grind capacity	34%	30%	45%	67%
Share top 5 producers	87%	78%	64%	39%

3 METHODOLOGY AND DATA

3.1 Experience curves

This study approaches technological learning by quantifying the reductions in production costs. A concept to measure and quantify this, is the experience curve approach. Using experience curves can provide insight into technology development and enables us to predict future costs, and compare the U.S. to other countries.

The Boston Consulting Group was the first to show an empirical relation between cost reductions and accumulated experience of production in an entire industry [3]. It states that costs decline with a fixed percentage over each doubling in cumulative production. The experience curve can be expressed as:

$$(1)\ C_{Cum} = C_0 Cum^b$$

$$(2)\ \log C_{Cum} = \log C_0 + \log Cum$$

$$(3)\ PR = 2^b$$

In which C_{Cum}= *Cost per unit;* C_0= *Cost of first unit produced; Cum= Cumulative production; b= Experience index; PR= Progress ratio*.

Plotted on a log-log scale the function can be fitted as a straight line. The progress ratio (PR) expresses the rate at which costs decline for each doubling in cumulative production. For instance, a PR of 0.80 implies that unit costs are reduced by 0.20 (or 20%) over each doubling in cumulative production.

Most publications on experience curves relates prices or production costs to the cumulative production of a technology [4, 5]. This is based on the principle than most processes are focussed on improving cost effectiveness. The full report also assesses the applicability of using experience curves for energy use.

Any experience curve starts with an initial value of cumulative installed capacity or production on the x-axis. This value represents the previously produced amount of units (in this study: litres ethanol), which is important because it reflects the existing experience already gained with the technology. Methodological issues occur in the determination of the initial value, since it impacts the amount of cumulative doublings in production and thereby the calculated progress ratio [6]. The use of inflation indices, co-production allocation and system boundaries are among other important methodological issues [7].

3.2 Definition of the learning system

Ethanol production in the United States can be separated in production of feedstock material (corn) and industrial processing of corn into ethanol. In this study corn production costs are separately discussed from industrial processing costs. Taking into account capital costs has appeared to be complex. Capital charges heavily depend on the cost, investment life, tax treatment of investment, interest rate in debt financing, desired return on the equity, and inflation rate [8]. Estimates are made using a scaling factor, from which historical costs for capital can be derived by correcting current costs for scale (and by using historic scaling factors).

All corn production costs have been taken into account, including economic costs that most farmers do not directly consider as expenses. All industrial processing costs for ethanol have been taken into account but costs for corn (net corn costs) have been studied separately and thereby have been left out of analysis on industrial processing costs. In addition, total ethanol production costs are assessed in which a fraction is subtracted that corrects for the co-product, DDG, production. This is co-product credit is calculated by: *DDG price * DDG yield / ethanol yield*) and is subtracted from corn costs (*corn price/ethanol yield*). Note that net corn costs are determined by corn prices, and not corn production costs.

3.3 Data

Corn production costs data is available from Economic Research Service [1]. Two separate datasets have been combined. Ethanol production costs have not been quoted structurally for a longer time period. Several individual studies have been used, among feasibility studies, engineering reports and historic estimates [among 9, 10, 11]. In addition, three cost-of-production surveys have been conducted by USDA, representing reliable data on industry average production costs [8, 12, 13]. In total 16 studies have been used, quoting production costs over the period 1980-2005. Furthermore several semi-structured interviews were held with ethanol producers, experts, consultants and agricultural economists, for assessment and data quality check.

4 RESULTS

4.1 Corn production costs

Corn production costs have been reduced considerably over the past three decades. Increasing corn yields have lowered production costs per tonne corn, but also production costs per hectare showed significant cost decrease.

In 1975 the production costs corn amounted $260\$_{2005}$/T, compared to $100\$_{2005}$/T in 2005. This is a reduction of 62%. Production costs per tonne show large fluctuations among years, caused by varying yields. Corn production costs per hectare have also declined, from $1450\$_{2005}$/ha to $950\$_{2005}$/ha, this is a 35% reduction over the same timeframe (see Figure 3). It shows highest cost reduction between 1975-1990, costs since then have remained fairly constant.

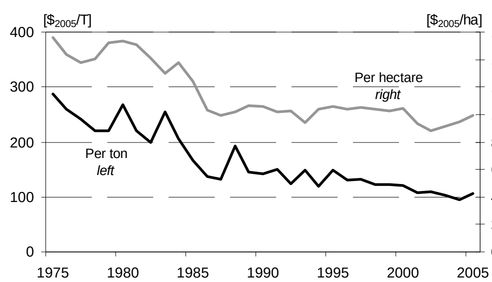

Figure 3: Corn production costs per hectare (upper line) and per tonne (lower line).

Most important contributors to total cost decline are capital costs (represent 28% of overall cost decline), taxes, insurance and land (30%) and general farm overhead (9%). Also, the costs for fertilizer have contributed 20% to overall cost decline. Only costs for fuels and electricity have increased slightly. This is caused by higher energy prices over the last five years.

Figure 4 shows the relation of corn production and corn production costs by means of an experience curve. The initial value on the x-axis is all corn produced between 1950 and 1975 (2.6 billion tonne corn). Production costs per hectare have been reduced by 36% over the timeframe 1975-2005. Over the same period, 1.85 doublings in cumulative production have taken place. This results in a progress ratio of 0.73, with a reliable fit (R^2=0.80). Corn production costs per tonne have been reduced 63% over the same 1.85 doublings in cumulative production, resulting in a lower (more benign) PR of 0.55 (R^2=0.90). This means that costs decrease by 45% over each doubling in cumulative production.

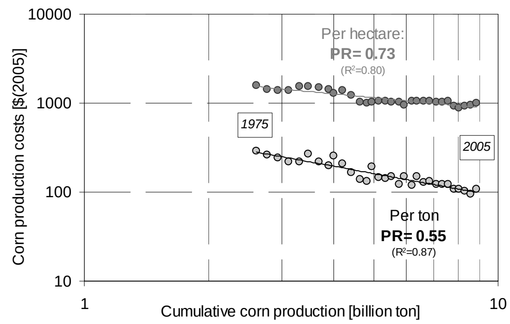

Figure 4: Experience curve on corn production costs per hectare (upper curve) and per tonne (lower).

The most significant driver behind these reductions is the achievement of higher corn yields. Corn yield have risen from 5.4 T/ha in 1975 to 9.3 T/ha in 2005. This is caused by the introduction of better corn hybrids, more optimal fertilizer use and efficient use of chemicals.

Another important driver, is the upscaling of corn farms. Average corn farm size rose from 30 ha/farm in 1974 to 80 ha/farm in 2002. This upscaling has caused 'overhead' categories such as capital costs, to drop significantly.

The use of fertilizer (mostly nitrogen) has recently decreased. This is stimulated by high energy prices, and therefore high prices for the energy intensive fertilizer and new studies that found an optimal fertilizer application rate, below the earlier used rate.

Genetic modified corn has been introduced since 1996. Largest benefit from these corn hybrids is the improvement of the seed's resistance to diseases and infections and eliminating the use of chemicals. Although, corn yields are not directly higher in these genetic modified crops.

For the future, corn prices will be more than ever determined by speculation and forecasts on future corn supply. Historically little integration of corn production and ethanol processing existed. However, high ethanol demand and high corn prices have now resulted in an announced 15% increase in corn hectares for 2007 [14]. Further integration of corn and ethanol production will be stimulated by the introduction of corn hybrids that have higher starch contents enabling higher ethanol yields in the ethanol plant.

4.2 Industrial processing costs

The costs for industrial processing of corn into ethanol have decreased as well. Costs for corn and capital are excluded in this section. Ethanol processing costs in 1983 amounted around $240\$_{2005}/m^3$ and have dropped to below 130 $\$_{2005}/m^3$ in 2005, representing a 40-50% reduction (see Figure 5).

The largest cost decline occurred in the early 1990's, when costs dropped from levels above $200\$_{2005}/m^3$ to below $150\$_{2005}/m^3$. It appears that costs remained about constant until the end of the 1990's. The remarkable drop in 1999 is due to assumptions in this (modelling) report. The slight increase towards 2005 is mostly caused by increasing energy prices. Three reliable industry average data points are available, it shows that costs in 1987, 1998 and 2002 were respectively 205, 129 and 118$\$_{2005}$/m^3 [8, 12, 13]. These numbers also show a larger decrease at first (1987-1998), which flattens out towards the end (1998-2002).

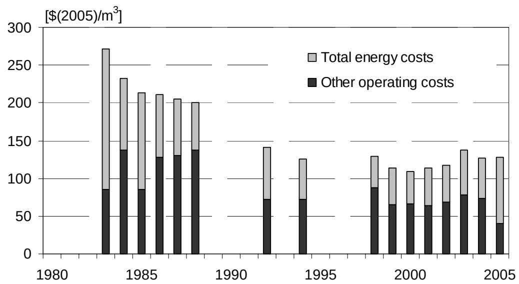

Figure 5: Industrial processing costs, separated in costs for energy and 'other operating costs' (excluding costs for corn and capital).

Major cost contributors are energy costs (fossil fuels and electricity), which represent the largest part (~40% in three industry surveyed years). Important other cost categories are labour, enzymes and chemicals (mostly yeast and chemicals used for boiler and process water treatment). Since the early 1980's labour costs dropped 70%, enzyme costs were reduced by 75%. Although energy prices rose, the costs for fuel and electricity dropped from around 140 to 70$\$_{2005}$/m^3 in 2005 (50% reduction).

By relating cumulative ethanol production with industrial processing costs, an experience curve can be constructed (see Figure 6). The initial value is set at 0.375 million m^3, representing five years experience gained in overlapping beverage and fuel ethanol production in the industries early ages. Cumulative dry grind ethanol production doubled 7.2 times since 1983. The progress ratio of this curve is given 0.87 with a reliable fit of R^2=0.90. Thus, industrial processing costs have decline 13% over each doubling in cumulative production.

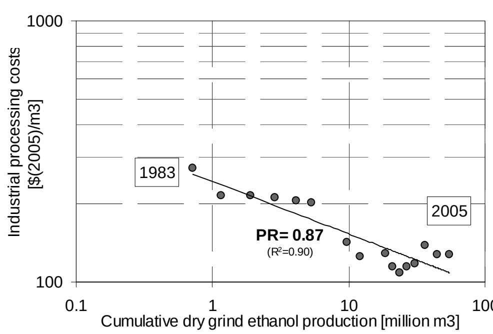

Figure 6: Experience curve on ethanol processing costs 1983-2005 (excluding corn and capital costs).

Key drivers behind the cost reduction in ethanol processing are first of all, higher ethanol yields. In 1983 yield amounted around 370 L/T, whereas average yield in 2005 was around 400 L/T. Yield fluctuates between plants and within months but average yield in the industry is estimated at 400 L/T.

Energy use in the industrial processing of ethanol has decreased considerably from around 35 GJ/m^3 in 1983, to 10 GJ/m^3 in 2005. In an extensive analysis on energy requirements (available in report), this reduction is attributed and quantified in detail to several technological developments. It was found that the largest drop in energy use, occurred in between 1983 and 1990, when energy usage was reduced to 15 GJ/m^3. Another 5 GJ reduction was obtained in the subsequent 15 years.

Dry grind ethanol plants have been upscaled considerably. An average sized plant in the mid 1980's was no larger than 10 million L/yr, whereas average dry grind plants in 2005 are around 150 million L/yr. Two phases of upscaling can be distinguished, first between 1983 and 1990, and secondly between 2003-2005. Economies of scale have probably effected both operating and capital costs.

Distributed control systems have cut costs in ethanol plants mainly by reducing the labour required, but they have also improved production efficiency in other ways, letting operators fine-tune processes they could not control as closely in the past [15]. Whereas in the early 1980 a 150 million L/yr plant used 150 employees [10], the same plant now only needs around 30 employees.

Other improvement include the achievement of higher ethanol concentrations in the fermentor, which lowers energy use. Azeotropic dehydration has been substituted by molecular sieves. This eliminated the use of (hazardous) cyclohexane or benzene in azeotropic dehydration and reduced costs of the installation [16]. Moreover, it reduced energy inputs for dehydration considerably from 4.75 GJ/m^3 to 3.90 GJ/m^3 for distillation [17]. Heat integration in general has improved. Reuse of energy from liquefaction and saccharification to remove water in the distillation column is applied now in many plants [13].

4.3 Total ethanol production costs

Figure 7 shows that total production costs have decreased 55-65% from around 800$\$_{2005}$/m^3 in the early stages of ethanol production, to around 300$\$_{2005}$/m^3 in 2005. Again, between 1988-1992 highest cost decline is observed.

Total ethanol production costs comprises total operating costs (see Section 4.2), plus capital charges ('capital recovery' or 'depreciation'), plus net corn costs. The latter represents the cost of corn per cubit metre ethanol with subtraction of a co-product credit to correct for DDG production. Note that corn costs for the ethanol producer are dependent on corn prices and not on corn production costs. Capital charges are only quoted in a few studies, and have been corrected for industry average plant sizes by using scaling factors.

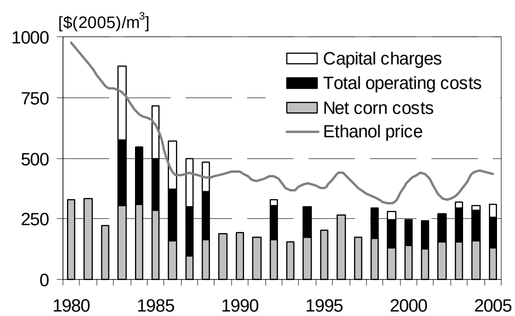

Figure 7: Total ethanol production costs.

Annual net corn costs have been calculated by using average DDG prices (1980-2005), keeping DDG yield fixed and extrapolating ethanol yield from 370L/T in 1980 to 400L/T in 2005. Operating costs (i.e. industrial processing costs) were not annually available; 16 data points have been plotted. No sufficient industry average data on capital charges was available. Mostly due to differences in plant design, owners preference and add-on capacity during operation. Nonetheless, a few studies quote capital charges and representative values (acknowledged by experts) have been plotted.

It shows that ethanol prices were slightly below total production costs in the 1980's. A government tax credit of approximately $240\$_{2005}/m^3$ (presently: 0.51\$/gallon blended), still made ethanol production, on average, profitable. Over the past 15 years ethanol production costs are below ethanol prices. Ethanol prices highly correlate with gasoline prices (0.66), so with increasing gasoline prices margins for ethanol producers are likely to increase. Total ethanol production costs correlate 0.87 with ethanol prices (using 11 available point on *total* ethanol production costs), indicating a sharp relation between costs and prices.

Construction of an experience curve on total ethanol production costs (not displayed) results in a progress ratio of 0.84 (R^2=0.90) by using similar assumptions as in Section 4.2. If we replace the 'net corn costs' by calculated corn costs, based on the production costs of corn and not corn prices, another curve is obtained. The fit turns out unexpectedly worse (R^2=0.87), whereas the PR is changed to 0.83. This indicates slightly lower technological development compared to actual ethanol production costs. The decline in corn prices appears larger than the decline in corn production costs. This stresses the importance of future corn prices for the economic feasibility of ethanol production in the United States.

It shows that within total ethanol production costs, the co-product DDG considerably contributes to the economic performance of U.S. ethanol. Net corn costs have always made up a large share in total production costs. Fluctating prices for DDG, energy and corn are among the most impartant factors that determine ethanol production costs in the future.

5 DISCUSSION AND CONCLUSIONS

5.1 Discussion

The use of experience curves requires sufficient consistent, industry average data. Limited data availability of ethanol processing cost leads to many uncertainties. Only three cost-of-production studies are available, which show nonetheless a downward trend. Studies on ethanol production should be considered individually, since also categorisation into several cost contributors varies among authors. For corn production however, the use of an experience curve appears legitimate because of the large and consistent data availability.

It showed that observed progress ratios are heavily dependent on the choice of inflation index to correct costs for inflation. In this study the U.S. gross domestic product (GDP-) deflator has been used. The full report available by the author, shows that if specific inflation indices are used for the different systems, a progress ratio can be significantly influenced.

The determination of the initial value influences calculated progress ratio's to great extent. Concerning corn production, an assumption is made on previous experience of production. In this study all production between 1950-1975 has been taken into account. The rapid increase in corn production and productivity since 1950 is the main reason for chosen this point in time. Concerning industrial processing costs, five year of beverage alcohol production has been taken as initial value. First dry grind ethanol production, had great similarities with beverage alcohol production and some plants between 1978-1983 probably produced both. Progress ratio's will increase, the less initial production one takes into account. Relative low progress ratio's for U.S. corn production are mainly caused because few doublings in cumulative production have taken place since 1975, because of a large initial value is chosen. Relative high progress ratio's are obtained for ethanol processing costs. This is due to the fact that ethanol production has been analysed from the early beginning of the industry when still small amounts of ethanol were produced. By having taken less previous production into account (simply, because there wasn't any significant production), the number of cumulative doublings is high resulting in lower progress ratio's.

Despite assumptions and uncertainties, results in this study can be used for extrapolation. The full report provides an analysis on future ethanol production costs by following prescribed levels of ethanol production until 2012. It also provides an overview of current technologies under development to further decrease production costs and increase productivity.

Comparing the United States ethanol production with Brazil, shows that Brazil has significant more experience of production in terms of years, but even more in terms of cumulative production up to 2005. Whereas the Unites States has produced up to 125 billion litres in 2005 (of which only 55 billion litres in dry grind production processes), Brazil has produced 300 billion litres since 1975. Both countries show that feedstock production costs (for Brazil: sugarcane) have decreased by approximately 60%. But differences in cumulative (corn) production lead to a higher progress ratio for Brazilian sugarcane production than for U.S. corn production. Concerning industrial processing costs, Brazil has shown more cost reduction since the (commercial) start of the ethanol industry in 1975, around 70% whereas U.S. processing costs have decreased 45% since 1983. For Brazil, this results in a progress ratio of 0.81 and for the United States a PR of 0.87 is obtained. Current production costs are lower in Brazil as they are in the United States (175 $\$/m^3$ vs. 300 $\$/m^3$).

5.2 Conclusions

The analysis has proven that the total costs of ethanol in the United States have decreased with cumulative production. Feedstock production costs follow an experience curve from 1975-2005, resulting in a progress ratio of 0.55. Analysis of industrial processing costs (excluding corn and capital costs) since 1983, resulted in a progress ratio of 0.87. However, the validity of plotting an experience curve based on a wide variety of studies triggers limitations. Nonetheless, the cost reduction in U.S. ethanol production is substantial. By also taking into account (net) costs for corn and capital, cost decline since 1983 amounted 60%. Ethanol is currently produced for around 30$ct per litre. Costs reductions have been achieved throughout the whole, compound, production system.

Because feedstock costs contribute significantly to the total production costs of ethanol, the conclusion can be drawn that the experience curve approach presents better insights when using compound systems, surely when analyzing cost reductions in bio-fuel supply chains. However, U.S. production costs are dominated by corn prices. This raises questions about applying the experience curve approach on corn production costs, since little correlation exists between corn prices and corn production costs. Also, the two systems are in practice separated, even with high involvement of farmers.

Higher corn yields, by introducing better corn hybrids and efficient usage of chemicals and fertilizers have reduced corn production costs most. Increasing farm sizes are likely to have reduced overhead costs considerably. Upscaling of ethanol plants, the use of better enzymes and a significant reduction in energy use are among the most important causes of the industrial cost decline.

Insight into the various contributors to production costs, is essential to understand and predict further cost decline in the future. Using experience curves for extrapolation is of limited value, when prices for energy and corn determine production costs the most. However, it can function as a valuable tool for policy makers, who can observe the increasing (beneficial) gap between decreasing corn production costs and increasing corn prices. For ethanol producers, the future is looking bright as well: while ethanol production costs decline, ethanol prices increase by following the continuous increase of gasoline prices.

FURTHER RESEARCH

The full report of this study is available at the website of STS (www.chem.uu.nl/sts) or can be requested by contacting the main author. This report also covers the development in energy efficiency of ethanol production and the applicability of using experience curves for energy requirements. In addition it provides in-depth data on the structure of the industry and the historic developments over time. The report is in progress for publication.

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