Understanding the reductions in US corn ethanol production costs: An experience curve approach

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ABSTRACT

The US is currently the world's largest ethanol producer. An increasing percentage is used as transportation fuel, but debates continue on its costs competitiveness and energy balance. In this study, technological development of ethanol production and resulting cost reductions are investigated by using the experience curve approach, scrutinizing costs of dry grind ethanol production over the timeframe 1980–2005. Cost reductions are differentiated between feedstock (corn) production and industrial (ethanol) processing. Corn production costs in the US have declined by 62% over 30 years, down to $100\$_{2005}$/tonne in 2005, while corn production volumes almost doubled since 1975. A progress ratio (PR) of 0.55 is calculated indicating a 45% cost decline over each doubling in cumulative production. Higher corn yields and increasing farm sizes are the most important drivers behind this cost decline. Industrial processing costs of ethanol have declined by 45% since 1983, to below $130\$_{2005}$/m^3 in 2005 (excluding costs for corn and capital), equivalent to a PR 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 1980s, 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, the average size of dry grind ethanol plants increased by 235% since 1990. For the future it is estimated that solely due to technological learning, production costs of ethanol may decline 28–44%, though this excludes effects of the current rising corn and fossil fuel costs. It is also concluded that experience curves are a valuable tool to describe both past and potential future cost reductions in US corn-based ethanol production.

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1. Introduction

Worldwide, countries are facing the consequences of finite and unequal distributed fossil resources, such as increasing concerns on the security of energy supply and increasing fossil fuel prices. Also, the reduction of anthropogenic greenhouse gas emission is a key policy priority in many countries of the world. Subsequently, there is a growing demand for biofuels in the transportation sector, stimulating the production of biodiesel, derived from vegetable oils such as rape seed and soybean oil, and ethanol from feedstock such as sugarcane and corn.

In 2006, the US has surpassed Brazil as largest producer of ethanol in the world, which production has increased from as little as 0.7 million cubic metre (m^3) in 1980 to over 18 million m^3 in 2006. In the 2006 and 2007 State of the Union, the US was claimed to be 'addicted to oil' and large increases in biofuel production were announced, up to 130 million m^3 in 2017.

While US ethanol production is expanding rapidly, debates continue on its cost competitiveness and energy balance. Some claim that ethanol is only viable with subsidies, at high oil prices, and tariffs still protect US ethanol producers from cheap imports from Brazil. Insight into historical technology development of ethanol production can provide valuable information on (the success or failure of) the biofuel production chain and support system; moreover, this could indicate the potential for future reduction of production costs. One method that enables us to quantify technology development over an extended period of time is the experience curve approach.

The experience curve concept links developments in production costs (or prices) with cumulative production, representing accumulated experience of production. Production costs tend to

decline with a fixed percentage over each doubling in cumulative production. For the energy sector, this concept has been applied to production costs of several renewable energy technologies in order to evaluate policies and chart possible future developments (see McDonald and Schrattenholzer (2001) for an overview).

A variety of studies exist on US ethanol production costs[1] for particular time periods and production technologies. However, to date, no comprehensive overview of the developments in production costs in US ethanol production has been published. Insights into the declining costs and driving factors behind the cost reductions can provide both valuable lessons and indicate further potential for cost reductions. Furthermore, to the authors' knowledge, an experience curve approach has never been applied to ethanol production in the US.

The objective of this study is to assess technological learning in US ethanol production by quantifying the reductions in production costs. Underlying reasons for these reductions will be identified by means of a qualitative analysis of the technology development and allocated to either feedstock production (corn) or industrial processing (ethanol). The study focuses on corn-derived ethanol production in a dry grind production process only, over the timeframe 1980–2005.

Background and case setting are presented in Section 2. Theory and methodology are described in Section 3. In Section 4, an overview of the data collection is provided. Next, in Section 5 results are presented, subdivided in qualitative developments, corn production costs and ethanol processing costs. In Section 6, the context and limitations of the study are described. In Section 7, the results are compared with a similar study scrutinizing cost reductions for ethanol from sugarcane in Brazil (Van den Wall Bake et al., 2008). An outlook for potential future cost reductions for ethanol from corn is presented in Section 8, and finally general conclusions are presented in Section 8.

2. Case background: US ethanol production

2.1. Corn and ethanol production volumes

In 2005, the US consumed 530 million m^3 of gasoline (EIA, 2007). In that year the production of ethanol reached 15 million m^3 (RFA, 2007). Ethanol made up 2.8% of US fuel supply by volume (1.9% based on HHV energy content). With US production growing to 18 million m^3 in 2006, the US has become the world's largest ethanol producer. Ethanol is now blended in 46% of US gasoline. Historic and mandated ethanol production is displayed in Fig. 1. Future production is likely to exceed prescribed levels in the Renewable Fuels Standard (RFS) considerably (Urbanchuk, 2006).

Corn-based ethanol accounts for 97% of total US ethanol production (Urbanchuk, 2007). The US is the largest corn producer in the world, with production in 2005 reaching 282 million tonnes (see Fig. 1), representing 40% of the world's corn production. Highest corn yields up to 10 tonnes/ha are obtained in the US (USDA/FAS, 2007). US corn supply almost doubled between 1975 and 2006. In 2006, 17% of total US corn supply went to ethanol production (equal to at least 7% of world corn production). The increased share for ethanol is mostly compensated for by lower stock levels, which are presently at a historical low level. Relative
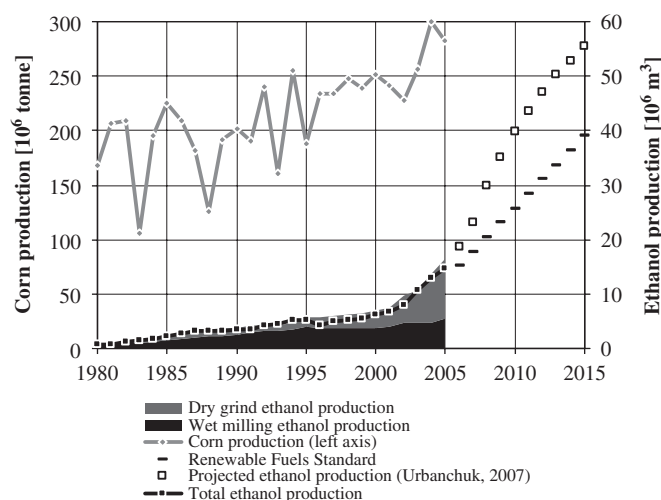
Fig. 1. US Corn and ethanol production volumes 1980–2005. Ethanol is separated in dry grind and wet milling. The horizontal bars represent mandated ethanol production by the RFS. Projected production by Urbanchuk (2007) exceeds the RFS largely. (*Data sources*: Keim, 1983; Swank et al., 1987; RFA, 2007; Urbanchuk, 2007; USDA/ERS, 2007).

corn exports decreased as well, while the share for animal feed remained constant (USDA/ERS, 2007).

Ethanol is currently produced in 136 plants with a further 77 under construction, mostly located in the corn rich Midwest area, or 'Corn Belt'[2] (RFA, 2007). A significant share of the plants is owned by farmers' cooperatives, but investments from Wall Street are rising. Ethanol plants generally require feedstock sourcing within a 80 km radius to keep transportation costs low (BBI, 2000). Farmers' cooperatives are closely located to corn supply and involved farmers are obliged to bring a share of their corn to the ethanol plant. However, the production of corn ethanol is a non-vertically integrated market, since ethanol producers still pay market prices for corn. This is in contrast with Brazil, were ethanol producers own (shares of the) sugarcane plantations. The majority of the growth in US ethanol production has been the result of farmer ownership and investment in dry grind ethanol facilities, but significant investments now come from non-farmer investors (Hansen, 2006).

2.2. Ethanol production technology

Two processes for producing ethanol from corn exist: wet milling and dry grinding. Fig. 1 shows the growing contribution of dry grind production within total US ethanol production. In the wet milling process, the corn kernel is fractionated into starch, fibre, corn germ and protein. Only pure starch is used in the production of ethanol. Various co-products are produced, i.e. corn oil, corn gluten meal, corn gluten feed, and carbon dioxide and some large wet milling plants also produce vitamins, food and feed additives. Market prices determine which product will be produced most (Coltrain et al., 2004).

In the dry grind process, the whole kernel is grinded and water is added. The corn mash is cooked, and enzymes are added to convert starch to glucose. The glucose is then converted to ethanol through fermentation. After the ethanol is removed and distilled, a denaturant (generally gasoline) is added to make it non-potable. The residual liquid passes through a centrifuge and is converted to

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[1] Among which the US Department of Agriculture (USDA) has conducted three cost-of-production surveys (years 1987, 1998, 2002), McAloon et al. (2000) have developed cost models for ethanol production. BBI and Novozymes (2002, 2005) have documents in which developments are visually presented. For a comprehensive overview, see Hettinga (2007).

[2] Consisting of the states Illinois, Iowa, Indiana, Ohio (together accounting for 50% of the US corn production) and parts of South Dakota, Nebraska, Kansas, Missouri, Wisconsin, Minnesota, Michigan and Kentucky.

thin stillage and wet distiller's grains. This can only be fed to dairy and beef cattle within close distance to the plant, since the shelf life is limited. In most cases the distillers dried grains with soluble (DDGS) is dried and fed to cattle within a wider radius.

Consistent annual data on the type of production process is only available for years 1990–2005. These numbers provided by Urbanchuk (2007) have been combined with a small number of studies that describe the state of the industry in the 1980s (Keim, 1983; Swank et al., 1987). Fig. 1 shows ethanol production divided in dry grind and wet milling production. The increasing share of dry grind capacity passed wet mill capacity in 2002 as the prevalent technology, and in 2005, the share of dry grind plants represented 67% of total installed capacity (73 out of a total of 92 plants).

Yield in wet milling plants is generally lower compared with yields in dry grind plants (approximately 0.37 vs. 0.40 m^3/tonne as industry average in 2002 (Shapouri and Gallagher, 2005) since in wet mills a fraction of the starch is processed into other products. Dry mills are typically smaller and cost less to build. Wet mills focus on a variety of products, while dry grind plants are solely optimised on ethanol production. No new wet milling plants have been built since 1990, whereas the number of dry grind plants is expanding rapidly. The major development in technology has occurred in the dry grinding industry, primarily because of the variety of technologies from which to learn (Madson and Monceaux, 1999). For the future, dry grind production is likely to remain the dominant production process. Therefore, in the remainder of this paper, only dry grind ethanol plants are discussed. However, the technological gap between wet mills and dry grind operations is closing, since new technologies in dry grind plants can fractionate the corn kernel before liquefaction. The trend for new plants it to become 'bio-refineries' that produce a larger variety of valuable co-products (Rendleman and Shapouri, 2007).

3. Methodology

3.1. General experience curve theory

The way new technologies develop and diffuse is characterised by various stages from invention to wide spread implementation (Grübler et al., 1999). In each of these stages, different learning mechanisms play a role that lead to technological change and result in cost reductions (see e.g. Neij et al., 2003; Junginger, 2005).

A concept to measure and quantify the aggregated effect of technological development is the experience curve approach. This concept states that costs decline with a fixed percentage over each doubling in cumulative production. The experience curve can be expressed as

$$C_{Cum} = C_0 Cum^b, \tag{1}$$

$$PR = 2^b, \tag{2}$$

where C_0 is defined as the cost of the first unit of production; Cum is the cumulative unit production at present; b is the experience index; C_{cum} is the cost per unit at present; and PR the progress ratio. 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 20% over each doubling in cumulative production. The error in the PR, derived from σ_b that represents the standard error in the experience index (b), can be determined as follows (Sark, 2007):

$$\sigma_{PR} = \ln 2 PR \sigma_b. \tag{3}$$

Experience curves can be used for a number of purposes: to estimate future costs and to formulate a corporate strategy, as input for energy models, for policy evaluation and new policy formulation. For an overview, see Neij et al. (2003) or Junginger (2005).

Most publications on experience curves relate prices or production costs to the cumulative production of a technology (IEA/OECD, 2000; McDonald and Schrattenholzer, 2001). Production costs are preferably used as a performance indicator for technological learning. Prices can be used as proxy for costs, but only in a competitive market where profit margins are a fairly constant share of total prices and no forward pricing, price umbrella or shakeout effects exist (IEA/OECD, 2000). As an alternative, energy consumption in the production process ('specific energy consumption') can be used as a performance indicator for technological learning, this has been assessed by Ramirez and Worrell (2006) and Hettinga (2007).

The cost of most renewable energy technologies are determined by investment, and operating and maintenance costs. The use of experience curves for bioenergy systems differs from most other (renewable) energy technologies since they also require fuel, which is produced in a different (agricultural) system. We analyse these two learning systems separately, following the compound learning system for biomass energy systems suggested by Junginger (2005), allowing a more detailed analysis of the contribution of specific processes in each system. Costs for feedstock production are separated from the industrial processing costs of ethanol. Capital costs form a third separate category in this study.

3.2. Definition of the learning system

For constructing experience curves on US corn production, annual production numbers are aggregated to a cumulative production volume. Important here is the point in time where you start to count production volumes ('initial value') and what production you take into account (system boundaries), as these determine the number of cumulative doublings to a large extent. All production between 1950 and 1975 is taken as initial value on the x-axis of the experience curve. During this time period 65% of total cumulative corn production since 1866 occurred. Yields have increased considerably since 1950, indicating the start of large scale commercial production. Geographical system boundaries are set on a domestic scale, whereby the learning from other countries' corn production is neglected. The US is the largest producer of corn in the world and is achieving highest yields. A national approach to analyse technological learning is in this study justified, since little technology and knowledge transfer is occurring between the US and China due to different production technologies, country and local markets. To measure the performance, all production costs in corn production are assessed, including costs for machinery and equipment, inputs (fertilizer, chemicals, etc.), energy, operation and maintenance, and labour. This also includes economic costs, such as 'opportunity costs for labour' that farmers do not directly consider as production expenses (McBride, 2007).

The system for industrial processing consists of all stages of the process of converting corn to ethanol and its co-product (distillers dried grain with soluble, DDGS) in a dry grind production process. Transportation of ethanol to blenders has not been taken into account neither has the transportation of fuel blends (E10 or E85) to the pump been included. By constructing experience curves for industrial processing, experience is represented by cumulative ethanol production in US dry grind processes. The production process in the US differs strongly from processes in other

countries, mostly because other feedstock is used (e.g. sugarcane in Brazil). The dry grind production process of corn (starch)-based ethanol is unique and cannot be compared with existing wet milling processes, which legitimates our focus on national, dry grind ethanol production only. Early fuel ethanol dry grind plants used technologies originating from the beverage alcohol industry, and some plants produced both for a while (Keim, 1983). The experience gained in beverage alcohol production cannot be neglected. In this study, we choose to represent this experience by using an initial value of 5 years of overlapping fuel and beverage alcohol production of 75,000 m³/year between 1978 and 1983.

Production costs in industrial processing include all costs for equipment, operation and maintenance, inputs and labour. Costs for corn (input) are excluded, since a separate analysis on corn production has been conducted. Capital charges (costs annually charged for operating capital and initial investment) have been excluded from the analysis on industrial processing costs, as there were only very limited amounts of data available. However, in parts where total ethanol production costs are analysed in this study, feedstock and industrial costs are combined with estimates on capital charges, based on calculated expected capital costs, using a scaling factor and a few studies that reported capital charges.

Next to ethanol, DDGS is produced. A portion of the industrial processing costs has to be allocated to this co-product. This is based on market value, by calculating the value of DDGS produced for each volume unit of ethanol. This credit lowers the overall ethanol production costs and has been subtracted in parts where we look at total ethanol production costs (including costs for corn).

The effect of varying most of these methodological assumptions is discussed in Section 6.1.

4. Data collection and processing

4.1. Data collection

Data on corn production volumes has been collected from databases of the Economic Research Service (USDA/ERS, 2007) and National Agricultural Statistics Service (USDA/NASS, 2007) of the USDA. Data on ethanol production volumes has been acquired from the Renewable Fuels Association (RFA), Bryan & Bryan International (BBI) and John Urbanchuk (LECG consultancy).[3]

Data on corn production costs has been acquired from USDA/ERS in two separate data sets (1975–1995; 1995–2004). Corn prices were obtained from USDA/ERS and USDA/NASS. Data on ethanol production costs are not documented systematically and have in most cases been acquired in individual studies. The USDA has conducted three cost-of-production surveys (i.e. Kane and Reilly, 1989; Shapouri et al., 2002b; Shapouri and Gallagher, 2005), which provide representative industry average production costs. McAloon et al. (2000) have assessed ethanol production costs in a cost model. Several other feasibility and engineering studies are used (among Keim, 1983, 1989; Wood, 1993) and (BBI, 2000; BBI and Novozymes, 2005).[4] Ethanol prices were obtained via OPIS and Hart Oxyfuel News.

For assessment and insights in corn and ethanol production several interviews were held with experts and plant operators. Hosein Shapouri (Office of the Chief Economist/USDA) and John Urbanchuk (LECG) have provided additional data. Furthermore, an

ethanol production cost model is available at the Eastern Regional Research Center (ARS/USDA). This process and economic model is based on data from ethanol producers, engineering firms and equipment manufacturers, and was used to estimate production costs for 2005.

4.2. Data processing

All corn and ethanol production numbers have been converted to SI units. Costs and prices have been corrected for inflation using the US Gross Domestic Product (GDP)-deflator, and have been converted to constant US dollars of 2005 ($_{2005}$).

To enable the comparison with ethanol data, corn production volumes have been converted from marketing years (September–August) to calendar years. In parts of the study where corn and ethanol data are treated separately, data for corn are quoted in marketing years.

Two different datasets (USDA/ERS, 2007) on corn production costs have been combined by structuring cost contributors into identical categories. Ethanol production costs are reported inconsistently but have been grouped as much as possible. In order to avoid large differences in quoted costs, only data representing average-sized plants are taken into account. Therefore some existing studies have been left out of the analysis and from other studies that provide production costs for a range of sizes an average plant size for 2005 of 150,000 m³/year was taken.[5] Capital charges in the 1980s have been estimated by using scaling factors and the use of representative numbers on capital costs in literature.

Several (pre-)feasibility studies examine dry grind ethanol production costs in the early 1980s when no commercial dry grind ethanol production existed (e.g. Katzen Int., 1979; Office of Technology Assessment, 1979; Meekhof et al., 1980; Keim, 1983). These are mostly based on best available technologies, and do not represent industry averages. Still, it provides valuable (historic) data on technologies and the breakdown of costs. Numbers quoted in these publications are assumed to represent data for 2 years after the publication date, thereby representing production costs for early dry grind ethanol production.

5. Results

In Section 5.1, first qualitative developments in the corn and ethanol production are described. In Sections 5.2–5.4, the resulting cost reductions are quantified.

5.1. Qualitative description of developments

Increasing corn yields, upscaling of farms and the 'industrialisation' of agriculture have affected US corn production volumes and production costs. Key drivers are summarised in Table 1 and described below.

1. *Yield*: Yields have increased by 70% over 30 years. Before 1950, corn grew by open pollination with stable yields below 2 tonnes/ha. The first large increase was observed after 1950 when corn production became more commercialised and fertilizers were introduced. The introduction of better corn hybrids was a key driver behind the average yield increase to 5 tonnes/ha by 1970 (Haefele, 2006). Single cross hybrids have

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[3] John Urbanchuk has kindly provided unpublished datasheets on production volumes between 1990 and 2005.

[4] In total 16 studies have been used for ethanol production costs over the period 1983–2005.

[5] This had probably led to the reporting of lower costs than industry averages, due to smaller plant sizes in the early years and subsequently lower economies of scale.

Table 1
Changes in corn production and productivity (*Data sources*: Leath et al., 1982; Foreman, 2001, 2006)

	1980–1985	1985–1990	1990–1995	1995–2000	2000–2005	Unit
Corn yield	6.5	7.1	7.4	8.1	8.9	tonnes/ha year
Annual corn production	185	189	206	233	260	10^6 tonnes/year
Number of corn farms	700	630	500	450	350	1000 farms
Average scale	40	40	55	65	80	ha/farm

Table 2
Industry and production process overview (*Data sources*: Keim, 1983; Swank et al., 1987; RFA, 2007; Urbanchuk, 2007)

	1990	1995	2000	2005	Unit
Annual production	3.9	5.7	7.2	16	$10^6\,m^3$
Wet mill prod.	2.5	3.9	3.8	5.4	
Dry grind prod.	1.3	1.7	3.2	11	
Number of plants	37	45	53	92	
Wet mills (av. capacity)	9	11	10	10	
Dry grind plants (av cap.)	20	26	34	73	
Top 5 market share (%)	87	78	64	39	

been used since then, further increasing yield to a record height of 10 tonnes/ha in 2004.

2. *Average size*: US corn farms sizes have increased by 180% since 1974. While the number of corn farms more than halved, corn production almost doubled. The average operating and ownership costs per hectare and the total costs per hectare do not vary significantly among farms of different sizes. However, significant economies of scale exist in production per tonne. There are some major differences in the costs, characteristics and production practices that depend on the size of corn enterprises (see Foreman, 2001, 2006). For a more comprehensive description, see (Hettinga, 2007).

The *industrial process of converting corn to ethanol* has experienced changes in production technology, adoption of more energy-efficient technologies and plants have been upscaled over the last 25 years. Key drivers behind the decline in processing costs are summarised in Table 2 and described below.

1. *Shift from beverage alcohol-based technologies*: Early dry grind ethanol plants used production technologies that were based on beverage alcohol production. A large reduction in production costs and energy use has occurred when these technologies were substituted for specific and more optimal fuel ethanol technologies (Madson and Murtagh, 1991). These new technologies focussed on high ethanol yields, required a dehydration step and made use of automation leading to lower labour requirements.
2. *Structural changes in prevalent technology*: Several structural changes in US ethanol production and market have led to significant cost reductions. The large shift in prevalent production technology has been described in Section 2.2; this has led to a fast development of dry grind ethanol plants.
3. *Farmers' involvement*: Ethanol production in the mid 1980s was dominated by farmers' involvement. During the mid 1980s, a high numbers of small-scale dry grind plants switched from beverage alcohol to fuel ethanol production, but many of these small plants ceased operation before 1990 (Madson and Murtagh, 1991). In the early 1990s larger companies entered the market, and dominated it. However, since the year 2000 a renewed farmers involvement is observed. In 1991, the largest

producer Archer Daniels Midland (ADM) was responsible for 64% of total US ethanol production, this share dropped to 25% in 2005. The production has become more diffused: the top five companies made up 87% of total production in 1991, this share fell to 39% in 2005. In 2005, 46 plants were farmer owned accounting for 38% of total installed capacity. Larger scale generally relates to more efficient operations, but some very small-scale plants have benefits as well. These plants can often sell the DDGS to local cattle without drying, are in close distance with corn supply and require minimal overhead because ethanol production is carried out next to usual farming (Kane and Reilly, 1989).

4. *Upscaling*: Farmers cooperatives generally operate dry grind plants with low average capacities (137,000 m^3/year). These plants cost less and are easy to operate. Dry grind processes have been upscaled between 1990 and 2005 (135%). The number of plants (both wet and dry) has increased by 148% since 1990, whereas installed capacity increased 325%. Upscaling is responsible for 43% of total increase in capacity since 1990 and 57% by building new plants.

Next to the increasing scale of ethanol plants, six other major (technological) drivers for cost reductions have been identified (see Hettinga (2007) for an comprehensive overview):

1. *Higher ethanol yields*: Average ethanol yield has increased by 8%, from 0.37 m^3/tonne in the early 1980s to 0.40 m^3/tonne on average presently. Optimising ethanol yield results in lower costs for (expensive) feedstock and lower processing costs that relate to feedstock handling.
2. *Reduced enzyme costs*: Enzymes have decreased in prices and have become more efficient. This has reduced enzyme costs by 70% since 1980 (BBI and Novozymes, 2005).
3. *Better fermentation technologies*: Yeast propagation, SSF and SSYPF techniques have resulted in higher fermentation rates (presently: 15% ethanol concentration) that has reduced energy needs for evaporation.
4. *Distillation and dehydration*: Molecular sieves have replaced energy intensive dehydration technologies resulting in lower energy use and reduced investment costs.
5. *Heat integration*: Heat recovery and reuse of energy in the process have improved across the industry. Especially reuse of energy from liquefaction and saccharification to remove water in the distillation column is applied in many plants (Shapouri and Gallagher, 2005).
6. *Automation*: Distributed control systems have cut costs in ethanol plants mainly by reducing the labour requirements, but they have also improved production efficiency in other ways.

5.2. Development of corn production costs

Fig. 2 shows the decline in US corn production costs over the period 1975–2005. Production costs of corn declined by 62%, from
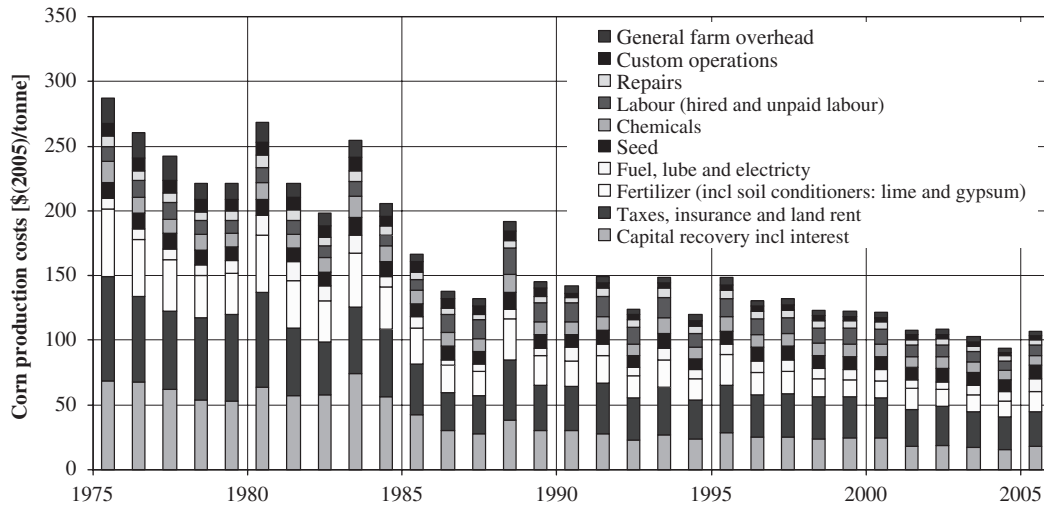
Fig. 2. Breakdown of corn production costs 1975–2005. (*Data source*: USDA/ERS, 2007).

260$_{2005}$/tonne in 1975 to 100$_{2005}$/tonne in 2005.[6] If the effect of increasing yields is excluded by analysing costs per hectare, still costs have declined by 35%. High cost reductions are observed in the early 1980s. After 1985 costs per hectare remained fairly constant, but ever increasing yields drove the production costs further down. Due to crop losses in 1980, 1983, 1988, 1993 and 1995, costs per tonne were considerably higher (for underlying causes, see: Hettinga, 2007).

Costs for 'taxes, insurance and land rent', 'capital recovery' and 'fertilizer' are the most important categories showing both highest shares in total production costs, and largest contributions to overall cost decline. Also 'farm overhead' costs have declined remarkably. Rising energy prices over the last 3 years resulted in higher costs for fuels, electricity and fertilizer. But increasing yield outbalanced the higher costs for fertilizer, resulting in a decline of fertilizer costs per tonne. Costs for fuels and electricity have nonetheless increased per tonne. Fig. 2 shows the breakdown of corn production costs.

Fig. 3 shows the relationship between corn production and production costs by means of an experience curve. Corn production costs have been reduced by 62% over 1.85 doublings in cumulative production, resulting in a *PR* of 0.55 ± 0.02 ($R^2 = 0.87$).[7] This states that corn production costs per tonne declined 45% over each doubling in cumulative production. By excluding major weather influences (as identified in Hettinga, 2007) the *PR* is unchanged, but the fit improves ($R^2 = 0.91$), which indicates of good representation of reality.

The sharp decline of production costs in 1986 is mostly caused by decreasing capital and land costs. Likely, the observed shakeout among small-scale farmers led to a higher availability of capital and land, and thus to lower prices for these categories. In general, much of the cost decline can be attributed to indirect 'overhead' categories, direct input costs have decreased less. The fact that several inputs categories have a direct positive effect on achieving higher yields strengthens this observation. Indirect costs are more dependent on farm size and subject to economies of scale.

Fig. 3. Experience curve on corn production costs.

5.3. Development of ethanol processing costs

Fig. 4 shows the development of industrial processing costs over time and presents a breakdown into several categories. Industrial processing costs mainly include costs for energy, enzymes, labour, maintenance and chemicals. Costs for corn and capital are not assessed in this section. Processing costs of ethanol declined between 40% and 50%, from around 240$_{2005}$/m^3 in 1983 to below 130$_{2005}$/m^3 in 2005.[8]

The largest cost decline occurred in the early 1990s, when costs dropped from levels above 200$_{2005}$/m^3 to below 150$_{2005}$/m^3. The slight increase towards 2005 is mainly caused by increasing energy prices. The available studies also show a larger decrease at first (1987–1998), which flattens out towards the end (1998–2002).

Energy costs (fossil fuels and electricity) represent the largest part (~40% in 3 surveyed years). Important other cost categories are labour, enzymes and chemicals (mostly yeast and chemicals used for boiler and process water treatment). Insufficient data limits a detailed quantitative analysis of the various categories to

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[6] Three year averages have been used, so 1975–1977 and 2003–2005 to exclude annual fluctuations.

[7] R^2 gives an estimate in the amount of variation explained by the model and provides information about the goodness-of-fit of a model. R^2's are commonly quoted in papers on experience curves.
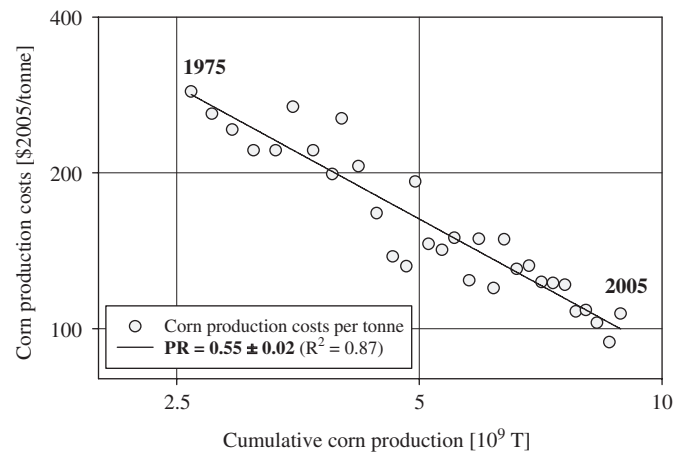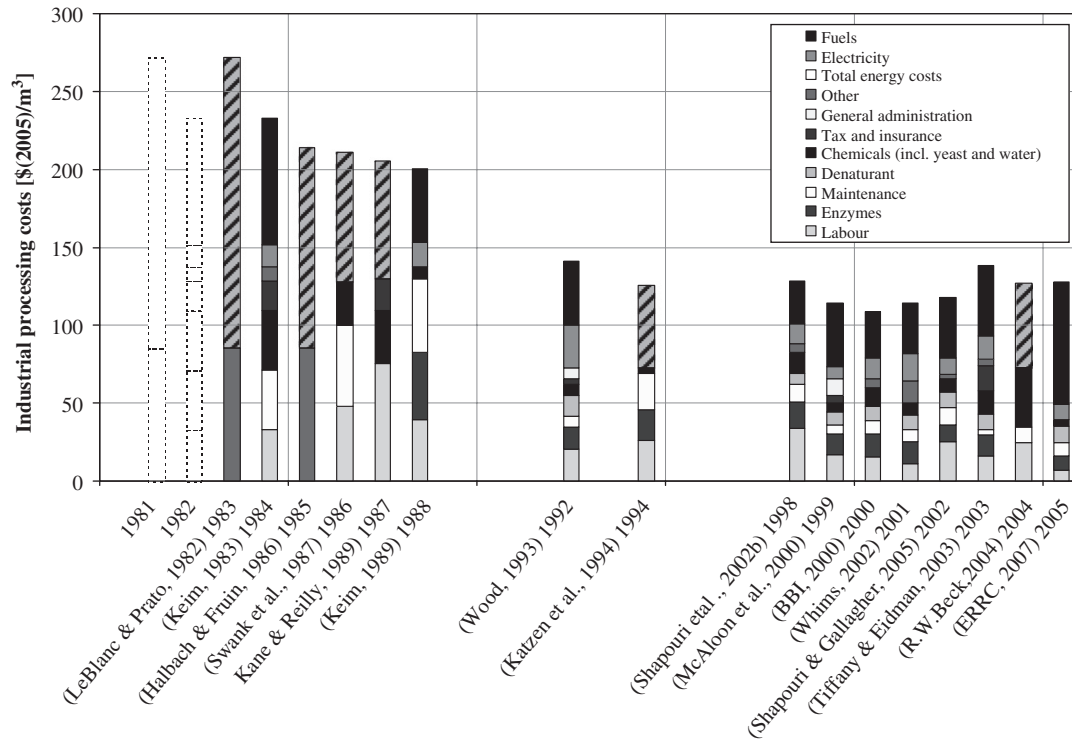
[8] The average processing costs for 1983–1984 and 2004–2005 have been averaged.

Fig. 4. Breakdown of ethanol processing costs between 1980 and 2005. Engineering studies of 1981 and 1982 are assumed to represent actual costs for 1983 and 1984. Note that different studies use different cost structures (LeBlanc and Prato, 1983; Keim, 1983; Halbach and Fruin, 1986; Swank et al., 1987; Kane and Reilly, 1989; Keim, 1989; Wood, 1993; Katzen et al., 1994; Shapouri et al., 2002b; McAloon et al., 2000; BBI, 2000; Whims, 2002; Shapouri and Gallagher, 2005; Tiffany and Eidman, 2003; Beck, 2004; ERRC, 2007).

Table 3
The decline in ethanol processing costs and its main contributors

	Early 1980s		2005		Reduction (%)
	$_{2005}$/m³	Share in total costs (%)	$_{2005}$/m³	Share in total costs (%)	
Energy costs	140	58	70	54	50
Labour costs	55	23	16	12	70
Enzyme costs	40	17	10	8	75
Total	240	98	130	74	40–50

development in costs for energy, labour and enzymes, but most important categories are highlighted in Table 3. Other qualitative cost-reducing developments and technological changes have been described in Section 5.1.
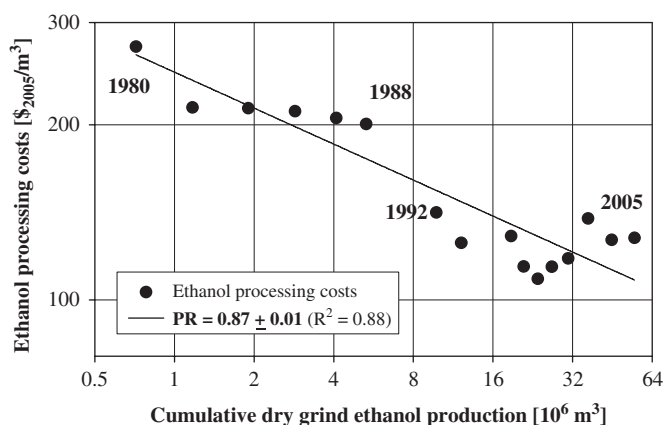
Energy costs are the largest contributor of processing costs. The cost reduction is caused by the decrease in energy consumption as can be seen in Fig. 5. Increasing prices for energy have increased the pressure on producers to implement energy-efficient production technologies. Furthermore, debates on the energy balance of US ethanol have stimulated optimisation on energy use. Average dry grind plants used 22 GJ/m³ in the early 1980s that has been reduced to below 10 GJ/m³ for present average dry grind plants. In Fig. 5, various studies on energy consumption in ethanol production over the years is plotted. In this graph only industrial energy use is displayed. Large energy efficiency gains are visible in the late 1980s. This is mostly caused by the replacement of dehydration technologies, and other developments described in Section 5.2. Hettinga (2007) assessed energy consumption as a performance indicator for technological learning in experience curves.

By plotting cumulative dry grind ethanol production against industrial processing costs, an experience curve is constructed (see Fig. 6). Cumulative dry grind ethanol production doubled 7.2 times since 1983 (see gridlines in graph). Over the same timeframe costs have been reduced by 45% on average. The progress ratio of this curve is given 0.87 ± 0.01 with a reliable fit of $R^2 = 0.88$. This indicates that ethanol processing costs decline 13% per doubling in cumulative production.

The large decline in ethanol processing costs between 1988 and 1992 parallels with the shift in the industry towards optimised ethanol production technologies that were designed for fuel ethanol production only. Beverage-based technologies was phased out in the industry, since new dry grind plants were being built rapidly. Most of the described technological developments in Section 5.1 occurred at the end of the 1980s, such as the introduction of molecular sieves, distributed control systems and SSF technologies. Industry average costs from the 1990s onwards settled at about 125$_{2005}$/m³. Improved efficiencies and operation lowered operating expenses, even though since 2003 varying numbers are quoted. Costs for energy have decreased
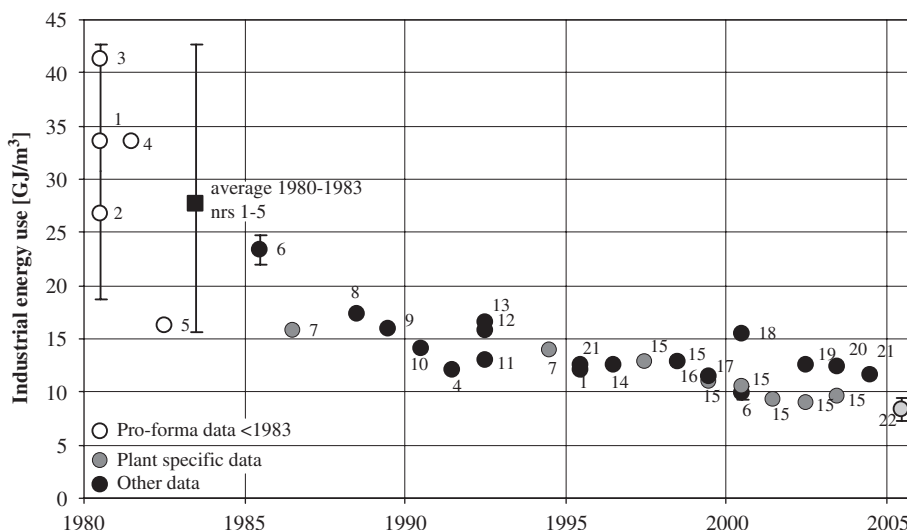
Fig. 5. Industrial energy use for ethanol processing between 1980 and 2005. *Data sources*: (1) (Lorenz and Morris, 1995); (2) (Madson and Murtagh, 1991); (3) (Chambers et al., 1979); (4) (Hohman and Rendleman, 1993); (5) (Keim, 1983); (6) (BBI and Novozymes, 2002); (7) (Katzen et al., 1994); (8) (Keim, 1989); (9) (Ho, 1989) in (Shapouri et al., 2002a); (10) (Marland and Turhollow, 1991) in (Shapouri et al., 2002a); (11) (Morris and Ahmed, 1992); (12) (Wood, 1993); (13) (Shapouri et al., 1995); (14) (Shapouri et al., 2002a); (15) ((S&T)2, 2004); (16) (Shapouri et al., 2002b); (17) (Wang et al., 1999) in (Shapouri et al., 2002a); (18) (BBI, 2000); (19) (Shapouri and Gallagher, 2005); (20) (Tiffany and Eidman, 2003); (21) ((S&T)2, 2004); and (22) (Strohm and Bates, 2006).
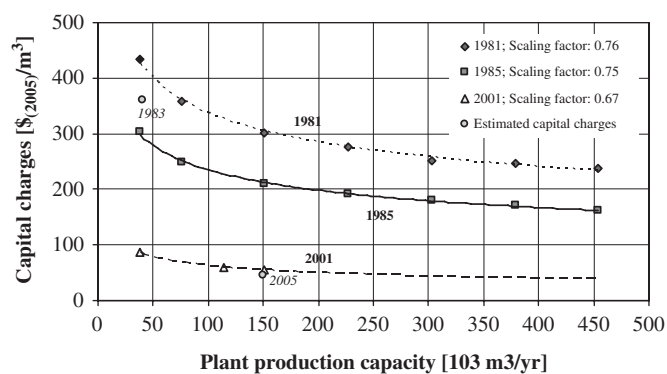

Fig. 6. Experience curve on ethanol processing costs.

Fig. 7. Scaling factors for capital costs in different years. Capital costs have been reduced by upscaling, but even more by learning and other non-scale-related development. (*Data sources*: LeBlanc and Prato, 1982; Gavett et al., 1986; Whims, 2002).

until the year 2000, but higher energy prices led to increasing energy costs ever since.

5.4. Development of capital costs

Next to feedstock costs and processing costs, capital costs make up total ethanol production costs. Capital charges are based on an annuity and represent costs for recovery of the initial investment. Due to limited data availability and wide ranges in quoted costs caused by different definitions and boundaries, it is impossible to devise meaningful experience curves for the capital charges. However, as capital charges make up a significant share in total ethanol production costs, they cannot be left out of the analysis. Capital costs fluctuate significantly among reports and only 10 out of the 16 quoted production costs studies in Fig. 4 provide data on capital costs. Most of these publications provide data for plants larger than the industry's average at that time (since e.g. a feasibility study most likely does not represent averages). To correct for this, the concept of scaling factors is used (see Remer and Chai (1990) for more information on scaling factors). In principle, a scaling factor represents economies of

scale and is in most cases technology or sector specific. Scaling factors can usually be applied to capital-related costs, although economies of scale are likely to exist on operating costs as well. Nonetheless, in this study scaling factors are only applied to capital costs. In order to assess technological development in capital costs, two approaches are combined. Firstly, capital charges quoted in literature are assessed (data for 10 different years). Secondly, these costs have been corrected to costs that represent average size plants by using (historic) scaling factors. Note that scaling factors do not take any 'learning' or development into account; it solely calculates the benefits of a larger plant.

Fig. 7 shows scaling factors for 3 years between plant size and capital charges (costs have been corrected for inflation). Remarkably, scaling factors have changed over time, i.e. the economies of scale may have been higher in the past than they are now. By combining historic and current scaling factors with average plant sizes over time, valuable information can be obtained about the development of capital charges (or at least the difference between present and the early 1980s can be assessed). The individual curves in Fig. 7 reflect scaling effects, whereas the vertical distance between the curves reflects the development in the amount of capital charged over time (scale-independent learning).

The most recent data[9] are indicated by the grey dot, representing an average plant size of 150,000 m^3/year, having capital charges of 45$_{2005}$/m^3. Capital charges in the early 1980s are derived by taking an average plant size of less than 40,000 m^3/year, and using the scaling factors applicable for that time. Scaling factors are only available for 1981 and 1985, therefore the average between 1981 and 1985 is taken, resulting in capital charges of 360$_{2005}$/m^3 in 1983 when first dry grind ethanol was commercially produced.

Comparing current capital charges of 45$_{2005}$/m^3 with 360$_{2005}$/m^3 in 1983 for industry average plant sizes,[10] a remarkable reduction of 88% is observed. This includes both upscaling effects and technological progress.

5.5. Total ethanol production costs

In this section we determine the development of total ethanol production costs comprise costs for industrial processing (both energy costs and other operating costs), capital and corn. The latter is in practise determined by corn market prices, and not by corn production costs as presented in Section 5.2, therefore we focus on costs derived from actual corn prices in stead of corn production costs. In addition, a co-product credit for DDGS is subtracted (also based on prices).

Total production costs declined by 57% from around 712$_{2005}$/m^3 in the early 1980s[11] to approximately 300$_{2005}$/m^3 in 2005 (see Fig. 8). The value of the co-product credit has been subtracted from corn costs. The development of ethanol production costs shows a similar trend as prices for ethanol, which in 2005 were 134 $_{2005}$ above ethanol production costs. Major cost reduction are achieved in capital costs, also corn costs have decreased considerably. Energy costs are another category, which is heavily influenced by energy prices and have decreased significantly as well. Operating costs showed smallest decline, but have nonetheless decreased 38%.

Total ethanol production costs can be linked with total cumulative dry grind ethanol production in an experience curve. The experience curve with ethanol production costs shows a PR of 0.82 and a R^2 of 0.96, indicating a 18% costs decline over each doubling in cumulative production.

Net corn costs have always made up a large share in total production costs, up to 50%. Contribution of capital charges in the 1980s was higher than its present share. Recently, the share of energy costs in total is increasing. Also, results show that within total ethanol production costs, the co-product DDGS considerably contributes to the economic performance of US ethanol. Energy prices, DDGS prices and corn prices are important drivers of total production costs.

Table 4 summarises the breakdown of total ethanol production costs over the years. Values have been averaged over 3 years and might therefore slightly differ from values used throughout the text; moreover, the lack of detailed real capital charges leads to higher uncertainty in total ethanol production costs.

6. Methodological discussion

6.1. Main methodological issues and sensitivity analysis

As discussed in the previous sections, applying the experience curve concept to corn and ethanol production in the US required a number of assumptions. We briefly discuss the sensitivity of the most critical assumptions on the results below:

- A legitimate use of experience curves requires sufficient data that represents consistent data series on production costs. Lack of sufficient industry average cost data is often a problem, which in our case made it impossible to construct a meaningful experience curve for ethanol capital charges and total ethanol production costs (although still clearly declining trends are visible). In our study, cost data from several sources has been used, of which not all studies surely represent industry averages. Yet, the number of studies found and the quality of the data enabled us to develop meaningful experience curves for corn production and ethanol processing costs.

- A main methodological uncertainty is the assumption of already accumulated experience (i.e. corn/ethanol produced) at the starting point of the experience curve. The less production one takes into account, the lower the 'initial value' that determines the number of cumulative doublings. Consequently, this results in higher observed progress ratio's. For the US ethanol production the starting point has been determined at 1983 when still small amounts of fuel ethanol were produced. For corn production costs, the high initial value (representing a large experience of production) results in a low progress ratio, since observed costs reductions are spread out over less cumulative doublings. As a sensitivity, in Table 5, the effects of varying the initial values on the PR's for corn and ethanol are shown.

- As geographical system boundaries, the US learning system was chosen. This means that we may neglect experience gained outside the US, and any knowledge swap-over from or to the US from abroad. However, given the overwhelmingly leading role of the US in corn-based ethanol production, we deem these effects to be minimal.

- As was shown in Fig. 7, significantly different scaling factors were found for the first half of the 1980s (R of 0.75–0.76) and 2001 (R of 0.67). As an average, we used a scaling factor of 0.71 to extrapolate capital charges from various studies, resulting in an average decline of capital charges of 41% between 1980 and 2005. Using scaling factors of 0.76 and 0.67, this cost reduction would have been 32% and 49%, respectively. Note, however, that this is only a small fraction of the total decline of capital charges, and that a far larger part of the cost reduction is caused by technological advances (see also Fig. 7).

6.2. Determining hypothetical total ethanol production costs based on corn production costs

In this paper the production costs of corn and ethanol processing have been analysed. Total ethanol production costs on the contrary have been analysed on the basis of corn *prices* in stead of corn *production costs* as ethanol producers regularly pay prices for corn. As an academic exercise, also total *hypothetical* ethanol production costs can be assessed, in which corn costs are not based on corn prices, but on corn *production costs* instead, which allows us to measure the performance of the compound system as a whole.

It appears that these hypothetical total production costs are actually overall higher than actual production costs. Corn production costs are slightly higher than corn prices, since also economic costs have been taken into account that farmers do not directly consider as expenses (such as labour costs of the

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[9] Current average capital costs is the average of 2003–2005, early capital costs is the average of data for years 1983–1985.

[10] If the difference in size is not taken into account, still significant cost reductions have been achieved, i.e. when comparing a 150,000 m^3/year plant of 1983 to a current plant, capital costs declined 83% (260 vs. 50$_{2005}$/m^3 at present).
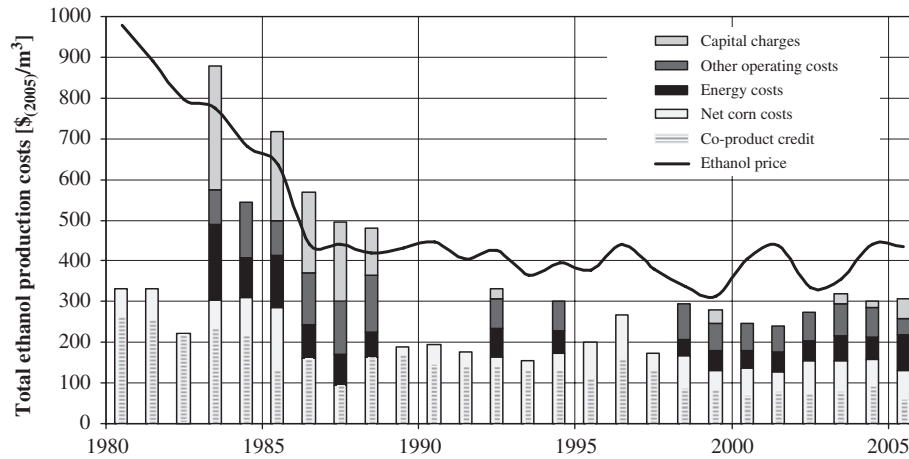
[11] Based on 3 years averages.

Fig. 8. Development of total ethanol production costs and ethanol prices between 1980 and 2005. Note that not for all years full costs data are available.

Table 4
Total ethanol production costs (incl. corn costs and co-product credit) 1980 vs. 2005

Cost category	Average 1983–1985 ($_{2005}$/m^3)	Average 2003–2005 ($_{2005}$/m^3)	Reduction (%)
Net corn costs (based on prices)	295	148	50
Co-product credit	248	78	69
Energy costs	156	67	57
Other operating costs	103	64	38
Capital charges	360–235	30–45	81–92
Total ethanol production costs	789–914	309–324	59–66

Table 5
The effect of different initial cumulative production values of progress ratio's for corn and ethanol production

Scenario	I All	II Base case	III Zero
Corn production			
Initial cumulative production	1866–1974	1950–1974	1975
Initial value (10^9 tonnes)	7.1	2.6	0.0
Progress ratio	0.31±0.03	0.55±0.02	0.83±0.01
(R^2)	(0.87)	(0.87)	(0.77)
Ethanol processing			
Initial cumulative production	1980[a]	1978–1982	1983
Initial value (10^6 m^3)	2.8	0.375	0.0
Progress ratio	0.84±0.01	0.87±0.01	0.88±0.01
(R^2)	(0.91)	(0.88)	(0.88)

[a] All ethanol (wet milling+dry grind) production is plotted on the x-axis.

Table 6
Excluding the effect of prices

	1983	2005	Change (%)
Assumptions			
Ethanol yield (m^3/tonne)	0.37	0.40	+8.1
DDGS yield (tonne$_{DDGS}$/tonne$_{corn}$)	300	300	0
Thermal[a] (GJ/m^3)	20	10	−50
Electricity (kWh/m^3)	662	291	−56
Assumed constant prices			
Natural gas ($/GJ)		5.00	0
Electricity ($/kWh)		0.05	0
Corn ($/tonne)		86	0
DDGS ($/tonne)		80	0
Calculated production cost decline with constant price			
Co-product credit	112	60	−47
Corn costs[b]	401	215	−46
Industrial processing costs	327	161	−51
Total ethanol production costs	616	332	−46
PR = 0.77			
Observed actual production cost decline[c] as described in the paper			
Co-product credit	240	62	−74
Corn costs[b]	541	192	−65
Industrial processing costs	272	128	−53
Total ethanol production costs	573	258	−55
PR = 0.82			

[a] All thermal energy is assumed to be generated by burning natural gas.
[b] Based on corn prices.
[c] This is base case scenario as presented in Section 5.2. Numbers can differ since annual (not average) numbers are assessed.

6.3. Excluding the effect of other prices and other exogenous factors

Taking the academic exercise of Section 6.2 one step further, we also attempted to exclude the influences of the prices of fossil fuels, electricity and DDGS from the analysis. Fluctuating prices of these parameters influence the annual ethanol production costs, but have nothing to do with technological learning. By excluding these exogenous factors, a better picture is obtained of the 'true' effects of technological learning on reducing production costs, enabling us to assess the effects of technological advances such as higher ethanol yields and lower specific (thermal and electric) energy use.[12] Results are summarised in Table 6, and indicate that prices for corn affect total actual ethanol production costs

owner/farmer). However, the consistency of reporting still enables us to assess development in hypothetical ethanol production costs. Interestingly, we found that the progress ratios for both hypothetical and real production costs are both 0.82. This shows that the impact of decreasing corn production costs in the past has been identical to the impact of decreasing corn prices. Whether this will also hold for the future is questionable, given the recent strong increase in corn prices. For a more elaborate discussion, see Hettinga (2007). For the future, this analysis shows that corn prices tend to follow corn production costs although much steeper increasing corn prices are currently observed than ever before.

[12] Capital costs have been excluded in this analysis.

strongly, but varying DDGS prices have also a significant impact on industrial processing costs. Interestingly, the impact of energy prices is the lowest of all variable categories. Cost reductions are mainly caused by increasing energy efficiencies and not by overall decreasing energy prices Overall, it appears that changes in the exogenous factors added to the overall costs reductions, but that about 84% of the overall ethanol cost reductions is caused by technological learning. However, for the future, strongly rising fossil fuel prices or fluctuating DGGS and corn prices may of course strongly impact the production costs of ethanol. For a more elaborate discussion, see Hettinga (2007).

7. Comparison with Brazilian ethanol production cost reductions

Nowadays the US is producing more ethanol than Brazil, which formerly was the world's largest ethanol producer. However, the use of ethanol in Brazil is more widespread: 20% ethanol blends are common and almost all new cars are flex fuel vehicles. Brazil has a longer history of ethanol production and has produced far more on a cumulative basis. Despite using other feedstock, similarities can be drawn in the reduction of feedstock production costs (sugarcane for Brazil). Van den Wall Bake et al. (2008) has published a similar experience curve analysis for Brazilian sugarcane and ethanol production, which allows a brief comparison.

In both countries costs have declined by approximately 60% since 1975. Different numbers of cumulative doublings, caused by taking a large amount of previous production in the US into account (high initial value) lead to varying outcomes in progress ratios. The US shows a lower PR, indicating higher cost reductions over cumulative production. Technological development in Brazilian sugarcane production is slower than in US corn production. Brazilian ethanol production started earlier and ethanol processing costs (including capital costs) have declined by 70% since 1975 versus 49% reduction is US ethanol processing costs (without capital costs) since 1983. Taking these reductions into account as well as the lower number of cumulative doublings in Brazil (more previous ethanol production is considered), a lower progress ratio in Brazil is calculated. A comparison of the actual total production costs of ethanol is difficult, as this comparison is highly sensitive to the exchange rate. Van den Wall Bake et al. (2008) describes this sensitiveness and for 2004 costs an average exchange rate of 3.6 R$ has been used Table 7 presents a comparison on several key parameters.

The overall experience of production has led to current ethanol production costs of approximately 188$/m^3 in Brazil, whereas the US is producing ethanol for approximately 310$/m^3. Whereas Brazilian ethanol production is more vertically integrated with the feedstock production system, US ethanol plants pay corn prices, which are subject to a current increases. From a methodological point we note that PR's for feedstock production seem to be much better (55–68%) compared with the PR's of the industrial processing (81–87%).

8. Outlook on future ethanol production costs

One of the possible applications of experience curves is their extrapolation to investigate potential future production cost reductions as a function of further production. However, such extrapolations have to be handled with care. As discussed, in Section 6, data uncertainties, choices of system boundaries and especially development of exogenous factors such as DDG, fossil fuel and corn prices can strongly influence future ethanol prices. Yet, an analysis on how much production costs reductions may be achieved through technological learning as a function of cumulative production may be of interest for both the ethanol-producing industry and policy makers. We therefore made an attempt to estimate ethanol production costs in 2020.

Regarding future corn production, USDA's Agricultural Projection to 2016 (USDA/OCE, 2007) is extrapolated to the year 2020, reaching 370 million tonnes annual corn production. Following the experience curve the estimated corn production costs in 2020 amount 74–76$/tonne (ranges are achieved using the standard error in the progress ratio). Thus, corn production costs are estimated to decrease 30% compared with 2005 (see Table 8). Concerning future ethanol production, two scenarios are assessed: firstly, extrapolation of the Renewable Fuels Standard until 2020 (up to 52 million m^3/year). This results in an estimation of ethanol processing costs of 69–77$/m^3 in 2020. Secondly, extrapolation of an outlook provided by Urbanchuk (2007) forecasts production of up to 68 million m^3/year in 2020. The higher predicted production volumes will lead to higher cost decline that results in processing costs of 60–70$/m^3 in 2020. On average the same percentage of cost reduction for the future is expected as has occurred over 1983–2005 (46%).

This analysis shows that lower (i.e. better) progress ratios (for corn) do not per se lead to high cost decline, as until 2020, only few doublings of cumulative production will occur. On the

Table 7
Comparison of ethanol production in Brazil and the US

	Brazil (data from Van den Wall Bake et al., 2008)	US
Total cumulative ethanol produced by 2005 (million m^3)	300	125
Agricultural yield (tonne$_{cane}$/ha)	75–82	9–10
Ethanol yield (m^3/tonne$_{cane}$)	0.082	0.4
Feedstock production (1975–2005)		
Cost reduction (%)	60	63
Number of doublings in cumulative production	3	1.9
Progress ratio	0.68 ± 0.03	0.55 ± 0.02
2005 costs ($/tonne$_{cane}$)	14.9	107
Industrial processing (start-2005)		
Cost reduction	(1975–2005) 70%	(1983–2005) 49%
Number of doublings in cumulative production	5	7.2
Progress ratio	0.81 ± 0.02	0.87 ± 0.01
2005 costs ($/m^3)	103	128 (+50$ capital)
Current total ethanol production costs ($/m^3)	~188	~310
Current ethanol price ($/m^3)	365	430

Table 8
Corn and ethanol production costs in 2020, calculated by extrapolating the experience curve (RFA, 2008; Urbanchuk, 2007; USDA/OCE, 2007)

Corn production	USDA agricultural projection (extrapolated)	
2005 production costs	107$_{2005}$/tonne	
Predicted cumulative production in 2020 (1975–2020)	14×10^9 tonne	
2020 predicted production costs	74–76$_{2005}$/tonne	
Ethanol processing	**I. RFS extrapolated**	**II. Urbanchuk outlook**
2005 production costs (minus corn and capital costs) ($_{2005}$/m^3)	128	128
Predicted cumulative production in 2020 (1983–2020) ($\times 10^6$ m^3)	560	767
2020 predicted production costs ($_{2005}$/m^3)	69–77	60–70

other hand, a high (i.e. less benign) progress ratio for ethanol processing nevertheless results in relatively high cost reduction because of large predicted future ethanol production volumes, leading to several further doublings of cumulative production.

Ideally, to support these findings, they should be compared with expectations from bottom-up engineering studies for future cost reduction potentials. Unfortunately, while several studies exist that examine the impact of new production process technologies on production costs, and these clearly show further technical improvement potential, we did not find an integrated analysis that combines these various studies. Rendleman and Shapouri (2007) expect savings in the future to be smaller than those of the last 10–15 years, since ethanol production is becoming a mature industry, thus representing a more conservative estimate than our analysis. A brief analysis of a paper that was published by Argonne National Laboratory (Wu, 2008) shortly after the final findings of this paper shows that significant efficiency gains have been observed in the ethanol industry since 2002. Amongst others, ethanol yield increased by 6%, less producers dry the DDG, which saves energy. The industry's average energy use in 2007 amounted 7.8 GJ/m^3, which is supported by our data and extrapolation. This strengthens our analysis on energy and its decline over time or accumulated production. We recommend further research on a better comparison of bottom-up engineering and top-down experience curve analysis results in order to identify areas of possible further improvement.

We emphasise again, that the cost reduction outlook is solely based on further technological progress. Although this study shows that ethanol processing costs (including energy costs, excluding corn and capital costs) have decreased in the past, especially corn price developments are highly uncertain. Current speculation on ethanol demand leads to extraordinary high corn spot prices (up to 160$/tonne). While these have so far little influenced long-term corn supply contracts of ethanol plants, also in long-term projections (USDA/OCE, 2007) an increase in corn prices is expected.

9. Summary and conclusions

The objective of this study was to assess technological learning by quantifying reductions in production costs and energy use in US ethanol production. This technological learning can be identified in two separate systems: corn production and ethanol processing.

Corn production costs declined by 62% over the period 1975–2005. Main drivers behind cost reductions are higher corn yields and the upscaling of farms. Ethanol processing costs (without corn and capital costs) declined by 45% over the period 1983–2005. Costs for energy, labour and enzymes contribute most

to overall cost decline. Key drivers behind these reductions are higher ethanol yields, the introduction of fuel ethanol specific and automated technologies that require less energy and labour. Recent higher energy prices have partly outbalanced reductions in other operating costs. Overall, corn prices determine feedstock costs for the ethanol producer, which have shown decreases as well (caused by more than just technological learning in corn production). Total ethanol production costs, which include capital and net corn costs, have declined by 57% since 1983. Costs reductions have been achieved throughout the entire production chain, i.e. net corn costs, industrial processing costs and capital costs have all contributed to overall cost decline.

The analysis has shown that corn production and ethanol processing costs have decreased with cumulative production and that the experience curve concept can be used to describe this trend reliably. The calculations on the experience curve present a progress ratio of 0.55 ± 0.02 for corn production costs over the period 1975–2005. A progress ratio of 0.87 ± 0.01 is calculated for industrial processing costs (without costs for corn and capital) since 1983. A comparison with Brazilian sugarcane and ethanol production reveal similar PRs for feedstock and industrial processing cost reductions.

Experience curves can also be used as a tool to assess future cost decline by taking projected production and detailed cost breakdowns into account. Extrapolating these experience curves to 2020, corn production costs are estimated to amount 75$ per tonne in 2020. Ethanol processing costs (without costs for corn and capital) are expected to come with the range of $60–$77 per m^3 in 2020. These are both significant further reductions, mostly driven by the large expected volumes of future (corn-derived) ethanol production. On the other hand, prices for corn and energy are expected to rise in the future, which ultimately determine ethanol production costs for the producer of which prices paid for corn will be most decisive. Also, ethanol prices closely correlate with gasoline prices, leading to expected higher ethanol prices in the future as well.

We conclude that experience curves are an adequate tool to analyse past technological learning and resulting cost reductions for US corn-based ethanol production, and, keeping all limitations of the analysis in mind, also show a significant cost reduction potential for the future.

Next to use within the ethanol-producing industry itself, the insights gained from this analysis may also be of relevance for policy makers. They show that despite being a 'first-generation' technology, significant further cost reductions may occur due to technological learning in the coming years. This indicates that future second-generation fuels (e.g. cellulose-derived ethanol) may have to receive extra support not only to compete with gasoline, but also with corn-derived ethanol. Furthermore, the expected cost reductions could be useful to review US policies on e.g. the future level of corn subsidy programs, and the blender tax

credit, and the necessity of ethanol import tariffs (for Brazilian ethanol). Discussing this in detail would extend the scope of this paper, we refer to Hettinga (2007) for a more detailed treatment of the topic.

Finally, the empirically found PR's for corn and ethanol production may also be of use for science, e.g. for use in energy models. Regarding recommendations or further research, we would like to emphasise that the developments in the energy efficiency of corn-based ethanol production deserves further attention. As shown in Fig. 5, energy inputs have decreased significantly since 1980, though especially within the first half of the 1980s. Future improvements in energy efficiency may lead to lower costs, but also to lower GHG emissions. Whether these efficiency improvements actually also follow an experience curve pattern (e.g. similar to ammonia production as found by Ramirez and Worrell, 2006) is a question worthwhile exploring further.

Acknowledgements

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