

Process Systems Engineering and Process Safety

An analysis of an ethanol-based, whole-crop refinery system in China☆



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ARTICLE INFO

Article history:

Received 2 July 2015

Received in revised form 20 July 2015

Accepted 23 November 2015

Available online 31 May 2016

Keywords:

Whole-crop refinery

Cellulosic ethanol

Biomass

Corn stover

ABSTRACT

Bio-fuel can be used to help transition from a petroleum-based society to a bio-based society. Ever since the China Development and Reform Commission suspended the approval of crop processing programs, second-generation bio-ethanol research and industrialization processes have attracted significant attention. In 2020, bio-ethanol production is predicted to reach 10 million tons. Currently, there are a few domestic enterprises that have established different scaled pilot or demonstration bases for cellulosic ethanol, which reduce the cost of ethanol by continuously improving pretreatment and hydrolysis techniques. In the next three years, these enterprises will realize large-scale commercial production. Given the practical problems in cellulosic ethanol plant construction and operation (e.g., marketing price variation and difficulties in feedstock collection), this paper began with the concept of a “whole-crop refinery” and presented a solution to the integration of industry and agriculture as well as multi-crop refining. This paper then took the whole-crop refining system of corn as an example and presented an analysis of the logistics, energy flow, and economical efficiency of the system. The results demonstrated that the integrated system could properly reduce the required fixed investments in production equipment, shared utilities, and wastewater treatment facilities, as well as reduction of energy consumption. Although the proposed system has several problems, it brings the long-term goal of large-scale commercial application closer than ever.

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1. Introduction

As a result of the rapid growth of the Chinese economy, which has led to an increasing dependence on foreign oil and serious environmental pollution problems, clean-green-renewable energy is attracting increasing attention. Bio-fuel, which is relatively carbon neutral and can be produced on a large scale as an alternative transportation fuel, has been the focus of government planning. Converting biomass into fuel or chemical products through industrial processes has become an efficient approach to resolving energy shortages and environmental problems [1]. A renewable bio-fuel economy is projected to be a pathway to reducing the reliance on fossil fuels and enhancing rural economies, and the efficient and cheap conversion of lignocelluloses into chemical products, such as ethanol, can become a basis for the transition from a petroleum-based to bio-based economy.

China is now the third-largest bio-ethanol producer in the world after the United States and Brazil with an annual bio-ethanol production of 1.7 million tons in 2009 [2]. Corn, wheat, and other cereals, such as sorghum and cassava, are the primary feedstocks for Chinese ethanol production. However, national policy and competing food demands on

grain supplies and prices will eventually limit the expansion of grain-ethanol capacity. Lignocellulosic biomass, such as crop residues, grasses and forestry biomass, is a second-generation feedstock material for ethanol production. This technology has made several breakthroughs in the past two years and several 10000-ton-level plants will be built in the next two years. Table 1 and Fig. 1 depict the production of primary manufacturers in the last three years [3] and the production of fuel ethanol in China from 2002 to 2020, respectively.

1.1. Cellulosic ethanol in china

Lignocellulosic feedstocks have great advantages over annual crops in terms of energy and economy [4]. In the long term, the primary feedstock is only a transitional material and is not sufficient to change China's entire energy structure. To fill that role, straw plant fiber will serve as the main source. Cellulosic biomass production, such as agricultural and forestry residues, major portions of municipal solid waste, and dedicated herbaceous and woody crops, is estimated to be 670 million tons per year in China [5,6] and could provide a meaningful alternative feedstock for ethanol production that is roughly equivalent to 4 billion barrels of petroleum (100 million tons). It is estimated that the total annual consumption by the Chinese auto industry is approximately 60 million tons of gasoline. Hence, approximately 5 to 10 million tons of fuel ethanol must be supplied within the next few years under an E10 (10% ethanol and 90% gasoline blend) standard. At

☆ Supported by the State Key Development Program for Basic Research of China (2006BAC02A17).

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Table 1

The bio-ethanol production of primary manufacturers in China from 2012–2014 (thousand t per year)

	2012	2013	2014
Tianguan CORP., Ltd.	40.2	46.9	49.5
Jilin Fuel Ethanol Co., Ltd.	41.9	48.0	60.0
Fengyuan CORP., Ltd.	34.9	39.8	42.0
COFCO Bio-Energy (Zhaodong) Co., Ltd.	16.2	15.0	19.4
Guangxi COFCO Bio-Energy Co., Ltd.	–	11.7	16.3

present, only 5 provinces and 27 cities utilize ethanol-blended fuel in China [2]. The annual consumption of fuel ethanol is approximately 1 million tons, and thus there will be a huge commercial market and very bright prospects for the development of cellulosic ethanol.

Many enterprises presently produce cellulosic ethanol, such as the Henan Tianguan Group, the Anhui Fengyuan Group, Jilin Fuel Ethanol Co. Ltd. and Zhaodong of COFCO. Among these, the Tianguan Group will build 12 cellulosic ethanol plants (10000 tons per plant) in 2010 and 100 plants by 2020. The Tianguan Group has also developed its own high-activity cellulase bacteria and has produced cellulose. By optimizing the process, the enzyme cost of cellulosic ethanol has declined to 100–150 USD per ton. The COFCO Group (presently, COFCO directly or indirectly invests in 3/4 of the ethanol enterprises in China), Purdue University, and Novozymes have signed a technology transfer and cooperation agreement for cellulosic ethanol fermentation. COFCO and Sinopec will build 10000-ton-level plants in the third quarter of 2011 and achieve commercial production in 2015. Novozymes will provide the plant enzyme [7,8]. Roughly, the current cost of cellulosic ethanol is about 800–1000 USD per ton and it still requires financial subsidies to maintain production in contrast to oil. Thus, there is still a long way to go for large-scale commercial applications. Table 2 compares the cellulosic ethanol-related technologies of the different aforementioned corporations.

The main processes of converting cellulose to ethanol include pretreatment, hydrolysis and subsequent fermentation [9–11]. The cellulose and hemicelluloses that are present in biomass are the sources of fermentable sugar, which have a purity of 66%–75% (oven-dry weight of lignocellulosic materials). When cellulase is used to hydrolyze lignocelluloses so as to produce sugar, cellulase must absorb the substrate to maintain the reaction. Hence, the accessibility of cellulose to cellulase is the key factor that determines the hydrolysis velocity. In the enzymatic hydrolysis process, it is necessary to pretreat the material to make the cellulose accessible to the enzymes. The currently available pretreatment techniques can be divided into four different categories: (1) biological,

(2) chemical, (3) physical and (4) thermal processes [10,11]. Presently, the most promising pre-treatments use dilute acid, ammonia expansion, concentrated phosphoric-acetone, aqueous ammonia, etc., or a combination thereof to destroy lignin and other ingredients so as to prevent microbial invasion, which is the key to making cellulosic ethanol cost competitive.

In China, the major pretreatment technology that is used by cellulose ethanol enterprise is still a dilute acid treatment in combination with steam explosion. Only Zhaodong cellulose ethanol experimental equipment from COFCO uses a continuous steam explosion method. This equipment has been obtained from SunOpta, Canadian company, and the cellulose fractional conversion rate can reach as high as 88%–90% [12]. For hydrolysis, commercial cellulose ethanol plants use a more mature enzyme hydrolysis technology. Although the cost of enzymes has greatly decreased in recent years, it still occupies a large portion of the total cost of cellulose biotransformation, which can be as high as 50% to 60%, resulting in a high cellulose ethanol cost. Enzyme cost is also significant barrier to the development of large-scaled cellulose ethanol industrialization.

Generally speaking, the scale of cellulose ethanol in China is less than 0.1 million tons and there is still a large gap in comparison to the more advanced technologies in America and Canada. Internally, the primary research centers are COFCO, the Tianguan Company, the LongLi Company, and the Zesheng Company, and foreign research centers include Iogen, Poet, Abengoa, SunOpta, Mascoma, Alico, Celunol, Choren, BioEthanol Japan Kansai Company and Dupont. The primary challenge to realizing a large-scale commercial ethanol plant is the perceived risk of employing the technology for the first time. In addition, attention should be paid to reducing processing costs by applying continually evolving biotechnology tools so as to enhance performance and realize the development of valuable co-products that improve portability.

1.2. Problems in current fuel-ethanol plants

Because the fuel-ethanol industry is not as mature as the petrochemical industry, it encounters various types of problems in development. The following problems have the largest influence on ethanol costs and enterprise benefits, and cannot be neglected.

1.2.1. Risk of an uncertain market

The cost of feedstock accounts for approximately 70%–80% of the first-generation ethanol costs, whereas this number is approximately 26%–34% for the second-ones. The sensitivity of fuel ethanol to

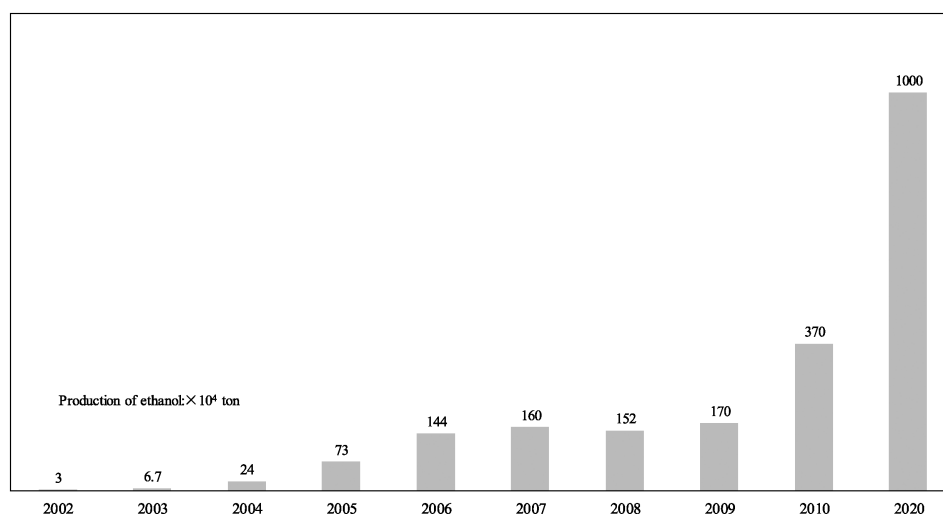


Fig. 1. Production of fuel ethanol in China from 2002 to 2020.

Table 2

Comparisons of the cellulosic ethanol-related technologies of the various corporations in China

Tech item	Tianguan CORP., Ltd.	Fengyuan CORP., Ltd.	COFCO CORP., Ltd.
Feedstock	Corn Stover	Wheat and corn stover	Corn stover
Pre-treatment	Dilute sulfuric acid, 1% Steam 180 °C, 0.9 MPa	Dilute acid	Steam explosion 200 °C, 6 min
Hydrolysis	Enzyme Cellulase: 30 IU · (g DM) ⁻¹ ② Xylanase: 20 IU · (g DM) ⁻¹ 50 °C, pH 4.8, 3 days	Enzyme	Enzyme 8–20 IU · (g DM) ⁻¹ 45–55 °C, pH 4.5, 5 days
Fermentation	Hexose	Hexose and pentose sugar	Hexose
Yield/t · a ⁻¹	3000	300	500
Cost/USD · (t Eth) ⁻¹ ③	900–1000	1200	1000–1200
Feedstock conversion rate/t · (t Eth) ⁻¹	5–6	7	6–7

① IU = international unit.

② DM = dry matter.

③ Eth = ethanol.

feedstock price is the most significant uncertainty in the ethanol feedstock market. Taking corn as an example, the price of corn per ton currently varies between 285 USD and 300 USD. If the consumption of corn to produce 1 ton ethanol is 3.3 tons, then the cost of 1 ton of ethanol from corn is 930–1000 USD. With the addition of other costs, the total cost is more than 1200 USD. Fig. 2 demonstrates the prices of corn and wheat in recent years and shows that corn and wheat prices frequently fluctuate.

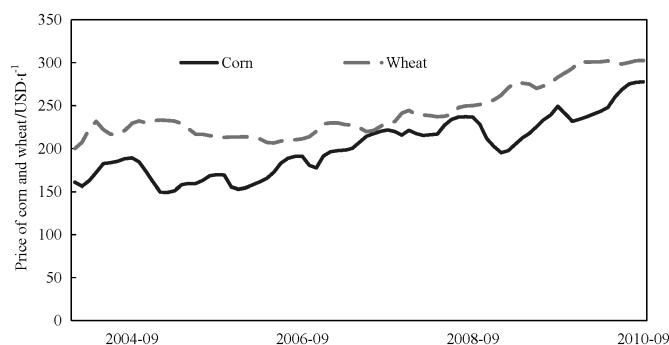
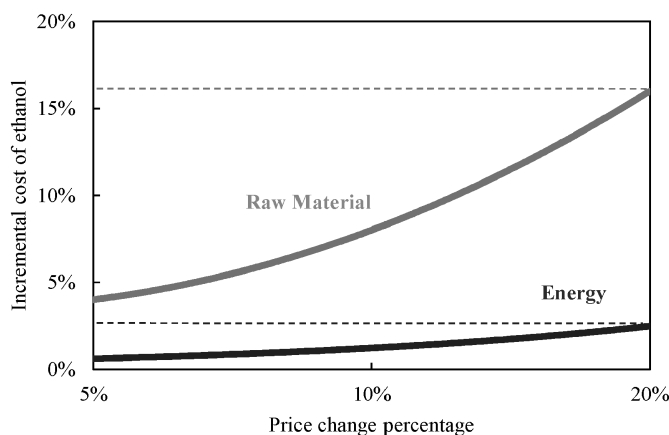
**Fig. 2.** Prices of corn and wheat in China from 2004 to 2010.

Fig. 3 demonstrates that an increase of both the marketing prices of feedstock and energy by 5%–20% enhances the percentage of the total cost of fuel ethanol. This figure also shows that the feedstock cost can change even more intensely than the energy consumption cost and

**Fig. 3.** Impact of feedstock & energy price variation on production cost of ethanol.

the influence of feedstock is more remarkable. The ratio of the feedstock cost to the total production cost of cellulosic ethanol and grain ethanol is 30% and 80%, respectively. Thus, the grain ethanol is more subject to feedstock cost fluctuation.

1.2.2. Risk of feedstock supply

Bio-fuel itself has many advantages, however, the feedstock shortage for bio-ethanol is severe. Currently, in China the most popular non-grain materials are cassava and sweet sorghum, and both of these plants are typically only harvested from small planting areas in dispersed parts of the country. The uncertainty of resources is a key factor that restricts large-scale bio-fuel development [13], and this uncertainty hardly meets the requirement of a stable supply for continuous industrial production. For lignocellulose, some plants use the method where the manufacturer signs a contract with farmers in order to guarantee corn stover supplies. Although there are many measures that can be used to solve land and transport problems, most enterprises have still been in short supply of feedstock in recent years.

1.2.3. Risk of technology

The feasibility and economic efficiency of the industrial production of cellulosic ethanol is primarily determined by the hydrolyzation rate and enzyme costs, which are also keys to fuel ethanol.

Pretreatment technology is one of the three bottlenecks in cellulosic ethanol production. The cost of pretreatment is a significant portion of the total cost of producing fuel ethanol using cellulosic material. Thus, selecting the most effective and clean pretreatment method will be of great significance to reducing the entire production cost. In the context of cellulose-ethanol production, the available chemical cellulose material pretreatments are different in terms of mechanism, and therefore they all have their respective advantages and disadvantages. Dilute-acid and dilute-alkali pretreatments have the disadvantages of high cost, equipment corrosion and environmental pollution. Alkaline solutions, such as ammonia, can break-down lignin and the reaction condition is relatively “mild” so that the damage to cellulose and hemicelluloses is small. Alkaline-solution-based pretreatments can also eliminate co-products that have adverse effect of fermentation, however, hemicelluloses are partially lost at high ammonia concentrations. Although ammonia is easy to recycle, the associated costs are still high. Thus, dilute-acid solution is still one of the most widely used technology.

In the hydrolysis process, enzymes can be repeatedly used as a kind of catalyst so as to reduce their total required quantities and costs. Research on this technology has far-reaching implications. One way to reuse enzymes is to separate the enzymes from the solution after the reaction via a membrane-separation technique. Based on this technique, several technologies have been developed, such as the multi-stage enzymatic hydrolysis technique and immobilized enzymes technique

[14–16]. The main problems of enzymatic hydrolysis are high cost and low conversion rate, which is due to the particularity of material and uncertainty of biochemical reaction process [17].

2. Integration of Multi-feedstock Ethanol Systems

2.1. Integration of industry and agriculture

Biomass energy systems are complex in that they use a variety of raw materials to produce products by various processes. In the economic environment, national policies, distribution and feedstock prices, market prices of fossil energy and manufacturing techniques frequently change. Therefore, the strategies of choosing material combinations, products and techniques, and determining the scale and layout of an enterprise, designing an industry chain so as to realize energy conservation and emission reductions and improving the overall efficiency are urgent problems in the progress of the current biomass energy industry. Currently, research on the entire crop-refinery process has focused on the production of individual technical routes, emphasized the all-around utilization of the root, stem and fruit of a single feedstock, and paid less attention to technical coupling or sharing utilities and even less concern about the investment waste on the small-scaled and repetitive construction of cellulosic ethanol plants in actual production. Based on the analysis above, in line with the integration of the agriculture-industry, this paper explores the possibility of combining grain and cellulosic ethanol plants, considers whole-crop refineries and multiple crop refineries, and analyzes the merits and feasibility of crop refineries to deal with a series of uncertain factors and risks in the development of the ethanol industry.

At the present, the cellulosic ethanol industry group that was founded by Tianguan CORP., Ltd. individually defines 6–8 towns as a unit zone and has separately founded 12 plants. The method of founding a factory in a certain zone can solve some of the problems that relate to resource shortages, however, the scales of the fixed investment, wastewater treatment, decreased fossil fuel burning, and electric power generation are all relatively small. And this method touches on the problems of personal credit, quality of the feedstock, etc., and it relies on cooperation with the farmers to satisfy the requirements on stover inventories. In the situation where the feedstock is in short supply due to seasonality, natural calamities, market prices, etc., presently in China, many ethanol enterprises are starting to plant, harvest, or import materials from other countries that have cheaper labor and land costs so as to achieve production. This method copes with the aforementioned marketing risks but, obviously, cannot solve feedstock availability issues in the long term.

If enterprises settle down and produce ethanol from land-growing crops that fully satisfy the scale of the industrial production or if enterprises that are producing fuel ethanol bond with forest centers,

rangelands, farms, etc. and form all-around groups, then the enterprises will perform the roles of both upstream peasant households and mid-stream manufacturers. This system will avoid the disadvantages in material supply and lead to increasing the pricing powers of ethanol and other biochemical products. Enterprises must have the capability to utilize all of the ingredients of some crop. At the same time, if they can achieve optimization matching in pretreatment, separation, utilities, etc. and combine the sugar and thermo-chemical platforms, it certainly will improve the entire financial feasibility. This phenomenon is the so-called whole-crop refining that integrates agriculture and industry.

In addition, for biomass enterprises, one kind of material can be used to produce different products and the same product can be produced from different materials [18,19]. For example, the category of feedstocks in the context of ethanol production includes wheat, corn, cassava, sweat guinea corn, sugarcane, etc., whereas, on the other hand, 1,3PDO can be produced using oil-bearing crops and also using the glycerol, which is the co-product of biodiesel production. Therefore, a single crop can lead to the implementation of an integration strategy, and moreover, industrial and agricultural enterprises with multiple crops, products, and techniques can also integrate to optimize the entire line, which is the so-called “multiple-crop refinery system.”

Fig. 4 demonstrates this biomass refinery system for a fuel-ethanol plant building in a large farm, which is similar to the new century farm mentioned by Jill Euker at Iowa University. The central corn-ethanol plant primarily uses circumjacent corn as the feedstock, whereas the cellulosic ethanol plant is located close to the corn ethanol plant or around it so as to establish several small factories according to the farm scale after considering harvest and shipment costs. The ethanol produced at these small cellulosic ethanol factories is shipped to a large-scale corn ethanol plant after primary distillation for rectification, dehydration, and packaging sales.

2.2. Advantages of the system

The integrated system discussed in this paper adds the selectivity and adaptability of a variety of materials, decreases the risks faced by enterprises in the situation that upstream supply is insufficient, and conforms to the developing trend of the ethanol industry. There are obvious merits as follows:

2.2.1. Ability to control the pricing risks

Founding the industrial park for the integration of agriculture, self-production, and self-use can cope well with the problems of changing prices in the market and improve the flexibility of the enterprise. A high degree of flexibility is typically associated with the production of alternative fuels due to the ability to source from different input feedstocks or to produce different output products based on the market.

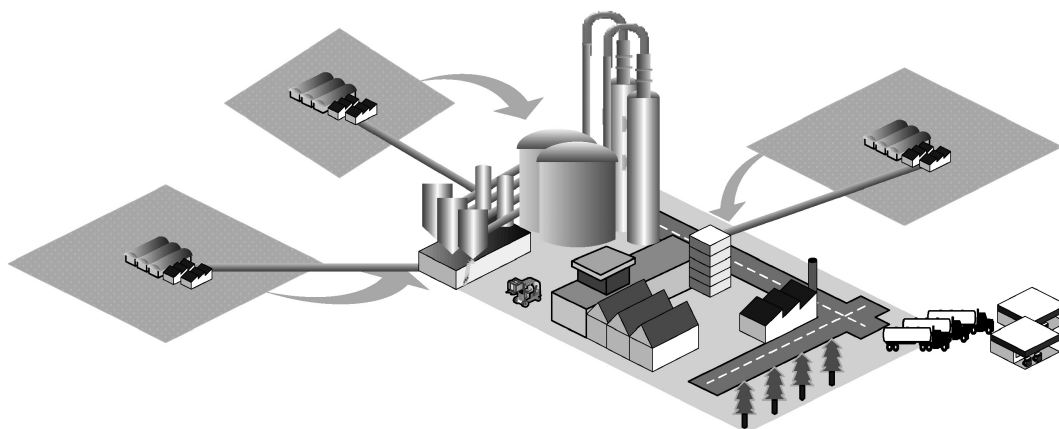


Fig. 4. Schematic diagram of an integrated biomass refinery system.

The supply and demand of each kind of fuel-ethanol material varies with the seasonal characteristics. Using a strategy of a single material might result in an insufficient supply or no way to adjust the production strategy in the face of increasing marketing prices, etc.

2.2.2. Flexible arrangement on the materials

The selection of materials can be diversified if there are several pre-treatment product lines, not only for grains, such as wheat and corn, and non-grains, such as cassava and sugarcane, but also for lignocellulosic materials that can be utilized to produce ethanol. In addition, according to the quantity of available farmland area, the enterprise can aptly purchase certain amounts of material at harvest time when the market price of the material is relatively low to supplement the shortage of its own supply. When market prices are high, the enterprise must use more of its own raw materials in production. During the selection process (the type of material, the time of purchase and the quantity purchased), the enterprise decision maker will face the problem of choosing the optimal production scheme. They can utilize the method of system engineering optimization to help in the decision making such that the profit can always be maximized.

If the factory is built on a large farm and relies both on its farm to provide cheap materials and on purchases from the market to achieve production, it can dramatically reduce ethanol costs. Figs. 5 and 6 indicate that when the farm portion varies as per the three differently colored lines that correspond to three assumed prices of corn, the unit ethanol cost changes. These figures also demonstrate that the higher the portion of materials that is provided by the enterprise's own farm, the lower sensitivity it has to market prices, i.e., the weaker the resistance is. This effect can be easily explained because, over time, the change in corn plant costs is not as severe as that in market price, and it will not be as influenced by varying supplies and demands.

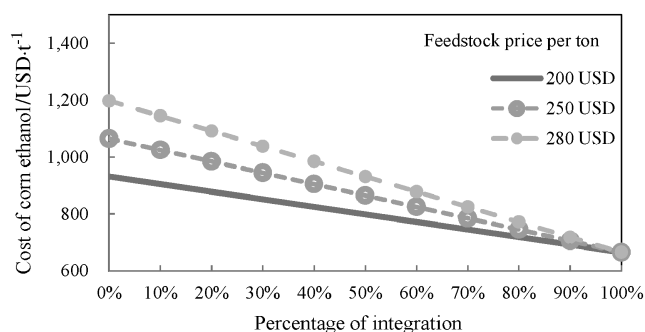


Fig. 5. Impact of feedstock self-sufficiency-rate on ethanol cost.

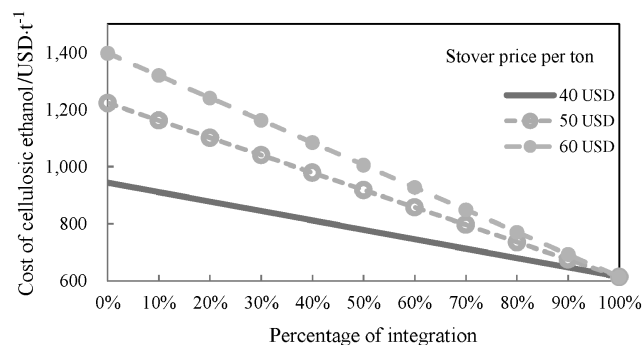


Fig. 6. Impact of feedstock self-sufficiency-rate on ethanol production cost.

2.2.3. Flexible arrangement on the process

The ability to relieve the high production cost problem is caused by the immaturity of the cellulosic ethanol. In this integration production

system, purchasing cost and stover quality are optimally controlled (self-produced and self-utilized). In the case where the pre-treatment is not mature and the enzyme cost is relatively high, the separation system, drying equipment and utilities for the grain ethanol system can reduce the fixed investment in the cellulosic system, which primarily relies on the scale effects of this processing equipment. Meanwhile, the electricity and steam obtained after the residue of the cellulosic ethanol is burned can also be used. The enterprise can also have a flexible arrangement on the production scale of a cellulosic plant. Until the technique is mature enough for production, this integration is the best option for R&D investment.

2.2.4. Other advantages

Fig. 7 demonstrates the investment ratio in each work section of grain ethanol and cellulose ethanol production. For these two ethanol system types, the investments in the pre-treatment (including de-impurity, hydrolysis), separation and wastewater treatment, and electricity generation are the largest [20]. If the system described in this paper is integrated together with common system, i.e., separation, waste-water treatment, combustion generation, and marsh-gas generation, then the production scale of these projects will increase, which prevents the problems of repeated, small-scale construction and leads to a large-scale profit. In the two situations of fixed investment as shown in Fig. 8, in which the increase of the system scale profit is dramatic, the unit investment of ethanol can be reduced by about 20 million dollars per ton. Because of the difference between the pre-treatment procedures of grain ethanol and cellulosic ethanol and based on current research technology, it is hard to realize high-efficiency production. However, the integration of the pre-treatment and fermentation of different materials will be a trend for fuel ethanol. The ability to achieve full usage of the plant can produce not only ethanol but also other chemical products and fuels. According to the analysis, when ethanol prices significantly diverge from gasoline, which results in a loss, normally, the co-product price is relatively stable, and most of the prices of the co-products are high, which can dramatically improve the enterprise's profits. For example, wheat has the co-product wheat gluten, corn has the co-product corn oil, and corn cobs can be processed into packing material. The profits of these co-products are always much more stable than that of fuel ethanol.

Whole-crop refining can promote the techniques integration of bio-refinery. The future bio-chemical plant must be an all-around, large-scale industrial group that uses multiple crops for the refining and producing of multiple-platform chemical products. Taking bio-ethanol as a gateway, the development of 1,3-PDO, bio-ethylene, and butanol production technology at the same time and realizing the extension and coupling of the industry chain will be of great significance to the development of the entire industry.

3. Technical Economic Analysis

3.1. System boundary

For comparison, corn was chosen as a case to analyze the material, energy, and economic flow of the whole-crop refinery system. Fig. 9 demonstrates an integrated enterprise that takes corn as the primary material. The scale of this enterprise is 0.2 million tons of ethanol per year which is the typical representative of large enterprise in China. All relevant processes in the biomass production (corn agriculture that produces corn and stover) and the conversion to ethanol are included within the system boundaries of the ethanol life cycle. Capital goods production and wastes management are also included. For the sake of simplicity, the environmental impacts of the process have been left out of the account as well. From the start of fermentation, there are many processes that can be combined together and utilities that can be shared.

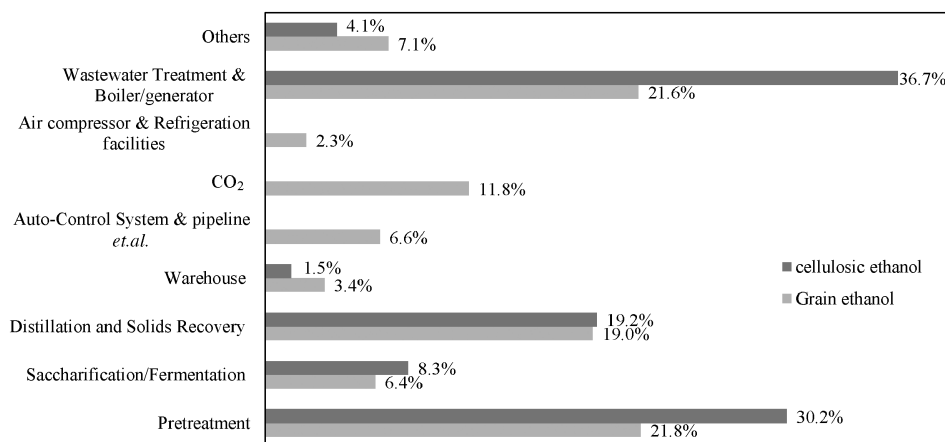


Fig. 7. Investment cost of different processes of ethanol plant.

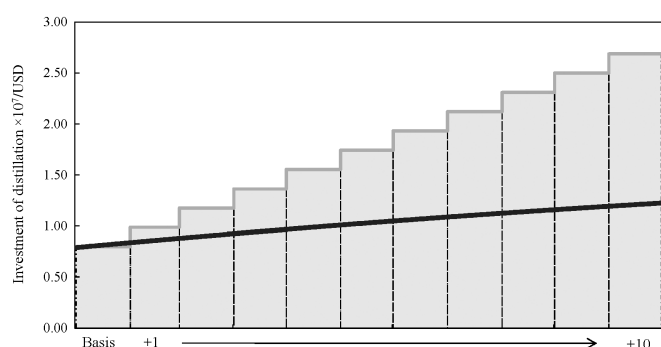


Fig. 8. Scale merit of equipment in ethanol plant.

Because the ratio of grain to corn stover is usually 1:1.2–1.5 [21–23], 1 ton of ethanol consumes 3.1–3.3 tons of corn and 4–6 tons of stover. As for corn and stover, the same land has roughly the same output for both fruits and stover, *i.e.*, it is reasonable to assume that, for one land output, its corn can be used to produce 0.1 million ton of ethanol, and the associated cellulose stover can produce the same yield. If it is assumed that a certain piece of land can provide 0.3 million tons of corn production and

the corn grass ratio is 1.5, then the corresponding output of corn stover will be approximately 0.45 million tons. According to the unit area crops output, the land area can be calculated to be approximately 200 km², which roughly equals to the entire corn acreage under cultivation of one county. In Chinese-cultivated land, few farms of this scale exist, and hence, this discussion is mostly academic. Actually, in industrial production, the available corn scale must be considered, and then a certain quantity of corn, other crops and stover must be purchased from the market to meet production requirements.

3.2. Data source

The data that were used in this study were obtained from different sources, including the four largest fuel ethanol enterprises and some literature that has been published at home and abroad. Below are some explanations of the data.

- (1) Most of the agricultural production data are derived from internal agricultural yearbooks and literature. The ethanol production technical data are from the actual production statistics of Chinese domestic enterprises and not from Aspen or Excel simulation models. The data are detailed in one day and processed for this paper.

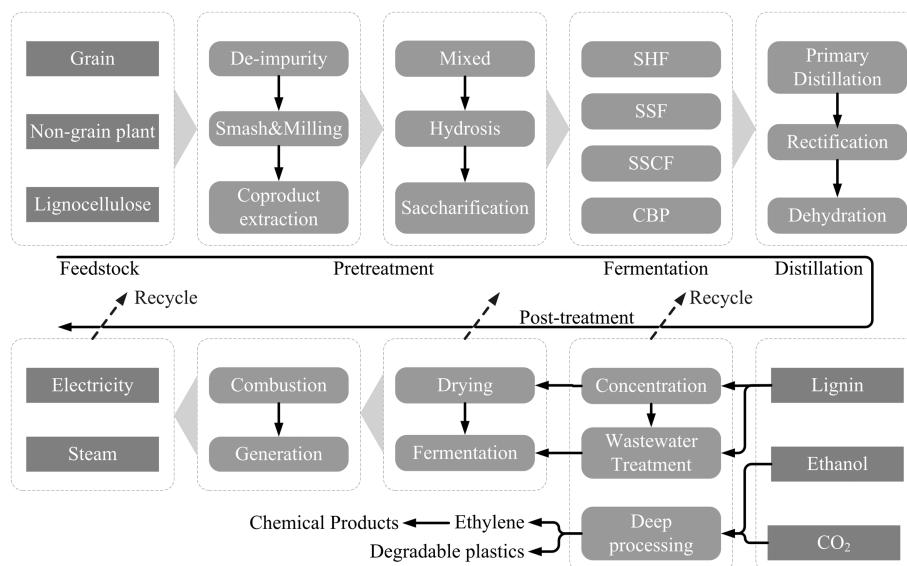


Fig. 9. Investment of distillation under increasing of equipment size.

- (2) The cellulosic ethanol data are derived from the 0.1 million ton-level cellulosic industrial group that will be founded in China.
- (3) Some water, energy-flow, and engineering investments are quoted from the reports of NREL and the EBAMM model [20,24], and a judgment is made according to the Chinese situation.

3.3. Material and energy analysis

3.3.1. Material-flow analysis

According to the Chinese agricultural yearbook, the statistical data from the Agricultural Ministry and data in recent literature [21–26], the yield of corn in China has increased from $3 \times 10^5 \text{ kg} \cdot \text{km}^{-2}$ to $8 \times 10^5 \text{ kg} \cdot \text{km}^{-2}$ [Table 3]. Some experimental fields can reach as high as $1 \times 10^6 \text{ kg} \cdot \text{km}^{-2}$. When calculating stover outputs, the Statistical Bureau takes the corn ratio of grain to stover to be 2.0. Some of the literature and books also take 1.8 [5], however, this ratio is obviously a little higher, and some of the external literature has set the value to be between 0.5 and 1 [27,28]. The authors deem that the value should be between 1.2 and 1.5, and take 1.5 as an assumption.

Table 3

Grain and stover yields per hectare in China

Yield	Unit	Corn	Wheat
Grain	$\text{kg} \cdot \text{km}^{-2}$	750000	600000
Stover	$\text{kg} \cdot \text{km}^{-2}$	1125000	1620000

Grain ethanol materials produce starch and protein, which influence the yield of ethanol and yield and quality of co-products. Ethanol materials depend on the amount of cellulose, hemicelluloses and lignin, which significantly influence the ethanol output. These parameters can be found from Table 4.

Table 4

The primary components of feedstock

Component	Unit	Corn stover	Corn cob	Wheat stover
Cellulose	%	37.2	45.2	30
Hemicellulose	%	25.3	35.0	50
Lignin	%	18.0	15.3	15

Component	Unit	Corn	Wheat	Cassava
Starch	%	62–70	65–70	75
Protein	%	10	15	3

Corn can be roughly divided into corn roots, corn stover, corn kernels and corn cobs. Except for corn roots, all parts can be utilized as raw materials in a bio-refinery factory, wherein corn can be fermented to produce ethanol and extract corn oil, CGF and CCF. Corn cobs can be produced into feeds, xylitol, furfural, etc. Corn stover can be burned to generate electricity and can also be used to produce ethanol by means of biological processes. Fig. 10 demonstrates the whole corn bio-refinery route, and the amounts of corn, corn cob and corn stover are well matched. For ethanol, the unit consumption of corn stover is 6.5 tons, whereas that of corn is 3.2 tons.

Most ethanol production include several processes of pre-treatment, saccharification, fermentation, separation, distillation, effluent disposal and electricity generation. The required production equipment for the latter four processes is similar, and there is some commonality. Therefore, these two production techniques can be integrated together or shared, and hence, a grain-ethanol plant is easy to transform into a cellulose-ethanol factory. Furthermore, the residue generated in cellulose-ethanol production can be burned to generate electricity and steam, which can provide energy to its own production needs and to those of grain ethanol manufacturing. The separation and sewage plants

of both methods can also be combined together to increase the production scale and reduce costs. Table 5 demonstrates the individual unit consumption of feedstock, accessories, energy and water for each part of production.

3.3.2. Energy-flow analysis

Net energy production was used to evaluate the energy efficiencies of grain- and cellulosic-derived ethanol [5]. Typically, studies have used net energy values (NEV), net energy ratios and net energy yields (NEY) to measure the sustainability of a bio-fuel [32–37]. In the initial analyses, stover was estimated to have a net energy ratio of 1.1–8.2 when used to produce biomass ethanol, whereas greenhouse gas was assumed to be near zero [23,38]. Before the energy analysis, a detailed calculation of the net energy of cellulosic ethanol and grain ethanol in China is presented in Table 6 because there have been few internal referable research studies. Part of the data are compared using the GREET model from Argonne National Laboratory, the EBAMM model and a report from NREL, which was revised according to the actual situation of China. In accordance with the definition of the net energy and energy ratio by Shapouri [35], this paper uses two indicators to evaluate ethanol energy profit. Detailed formulas are presented in the literature, so no more information is given here.

For the calculation, organic and solar energy inputs, such as animal power and human labor, are neglected, and only inorganic energy is considered. The shipment calculation assumes diesel vehicles and a 200-km shipment distance. The energy consumption of ethanol factory production is primarily from coal and not gas or oil [Table 7]. In the allocation method of energy, the market value method is used to assign on the co-products of corn ethanol and cellulose ethanol, the ratios of which are individually 34% (half-wet production, corn oil, DDGs, CO₂) and 1.17 (steam and electricity). This paper also takes the lignocellulose produced by agricultural into consideration. On the other hand, a cellulose ethanol system is similarly analyzed, as in Luo's paper [27], however, the data are slightly different.

In Table 8, before the energy allocation of the main products and co-products of the corn-ethanol and cellulose-ethanol plants, the net energy is negative. Non-renewable resource, the chemical N fertilizer and energy consumption are the key factors that make the net energy negative, however, after allocation, the net energy reaches 1.94 and 26.91 MJ·L⁻¹ for corn ethanol and cellulose ethanol, respectively, and the cellulosic ethanol system is obviously better than the grain ethanol system. Moreover, after the integration of the two systems, the NEV is generally better than corn ethanol because the energy output of the co-products significantly increases.

The NEV method used in this paper involves mechanical energy and some of the non-renewable resources in addition to fossil fuels. Thus, it is more accurate for measuring the entire system's energy flow. Although the net energy value cannot measure the quality of energy, it can illustrate the net energy gains and losses of fuel ethanol system quantitatively. Also, the NEV results can provide detailed energy data for sustainable analysis. If the environmental load, waste discharge and effect of investment are combined, some methods can be used to calculate the sustainable development index of the fuel ethanol system, which has important significance for sustainable evaluation.

3.3.3. Economic analysis

The economic efficiencies of first- and 1.5-generation fuel ethanol have been closely analyzed, which will not be repeated here. This paper provides a brief analysis of the economical efficiency of cellulose ethanol. In order to estimate the cost of producing cellulosic ethanol, the investment and actual operating data of a cellulosic plant in China are studied.

Based on the financial cash flow of construction and production, a cellulosic-ethanol project investment primarily includes three parts: production equipment, buildings and related costs. The time value of capital is not taken into account, and the cost of cellulosic ethanol is

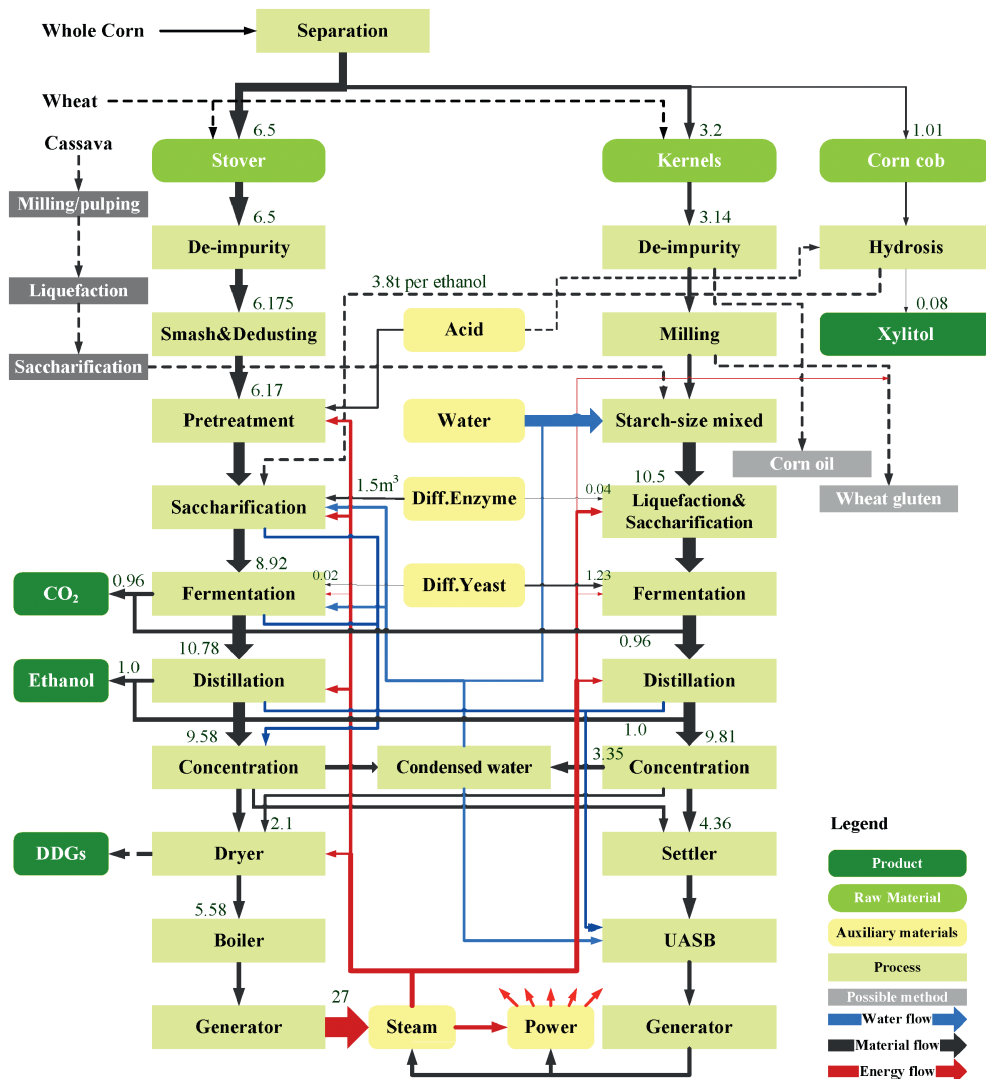


Fig. 10. Process of a whole corn refining plant.

ethanol technology. Based on a financial report of cellulosic ethanol plants, this paper analyses the cost of corn stover ethanol. From the data that are presented in Table 9, the cost of accessories and enzymes or just enzymes can be viewed as the most expensive component of cellulose ethanol production, followed by material costs. However, these costs are still low in comparison to those of starch materials due

The yield and product costs of cellulosic ethanol are important metrics that influence the commercial development of future cellulosic

Table 5
Main feedstock and auxiliary material for an integrated ethanol plant ($t \cdot (t \text{ Eth})^{-1}$)^①

Xylitol		Cellulose		Corn	
<i>Materials</i>					
Corn cob	11.63	Corn stover	5.5 ~ 6.5	Corn	3.10~3.30
Hydrochloric acid	2.46	Corn syrup	0.047		
Sulfuric acid	0.41	Inorganic salt	0.078		
Liquid alkali	4.62	Cellulose	0.093	Enzyme	0.20
Activated carbon	0.15	Yeast	0.02	Yeast	0.10
<i>Energy</i>					
Water/m ³ · (t Eth) ⁻¹	187 ^②	Water/m ³ · (t Eth) ⁻¹	12.8~20 ^③	Water/m ³ · (t Eth) ⁻¹	8.17 ^③
Electricity/kW · h · (t Eth) ⁻¹	3154 ^②	Electricity/kW · h · (t Eth) ⁻¹	695	Electricity/kW · h · (t Eth) ⁻¹	182
Steam/t · (t Eth) ⁻¹	56.47 ^②	Steam/t · (t Eth) ⁻¹	7~10	Steam/t · (t Eth) ⁻¹	2.77 ^③

④ Cited from [29].

Table 6

Energy inputs to corn farming per hectare in China

Agricultural inputs	Unit	Amount	Energy inputs/MJ
Nitrogen fertilizer	kg	187.5	10773.75
Phosphorus fertilizer	kg	75	527.25
Potassium fertilizer	kg	105	719.25
Herbicides	kg	2.71	722.38
Insecticides	kg	0.99	281.97
Seed	kg	30	1600.8
Diesel	L	63.53	2823.26
Electricity	kW·h	11.91	2679.75
Farm machinery	–	–	150.72 ^①
Total	–	–	20279.13

^① Farmers arrange agricultural production with a relatively low rate of mechanization in China, and this number is 3000–6000 in U.S.

Table 7

Energy inputs to bio-refining in China

Bio-refining inputs	Unit	Amount
Transportation of feedstock to bio-refining	MJ·L ⁻¹	1.10
Coal	MJ·L ⁻¹	19.67
Capital (plant and equipment)	MJ·L ⁻¹	0.13 ^①
Process water	MJ·L ⁻¹	0.38 ^①
Effluent restoration (BOD energy cost in MJ L ⁻¹)	MJ·L ⁻¹	0.29 ^①

^① Cited from [32–37].

to the cheapness of cellulosic materials. As the technology continues to develop, especially by additional breakthroughs in enzyme techniques, the cost of cellulose ethanol production will significantly decrease.

The external literature has reported cellulose-ethanol production costs ranging from 400 to 1300 USD per ton. If the price of cellulose ethanol is above 4 USD per gal, cellulose ethanol is not economically competitive, however, if gas prices increase a further 30% and the price of gasoline reaches 1200 USD per ton, cellulose ethanol will have competitive commercial value. If the cellulose-ethanol price is above 850 USD per ton, which is the current market price of fuel cellulose, it will occupy some market share, and if the cellulose price is lower than 500 USD per ton, which is already lower than the current price, it will replace the fuel-ethanol market.

In comparison to a cellulosic ethanol plant, the integrated whole-corn refining system discussed in the previous chapters has slightly greater transportation costs but a 20% lower investment cost. The total investment cost of a 10 thousand-ton-level cellulosic plant is about

Table 8

Summary of energy inputs and outputs of the ethanol system

Item	Unit	Corn	Cellulose	Combined
Farm	MJ·L ⁻¹	7.05	8.46 ^①	3.56
Transportation	MJ·L ⁻¹	1.10	1.32 ^②	1.21
Bio-refinery	MJ·L ⁻¹	19.67	27.02	21.6
Mixed	MJ·L ⁻¹	0.03	0.03	0.03
Sales	MJ·L ⁻¹	0.85	0.85	0.85
Input energy	MJ·L ⁻¹	28.67	37.68	27.25
Co-product in bio-refinery	MJ·L ⁻¹	9.42	43.4 ^③	26.41
Co-product in agriculture	MJ·L ⁻¹	36.5	69.4	0
HV of ethanol	MJ·L ⁻¹	21.19	21.19	21.19
Net energy value(no allocation)	MJ·L ⁻¹	–7.48	–16.49	–6.06
Net energy value(allocation 1 ^{④⑤})	MJ·L ⁻¹	1.94	26.91	20.35
Net energy value(allocation 2 ^⑤)	MJ·L ⁻¹	38.44	96.31	20.35

^① There is an additional cost of collection before the recycled biomass energy is subtracted; the yield: 5 tons of feedstock to produce 1 ton of ethanol.

^② Transport distance is 200 km.

^③ It refers to electricity and steam.

^④ In this study, it refers to the corn as a co-product in the agriculture; in all of the other studies, it refers to the harvested stover (60%, dry-mass basis) as a co-product; the values are estimated in this study.

^⑤ In this study, the co-product both in bio-refineries and agriculture is estimated; however, the method is different than that in the literature [32–37].

Table 9

The cost of cellulose-ethanol factory construction

	Investment				Total
	Construction	Equipment purchasing	Installation	Other costs	
Amount $\times 10^{-4}$ /CNY·(t Eth) ⁻¹	0.13	0.68	0.10	0.069	0.99
Percentage/%	13.34	69.32	10.34	7	100

Table 10The cost of unit cellulosic ethanol (USD·t⁻¹)

Item	Amount	Item	Amount
Feedstock	264.1 ^①	Production costs	22.6
Accessories and enzyme	309.1	Hydroxylation costs	75.2
Energy consumption	131.2	Sales cost	22.6
Salary and welfare	52.7		
Managerial costs	15.0	Total	892.6

^① The price of feedstock is 40 USD per ton.

14.75 million dollars according to the feasibility study report from the Tianguan Group. Thus, about 1.5 million USD will be saved when a new cellulosic ethanol plant is established. Figuring out the distance and scale for both the central and surrounding cellulosic ethanol plants will be an important task.

4. Conclusions

This paper studies the development of current Chinese bio-ethanol technology and explores a reasonable model to address several critical issues therein, including marketing risk, raw material supply risk and technical risk. This study takes an integrated corn-crop refinement system as an example and analyzes the logistics, energy flow, and economical efficiency of the system.

From the viewpoint of risk resistance, the discussed integrated system can absorb multiple feedstocks of grain and non-grain, and, based on production requirements, purchase and store an appropriate amount of feedstock so as to better respond to the impact of market price variations on profit. Moreover, under certain conditions, the integrated system can properly reduce the fixed investment in production equipment, share utilities and wastewater treatment facilities, and reduce energy consumption. The future development of the bio-ethanol industry chain will be deepened and extended, however, there must be a trend towards common multiple-crop refinement.

From the viewpoint of material usage and consumption, China's bio-ethanol production technology is not yet mature. The feedstock, energy, and water consumptions of unit ethanol production are still high. For example, Chinese steam consumption is two to three times higher than that of the United States, and water consumption is four times higher than that of the United States. Therefore, there is significant room for improvement in production equipment, production processes, and production control.

From the viewpoint of energy efficiency, the net energy values of China's grain-ethanol and cellulosic-ethanol industries are 1.935 MJ·L⁻¹ and 26.905 MJ·L⁻¹, respectively, which are lower than the reported values of similar studies abroad because China's grain output per ha is relatively low and the fossil energy consumption in the production of ethanol is relatively high.

For the system economy, the unit cost of second-generation bio-ethanol varies from 800 to \$1200 USD per ton and cellulosic ethanol is slightly more expensive than grain ethanol. The impact of feedstock cost on cellulosic ethanol is far lower than that on grain ethanol, and the proportions of feedstock costs in terms of total costs are 30% and 80%, respectively. If the oil price is 1000 USD per ton or greater, the ethanol corporations will make better profits in general. After integration

and a reduction in fixed investment costs and thermoelectric system sharing, ethanol enterprises can properly reduce ethanol production costs, wherein production efficiency is more significant than individual production. In this view, further experiments and practices are required to find an optimal path for bio-fuel development.

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