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Techno-Economic Modeling of a Corn Based Ethanol Plant in 2011

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ABSTRACT

As studies continue to examine new value added uses for ethanol coproducts, it is important to have means to easily determine the feasibility of the processing steps involved. Many industries widely use computer simulation programs for this purpose, and for planning the use of resources and equipment capacities, and to determine processing costs. The objective of this project was to determine the sensitivity of 40 million gal/y corn-based ethanol plant model to changes in input material prices, product market prices, and various coproduct processing scenarios (i.e., oil extraction and drying of DDGS). The techno-economics of the base case ethanol plant were examined by factorially adjusting material and market costs, as well as adjusting the quantities of distillers wet grains (DWG), distillers dried grains with solubles (DDGS), and corn oil produced. The simulations verified that corn price has the greatest impact on the overall annual operating costs for the ethanol plant, and that the market price of ethanol has the greatest impact on annual revenues. The effect of coproduct processing on utility usage was also observed; oil extraction and drying of DDGS consumed substantially more energy and had higher capital costs than production of DWG alone. It was apparent that coproducts are an essential component to the sustainability of an ethanol plant in that: 1) they have continued marketability to the livestock industry, and 2) processing is not overly-expensive. This study has provided a basis for further exploration of the feasibility of new coproduct processing options, and illustrates the use of the model for determination of processing costs and revenues, as well as mass and energy balances.

Keywords: Ethanol; Corn; Dry-grind; Oil; DWG; DDGS; Economics

INTRODUCTION

In the past decade the United States ethanol industry increased production from 1.6 billion gallons in 2000 to 13 billion gallons in 2010. The 13 billion gallons of ethanol produced could potentially replace enough gasoline to reduce the need of 445 million barrels of imported oil, this is 55 million barrels more than what was imported from Saudi Arabia in 2010 (RFA, 2011a). Between 2009 and 2010 alone, the US ethanol industry increased production by 743 million gallons, with an additional 840 million gallons expected from biorefineries under construction (Urbanchuk et al, 2011). During 2010 about 30% of the total American corn crop was transformed into ethanol (RFA, 2010a), which equated to 4.65 billion bushels of corn (RFA, 2011a).

The production of ethanol from corn begins with the breakdown of starch into useable sugars. In order for this to begin the corn must first be processed. The predominant method of processing corn into ethanol is dry grind processing, where corn in ground and then the starch transformed by enzymes into sugar, which is then fermented into ethanol by yeast (Singh et al, 2001). A small portion of ethanol is produced by wet milling methods, but dry milling is preferred as it requires less capital to build, a smaller staff to run, and has more flexibility (McAloon et al, 2000). More than 88% of the ethanol produced in the United States is produced using dry grind processing while the remaining 12% is produced from wet milling process (RFA, 2010b). In both types of processing proteins, minerals, fat, and fiber are left behind as they are unfermentable. In the dry grind process, co-products are generally in the form of distillers wet grains (DWG) or distillers dried grains with solubles (DDGS), while in the wet milling process they are in the form of corn gluten meal or corn gluten feed. RFA (2011b) reported that in 2010, around 32.5 million metric tons of these coproducts were produced, which is an increase of nearly 30 million metric tons over what was produced in 2000.

Somewhat variable, DDGS contains 86-93 % dry matter, 25-35% protein, 3-14% fat, and 7-10% fiber (Bhadra et al, 2009b; Ganesan et al, 2008; ISU, 2008; Kim et al, 2007; RFA, 2011b; Rosentrater and Muthukumarappan, 2006; Shurson and Alhamdi, 2008; Srinivasan et al, 2005; Srinivasan et al, 2009; Weigel et al, 1997). This nutrient balance makes it valuable as an animal feed ingredient. Of the 32.5 million metric tons of DDGS produced in 2010, 80% was used for feeding cattle (beef and dairy) (compared to about 9% for poultry and about 10% for swine) (RFA 2010a). A small percentage of the DDGS market is comprised of other uses, including aquaculture feed, deicers, cat litter, lick barrels, and worm food (Bothast and Schlicher, 2005; Kannadhason et al, 2010; Rosentrater et al, 2009a; Rosentrater et al, 2009b; and Schaeffer et al, 2009). Ongoing research is being done to find new, value-added uses and high-value applications for these coproducts (Rosentrater, 2007). For example, studies are being done on using DDGS as a human food ingredient (Rosentrater, 2007; Rosentrater and Krishnan, 2006), and in the production of biodegradable plastics (Bothast and Schlicher, 2005; Tatara et al, 2006; Tatara et al, 2007).

Most studies to find new uses for DDGS and other coproducts are done on a small scale (either bench top or in pilot plants). Many processes can be feasible at small scales, but determining their feasibility at a large scale can be tricky. At bench top or pilot scale, a few pennies may not make a big difference, but when scaled to a commercial scale, economic inputs can be increased by several orders of magnitude, and can have a huge impact on the feasibility of the process. For this reason, accurately predicting the cost of production prior to adding new technology to an existing large scale facility is important.

Computer based modeling and simulation allows for such economic predictions to be made, and permits planning for resources, for equipment capacities, and for the determination of required process parameters (Petrides et al, 2011). Modeling and simulating of processes is currently used in many domains, such as pharmaceutical production and waste water treatment (Akiyama et al, 2002; Prazeres et al, 2004; Petrides et al, 1998; Petrides et al, 2002). During the 1960's, the petrochemical industry began to model and simulate industrial processes in order to optimize production capacities (Petrides et al, 2011). Simulation programs have recently began to be used in the biofuels industry as well; for example, ASPEN PLUS has been extensively used to simulate the transformation of corn into ethanol, and to perform cost analysis of the production biodiesel (Hass et al, 2006; Rajagopalan et al, 2004; McAloon et al, 2000). Similarly, a corn ethanol plant model was created with SuperPro Designer (Intelligen, Inc., Scotch Plains, NJ); which allows for the estimation of process and economic parameters of a typical 40 million gal/y dry grind facility (Kwiatkowski et al, 2006).

While simulations have demonstrated the Kwiatkowski et al (2006) base model to be an accurate depiction of the overall dry grind process, additional simulations could be beneficial in many additional ways, including determining the viability of modifying coproduct processing operations. However, before new processing procedures are added to the base model, a complete understanding of the sensitivity of the model must be determined. Therefore, the objective of this project was to determine the Kwiatkowski et al (2006) model's sensitivity to changes in material prices, market prices, and coproduct processing (oil extraction, drying of DDGS, or producing DWG).

MATERIALS AND METHODS

Computer Model

SuperPro Designer (Intelligen, Inc., Scotch Plains, NJ) allows the processing characteristics, and equipment and economic parameters to be defined along with volumes, composition, and physical characteristics for each stream. These characteristics are then used by the program to determine mass and economic balances for the individual unit operations and in turn the mass and economic balances for the entire process. Kwiatkowski et al (2006) created a 40 million gal/y ethanol plant model using SuperPro Designer (Intelligen, Inc., Scotch Plains, NJ) that allows the user to estimate both process and economic parameters of a generic ethanol plant design. The model was not intended to replicate a specific plant design, but instead a generic plant design containing equipment and unit operations necessary to convert corn into ethanol. In June of 2011, A. McAloon and W. Yee updated the model to reflect new ethanol process technologies and current economic values of equipment and materials. It was this updated model (McAloon A. and W. Yee, 2011, unpublished model, Wyndmoor, PA: USDA) that was used to run the simulation scenarios discussed in this paper.

Typical ethanol plants operate 24 h/day year round with scheduled down time for maintenance and repairs; for this reason the model is set up to operate on a basis of 330 days/y and all annual costs are associated with this operation. The processing characteristics; equipment parameters; salaries; and utility, material, and equipment costs were updated from the original model and set by A. McAloon and W. Yee based on published materials and typical salaries in rural America. In addition to updating this information, A. McAloon and W. Yee added a few coproduct processing pieces to the process: an oil extraction system and an option to extract DWG before being sent to the dryers. The information programed into the model is used by

SuperPro Designer to produce a variety of reports based on mass and economic balances. These reports were generated for each simulation scenario in this study and used to compare the economic feasibility and sensitivities of processing scenarios and material prices.

Simulations

Simulations (Table 1) were run based on modifying four independent parts of the model (McAloon A. and W. Yee, 2011, unpublished model, Wyndmoor, PA: USDA):

1) prices of corn and utilities (Table 2) (prices used in the 2005 model (Kwiatkowski et al, 2006) versus the updated prices used in the 2011 model (McAloon A. and W. Yee, 2011, unpublished model, Wyndmoor, PA: USDA);
2) quantity of oil extracted from condensed distillers solubles (CDS) (1% versus 80%);
3) quantity of distillers wet grains (DWG) produced (1% versus 33.33%);
4) market price of ethanol, DDGS, and DWG (market prices from the 2005 model (Kwiatkowski et al, 2006); updated prices from the 2011 model (McAloon A. and W. Yee., unpublished model, 2011, Wyndmoor, PA, denoted as scenario 2011a; and actual market prices at the time of simulation (July 2011), denoted as scenario 2011b). All of these price scenarios are listed in Table 2).

These four independent variables provided a total of twelve simulation scenarios (Table 1). For each simulation scenario the fixed capital costs, the annual operating costs (AOC), the annual revenue, and the profits were compared. The fixed capital costs were broken down into the various components that comprise the entire facility: support systems, coproduct processing, ethanol processing, fermentation, starch to sugar conversion, and grain handling and milling. The annual operating costs were split into utilities, facilities, labor, and materials; of which the utilities and materials were broken down into their individual components. The annual revenues were broken down according the products produced: ethanol, corn oil, DWG, and DDGS. After these comparisons were made, each scenario's sensitivity was explored. The price of one material (corn, electricity, natural gas, and steam) was individually increased by 20%, while holding the other variables within the scenario constant, in order to determine the effect on the overall operating cost. The same was done for ethanol, oil, DWG, and DDGS, to determine their effect on annual revenues. These effects were then graphed so that their behavior could be described by linear regression slopes (Figures 8 and 9).

RESULTS AND DISCUSSION

Capital Costs

Capital costs are the initial investments put into the plant and can be comprised of equipment costs, process piping, instrumentation, buildings, insulation/electrical work, and the engineering/construction costs. In this particular model, the capital costs were calculated based on the total equipment purchase costs for the individual process sections: support systems, coproduct processing, ethanol processing, fermentation, starch to sugar conversion, and grain handling and milling. The effect that each of these components had on the overall capital costs can be seen in Figure 1. Based on the evaluation, coproduct processing contributed to more than 43.5% of the total capital cost for all 12 scenarios. This contribution was over two times greater than the contribution of the fermentation step which was the second highest contributor at approximately 20%. Ethanol processing itself only contributed to 16.5% of the total capital costs; while starch to sugar conversion contributed 8.5%, grain handling contributed 7%, and support systems contributed 4.5%. If any additional equipment were to be added for coproduct processing, it could easily contribute to the majority of the capital costs within the plant as the total ethanol production only contributes to a total of 52% of the capital cost.

Annual Operating Costs

The annual operating cost of an ethanol facility is comprised of the expenses associated with the facilities, labor, materials, and utilities required for operation. Figure 2 indicates the type of impact that these various components had on the overall annual operating cost of the process. It can be seen that regardless of the scenario, the material costs had the largest impact on the overall operating costs (average 76%) followed by utilities (average 10.9%).

Facility

Facility costs include maintenance expenses, equipment depreciation, insurance, taxes, and miscellaneous factory expenses. For this particular model the maintenance cost was determined as 3% of the capital costs, while insurance was determined to be 0.8% of the capital costs and factory expenses were determined to be 0.75% of the capital costs. Depreciation and taxes were not included for this model. The expenses associated with facilities comprised 6-14% of the total operating costs.

Labor

The cost of labor was determined based upon a lump estimate of number of working hours per year, $2.5 million/year for all scenarios. This quantity comprised 2-4.5% of the overall operating expenses.

Material Costs

In addition to corn, the materials used to compute the overall material costs include: octane, water, yeast, caustic, sulfuric acid, gluco-amaylase, alpha amylase, liquid ammonia, and lime. Figure 3 shows the impact that each of these materials had on the overall price of materials. It can be seen that the price of corn had the greatest impact on the overall material costs (average of 92%). Within the scenarios the corn price was the only material price to be adjusted. When the corn price was lowest ($0.087) the other materials had a greater impact on the overall material expenses; therefore, it is easier to see how these other materials affect the overall price. In these scenarios (1, 3, 5, and 7) we see that octane has the second biggest impact (5.44%) followed by gluco-amaylase (2.33%) and alpha amylase (1.61%). Caustic makes up approximately 0.62% of the material costs while yeast makes up 0.5% of the expenses. Gluco-amaylase and alpha amylase are important materials in the breakdown of corn starch into sugar; alpha amylase is used for liquefaction and gluco-amaylase reduces the starch to sugar. Yeast performs the fermentation and the caustic is used to sterilize the fermentation tanks at regular intervals.

Utility Costs

The quantity of the utilities used within the process (water, steam, gas, and electricity) can be seen in Figure 4. As this figure shows, the quantity of cooling water and steam did not change between scenarios (22,000 million kg/y and 270 million kg/y respectively). However, the quantity of natural gas and electricity did change when the quantity of DDGS produced was decreased. When the majority of DWG was collected and not dried, the electricity usage was about 38 million kWh/y, but when 2/3 of it was dried the electricity usage increased to 47 million kWh/y. A similar trend was seen with the natural gas usage: when 1/3 of the DWG was left wet 6.4 million kg natural gas was used, but when the majority of it was dried 9.5 million kg was used.

Figure 5 shows the effect of the individual utility cost on the overall expenses associated with utilities. For all scenarios steam had the biggest impact (approximately 39-50%) on the overall utility costs. Cooling water had the least impact only affecting the overall expense by 6-9% for all scenarios. When using the 2005 prices, it was observed that when most of the DWG was dried (scenarios 1 and 5) the natural gas made up around 26% of the total utilities, but when 1/3 was left wet (scenarios 3 and 7) natural gas only contributed to 20% of the total utilities. This opposite was seen with the steam prices associated with these scenarios: when most of the DWG was dried (scenarios 1 and 5) the steam made up around 44% of the total utilities, but when 1/3 was left wet (scenarios 3 and 7) natural gas contributed to nearly 50% of the total utilities. The electricity for the scenarios with the 2005 prices (scenarios 1, 3, 5, 7) contributed to approximately 21% of the total utility expenses, and coproduct processing did not significantly affect the impact caused by electricity.

As seen with the 2005 scenarios, adjustments in coproduct processing did not significantly affect how electricity impacted the overall utility expenses. The electricity for the 2011a and 2011b scenarios (scenarios 2, 4, 6, 8, 9, 10, 11, and 12) contributed to approximately 30% of the total utility expenses. It was observed that when most of the DWG was dried (scenarios 2, 6, 9, and 11) the natural gas made up around 20% of the total utilities, but when 1/3 was left wet (scenarios 4, 8, 10, and 12) natural gas only contributed to 16% of the total utilities. This opposite was seen with the steam prices associated with these scenarios: when most of the DWG was dried (scenarios 2, 6, 9, and 11) the steam made up around 39% of the total utilities, but when 1/3 was left wet (scenarios 4, 8, 10, and 12) natural gas contributed to nearly 44% of the total utilities.

Annual Revenues

The ethanol production process followed in the model produced five products: carbon dioxide, ethanol, oil, DWG, and DDGS; but for simulation purposes only ethanol, oil, DWG, and DDGS were assigned market values as very few companies within the ethanol industry market the CO2 produced. It is these products that are used to determine the annual revenue for the simulation. Figure 6 quantifies and shows the effect of each of these products. Part A shows how each product affects the overall annual revenue of the plant, while part B compares the annual quantity produced for each product.

Ethanol

Ethanol makes up approximately 31% of the total product produced annually by the ethanol process (Figure 6B), but it contributes to nearly 80% of the total annual revenue of the plant as show Figure 6A. Altering the price of corn used has little to no effect as the contribution of ethanol to the annual revenue did not change between 2005 scenarios (1, 3, 5, and 7) and the 2011a scenarios (2, 4, 6, and 8). However, when the price of the other products produced were adjusted to the current market values (2011b: scenarios 9, 10, 11, and 12) the effect that ethanol had on the overall revenue decreased to approximately 77.6%.

Oil

Figure 6A shows that when the 80% of the corn oil was extracted (scenarios 5, 6, 7, 8, 11, and 12) the contribution of oil revenue was minimal (1%) even though oil had the largest market price of all products produced. This was due to the fact that its contribution to the total products produced is also very minimal (<1%) (Figure 6B).

DWG

In the scenarios where 2/3 of the DWG was left wet (scenarios 3, 4, 7, 8, 10, and 12), DWG made up approximately 25% of the product produced (Figure 6A) and approximately 6% of the revenue.

DDGS

DDGS represent around 34% of the total products when the majority (99%) of the DWG was dried (scenario 1, 2, 5, 6, 9, and 11) and around 17% of the total revenue as show Figure 6A and 6B. When 1/3 of the product was left as DWG (scenario 3, 4, 7, 8, 10, and 12), DDGS contribution to the total annual revenue decreased to 11-15%.

Gross Profits

Figure 7A shows that when the 2005 prices were used (scenarios 1, 3, 5, and 7) the net benefits of the transformation of corn into ethanol were positive, while in the remaining scenarios they are negative. Since the main difference between the 2005 scenario and the 2011a and 2011b scenarios is the price of corn ($0.087/kg, $0.197/kg, and $0.286/kg respectively), it can be concluded that this difference in gross profit can be contributed to corn prices.

For their respective material costs (2005, 2011a, and 2011b) scenarios 7, 8, and 12 prove to have the greatest profits or least loss. Those scenarios were built with 80% oil extraction and 33.33% DWG. This allows two conclusions to be drawn: 1) coproducts with high marketability, regardless of the quantity produced can have an impact on the profitability of the facility, and 2) even if a coproduct contributes greatly to the overall revenue, it is not necessarily beneficial if the processing costs are too great.

This conclusion is further supported by looking at oil extraction and the drying of DDGS separately. When looking at scenarios where oil was extracted at 80% (5, 6, 7, 8, 11, and 12), we see that the revenue was determined to be about $2 million/year greater than those where only 1% of the oil was extracted. Scenarios that left 33.33% of the DWG undried (3, 4, 7, 8, 10, and 12) had higher benefits (on average $1.5 million/year more) than those that dried the majority of the DWG. This was due to the increase of utility costs (increased consumption of natural gas) associated with the drying used to produce DDGS. While the economics of this analysis show that production of DWG was more favorable, it does not take into account the costs associated with storage and transport of such grains after production. If these costs were taken into consideration, it may be more favorable to produce DDGS, as DWG require cool storage to keep from spoiling which may increase the utility costs associated with them.

The annual operating costs, annual revenues, and profits can also be broken down into a $/gal ethanol basis rather than $/y basis to allow for a visualization of how the costs are related to each gallon of ethanol produced by the plant. This breakdown can be seen in Figure 7B. The gross profits ranged from -$0.20/gal ethanol (scenarios 2, 9) to $0.86/ gal ethanol (scenario 7). The two scenarios with the least profit extracted only 1% corn oil, dried 99% of the DWG to DDGS, and had the highest corn prices. The high corn prices increase the operating costs, as does drying the DWG to DDGS. The annual revenue of these scenarios is also less than others due to the lack of corn oil contribution. The most profitable of the scenarios occurred when corn prices were at their lowest, 80% of the corn oil was extracted, and 33.33% of the DWG was left wet.

The annual operating costs of the plant ranged from $1.39/gal ethanol (scenarios 3, and 7) to $3.24/gal ethanol (scenarios 9, and 11). The scenarios with the lowest operating costs were those operating with the 2005 prices and producing the least amount of DDGS in turn using the least amount of natural gas. Those with the highest operating costs were producing the greatest amount of DDGS and operating with the 2011b prices. In addition to having one of the highest operating costs, scenario 11 also has the highest revenue at $3.06/gal ethanol. The lowest revenues occurred in scenarios 1, 2, 3, and 4 ($2.21/gal ethanol). These scenarios produced the least amount of bio oil and were performed with the lowest coproduct prices (2005 and 2011a).

Sensitivities

Sensitivity analysis provides support to conclusions developed based on modeling; it does this by looking at how variation in outputs can be attributed to the variation of inputs.

Since prices of materials and products are constantly changing with the markets, it is important to understand how deviation away from the values used in these scenarios would affect the outputs. In order to understand the models sensitivity to an increase of the prices of corn, electricity, natural gas, and steam their input prices were increased by 20% under each scenario. Only one price was altered at a time in order to get an accurate representation of that material’s overall effect. This was then repeated with the market prices of ethanol, oil, DWG, and DDGS. The changes of corn, electricity, natural gas, and steam prices were then plotted against the annual operating costs, while the changes in ethanol, oil, DWG, and DDGS prices were plotted against the annual revenues. The slopes of these plots were then used to quantify the impact of each input price or market value on the sustainability of the ethanol process.

Materials

Figure 8 presents the price versus operating cost plots of the four input materials. Since there were three different initial input prices (2005, 2011a, and 2011b), these graphs show three different starting points within the plots. However their starting values are not important as it is the variation in their slopes that is relevant to understanding the effect that changing the price has on the overall model. The slope values for the three different groups were averaged and can be found in Table 3. From the slopes it can be determined that the initial energy price has little to no effect on the how effect the annual operating costs changes, while the price of corn can have a much greater impact. This is important to know that the model being consistent with its calculations.

By comparing the four graphs, it is apparent that the corn has the greatest impact on total operating costs. To better quantify the impact, the slopes of the lines are presented in Table 3.

It can be seen that corn's slope is eight times greater than that of electricity, 1.5 times greater than that of steam, and nearly 46 times greater than that of natural gas.

Products

Figure 9 plots the effect of changing the market price of ethanol, DDGS, DWG, and oil on the overall process revenue. There were two different market prices (2005 (used in 2011a) and 2011b) used within the scenarios. However, unlike the material sensitivities the plots were not grouped solely by the input price, they were also grouped by the level of DWG produced. The slopes describing the sensitivity of the model to change in market price can be found in Table 4. The slopes indicate how market values can affect the revenue of the plant based on what products were produced.

By comparing the four graphs, it can be determined that the effect of the ethanol price remains fairly consistent (slope of 118.5 and 119.2) regardless of what the initial prices were or what other coproducts were produced. The effect of an increase in DDGS price can rival that of the ethanol's effect when nearly all the DWG was dried into DDGS. This indicates that expanding the market of DDGS in order to increase the demand, would allow DDGS to contribute to a large percentage of the income for an ethanol plant (comparable to that of ethanol). The effect that DWG had on the overall revenue appears to be very dependent on not only how much of it was produced, but also the prices of the other products. When the input market prices of ethanol, DDGS, and DWG were lower, increasing the price of DWG had greater than twice the effect than in scenarios where the input market prices of the three products were higher.

Implications

Based on the information provided by this model, the initial investments associated with ethanol production itself contributes 52% of the total capital costs; while those associated with coproduct processing provides around 43.5% of the capital cost. This means that in order to receive a payback on investment the largest amount of revenue must come from the ethanol stream itself. However, if more coproduct processing equipment is added to the facility it will cause the majority of the capital costs to come from the coproduct processing. This will mean that the coproducts will need to have a greater impact on the overall revenue in order to make the processing additions viable.

The material prices comprise around 76% of the annual operating costs of the processing facility. Of the materials, corn was the largest contributor, contributing an average 92%. The significance of the corn cost was also visible through the sensitivity simulation ran. As corn prices increased by 20% the annual operating costs increased by around $367 million/yr. This means that as corn prices increase the annual operating cost of the plant will rise significantly and the value of the products must also rise in order to keep the process viable.

The next highest contributor to the annual operating cost was the price of utilities at an average of 11%, and of the utilities steam had the greatest impact at 40-50% of the utility costs. The increase in utility prices had little effect on the overall operating costs when compared to the changes in coproduct processing. Increasing the amount of DDGS being dried from 66% to 99% caused the use of electricity to increase by 9 million kWh/y, and the use of natural gas to increase by 3.1 million kg/yr. These trends were also visible in the sensitivity simulations as a price increase of 20% for the natural gas led to an annual operating cost increase of $271 million/y, compared to an increase of $42 million/y caused by increased electricity prices, and $8 million/y caused by increased steam prices. This means that when considering adding coproduct processing to the facility, the amount of energy and the type of energy that will be consumed by the processing must be taken into consideration as it will have a significant impact on the utility costs and some impact on the annual operating cost of the plant.

Ethanol remains the largest product produced (average 31% total product) from the processing parameters selected for the scenarios of this study. Ethanol also made up the majority of the revenue for the plant averaging 77%. For product capacity ethanol was followed closely by CO2, which averaged 30% of the total product, but did not bring in any revenue for the plant. DDGS averaged 26% of the total product produced, but when the 99% of the DWG was dried it comprised 34% of the total product produced. When the maximum amount of DDGS was produced, its market comprised 17% of the annual revenue. DWG averaged 13% of the total product produced. When the maximum amount of DWG was left wet (33%) it comprised 25% of the product produced, but only was responsible for 6% of the annual revenue. When corn oil was extracted it made up less than 0.5% of the products produced, but contributed to 2% of the annual revenue. This data showed that expansion of ethanol coproduct markets can have a great impact on the annual revenue of an ethanol plant since the coproducts made up 70% of the products produced but only 23% of the annual revenue.

The gross profits of the scenarios performed determined the actual viability of the processing facility. From the scenarios performed, it was determined that only scenarios run with the 2005 prices were profitable. This is most likely due to the price of corn being only \$0.087/kg, which was less than half of the price used in the 2011a scenarios (\$0.197/kg) and less than one third of the price used in the 2011b scenarios (\$0.286/kg). This means that the price of corn is very significant for the viability of an ethanol plant and that in order to be viable with corn prices high the annual revenues must increase. Annual revenues can be increased by increasing the value of the products produced by creating new markets or expanding the existing markets.

When neglecting the input prices and considering only the processing parameters it was determined that scenarios where 80% of the corn oil was extracted and 33.33% of the DWG was left wet had the greatest profit or least loss. This means that any future processing that is added to the plant must produce a high value product with little energy usage.

CONCLUSIONS

As studies continue to look at new value added uses of ethanol coproducts, it is important to have a means of easily determining the feasibility of the processing steps involved. Computer simulations provide a tool for such determinations. In this study SuperPro Designer (Intelligen, Inc., Scotch Plains, N.J.) was used to gain a complete understanding of the how changes in material prices, market prices, and the adjustment of basic coproduct processing (oil extraction and drying of DDGS) affect the economics of a base ethanol plant model.

Through the scenarios simulated it can be concluded that coproduct production is a very important factor in the viability of an ethanol plant. Currently it makes up 43% of the capital costs associated with a basic processing facility, and 70% of the products produced. While coproducts play significant roles in capital costs and products produced, they make up only 20% of the revenue brought in by the facility. This is a very low percentage and can explain why many of the scenarios had negative net incomes. This supports the statement that coproducts are important to the viability of an ethanol plant and it is important to either increase their current market or create new markets for them to make facilities more profitable. In order to enter into these new markets different processing may have to be added to existing facilities and the information provided by this study will allow for analysis of these processes to begin.

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Table 1. Definition of factorial simulation scenarios *

Scenario	Oil Extraction (%)	Wet Coproduct (%)	Year
1	1	1	2005
2	1	1	2011a
3	1	33.33	2005
4	1	33.33	2011a
5	80	1	2005
6	80	1	2011a
7	80	33.33	2005
8	80	33.33	2011a
9	1	1	2011b
10	1	33.33	2011b
11	80	1	2011b
12	80	33.33	2011b

*Year refers to the time period from which prices were used. 2011a refers to prices taken from the June 2011 model (McAloon A. and W. Yee, 2011, unpublished model, Wyndmoor, PA: USDA). DDGS and DWG market prices in the 2005 and 2011a scenarios were automatically determined by the software based on their protein concentration. In the scenarios identified as 2011b, DDGS and DWG prices were based on actual market prices at the time of simulation. Corn and ethanol prices were also adjusted in these scenarios so that all were taken from the same time period. Prices are defined in Table 2.

Table 2. Input prices used for the simulations.*

	2005 Price	2011a Price	2011b Price
Corn ($/kg)	0.087	0.197	0.286
Steam ($/kg)	0.017	0.013	0.013
Natural Gas ($/kg)	0.289	0.196	0.196
Electricity ($/kWh)	0.050	0.060	0.060
Ethanol ($/kg)	0.610	0.610	0.793
Corn Oil ($/kg)	0.558	0.558	0.558
DWG ($/kg)	0.049	0.049	0.077
DDGS ($/kg)	0.125	0.125	0.220

* Year refers to the time period from which prices were used. 2011a refers to prices taken from the June 2011 model (McAloon A. and W. Yee, 2011, unpublished model, Wyndmoor, PA: USDA). DDGS and DWG market prices in the 2005 and 2011a scenarios were automatically determined by the software based on their protein concentration. In the scenarios identified as 2011b, DDGS and DWG prices were based on actual market prices at the time of simulation. Corn and ethanol prices were also adjusted in these scenarios so that all were taken from the same time period.

Table 3. Resulting slopes from sensitivity analysis of production expense effects.*

Year	Scenario	Slopes			
		Corn	Electricity	Steam	Natural Gas
2005	1, 3, 5, 7	367.32	41.38	270.47	8.00
		(0.01)	(4.30)	(0.25)	(1.80)
2011a	2, 4, 6, 8	367.30	42.67	258.57	8.00
		(0.07)	(0.44)	(0.01)	(1.79)
2011b	9, 10, 11, 12	367.33	42.66	258.57	8.00
		(0.01)	(5.22)	(0.01)	(1.81)

*Values in parentheses represent ±1 standard deviation. Slopes are defined as increase in operating costs over 20% increase in purchase cost.

Table 4. Resulting slopes from sensitivity analysis of market price and coproduct production effects.*

Year	% DWG	Scenario	Slopes			
			Ethanol	**DDGS**	**DWG**	**Oil**
2005 & 2011a	1	1, 2, 5, 6	119.17	119.61	2.32	0.04
			(0.01)	(2.01)	(0.97)	(0.01)
2005 & 2011a	33	3, 4, 7, 8	119.17	80.55	104.62	3.22
			(0.01)	(1.36)	(0.61)	(0.01)
2011b	1	9, 11	118.51	119.61	1.08	0.40
			(0.96)	(2.47)	(0.03)	(0.01)
2011b	33	10, 12	118.51	80.55	36.62	3.22
			(0.96)	(1.66)	(0.26)	(0.01)

*Values in parentheses represent ±1 standard deviation. Slopes are defined as increase in annual revenues over 20% increase in items market price.

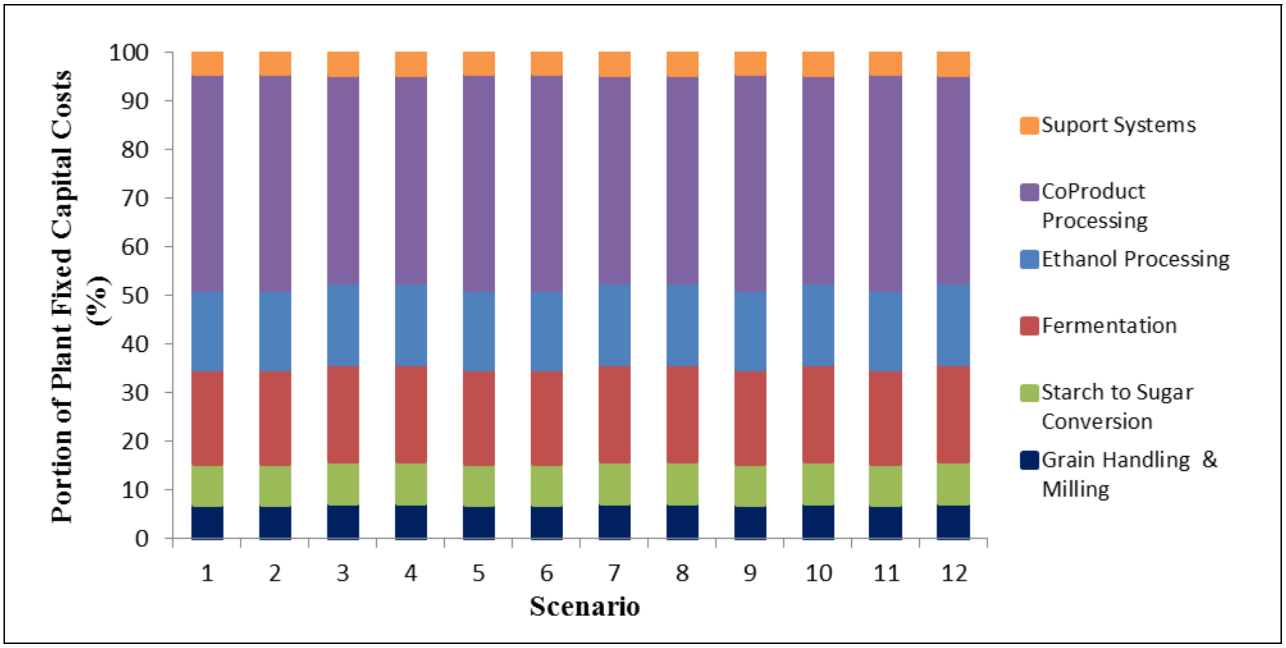

Figure 1. The effect of changing prices and coproduct processing on the overall fixed capital costs of the plant.

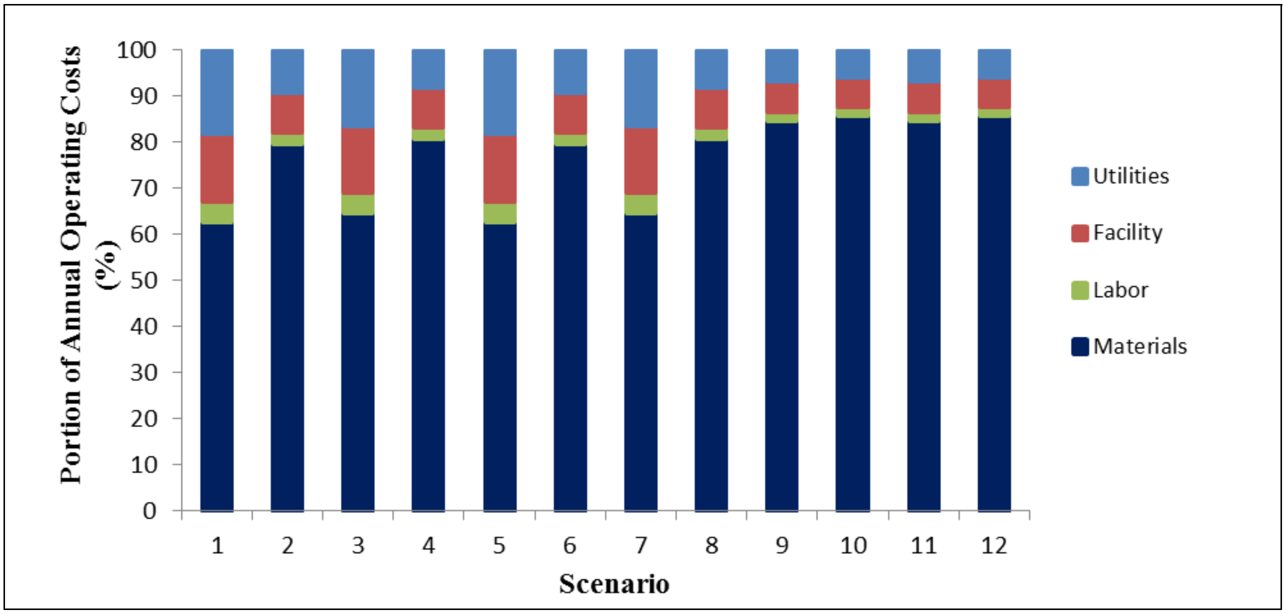

Figure 2. The effect of changing prices and coproduct processing on the overall operating costs of the plant. Utilities are comprised of cooling water, steam, natural gas, and electricity. Facilities are comprised of maintenance, capital costs, depreciation, insurance, taxes, and miscellaneous factory expenses. Materials are comprised of corn, lime, ammonia, enzymes, sulfuric acid, caustic, yeast, water, and octane.

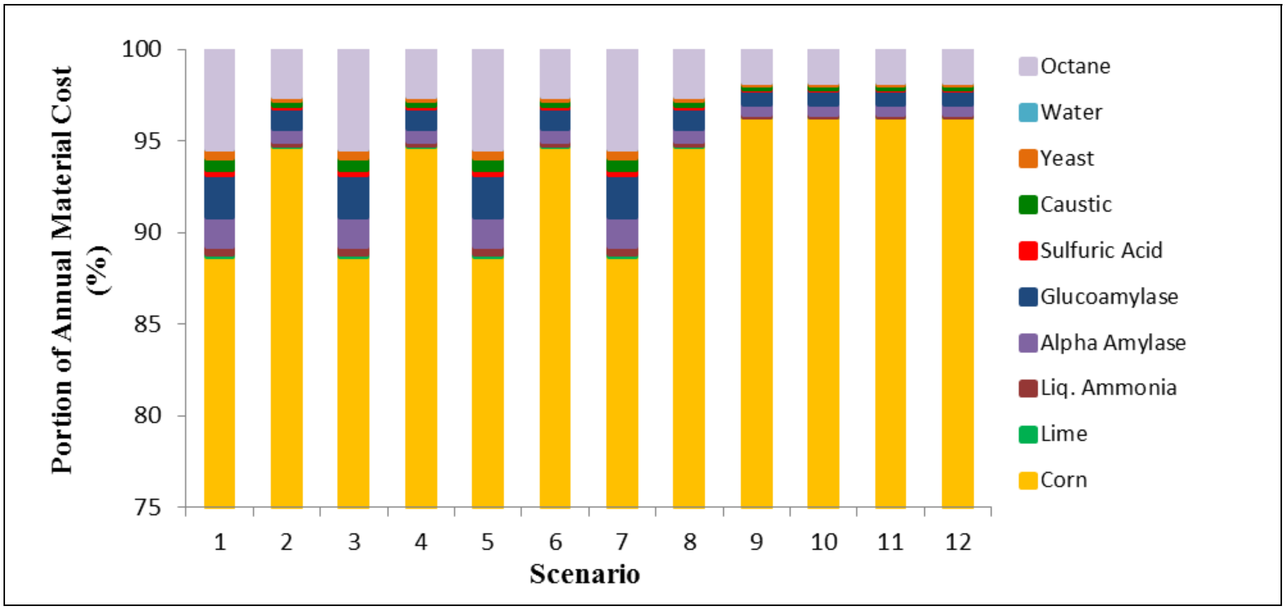

Figure 3. The effect of individual materials on the overall material costs of the plant.

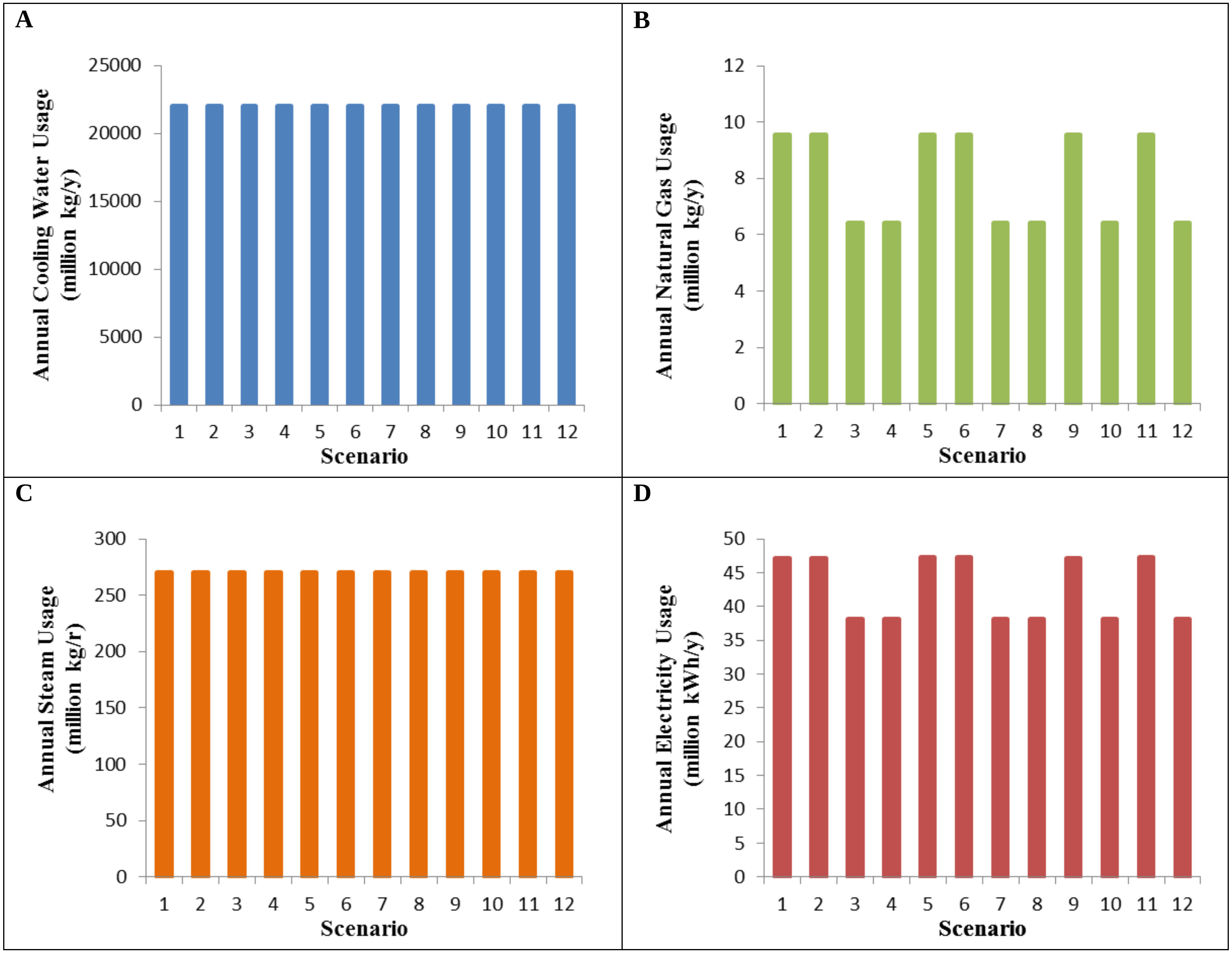

Figure 4. Quantity of utilities used annually for each scenario.

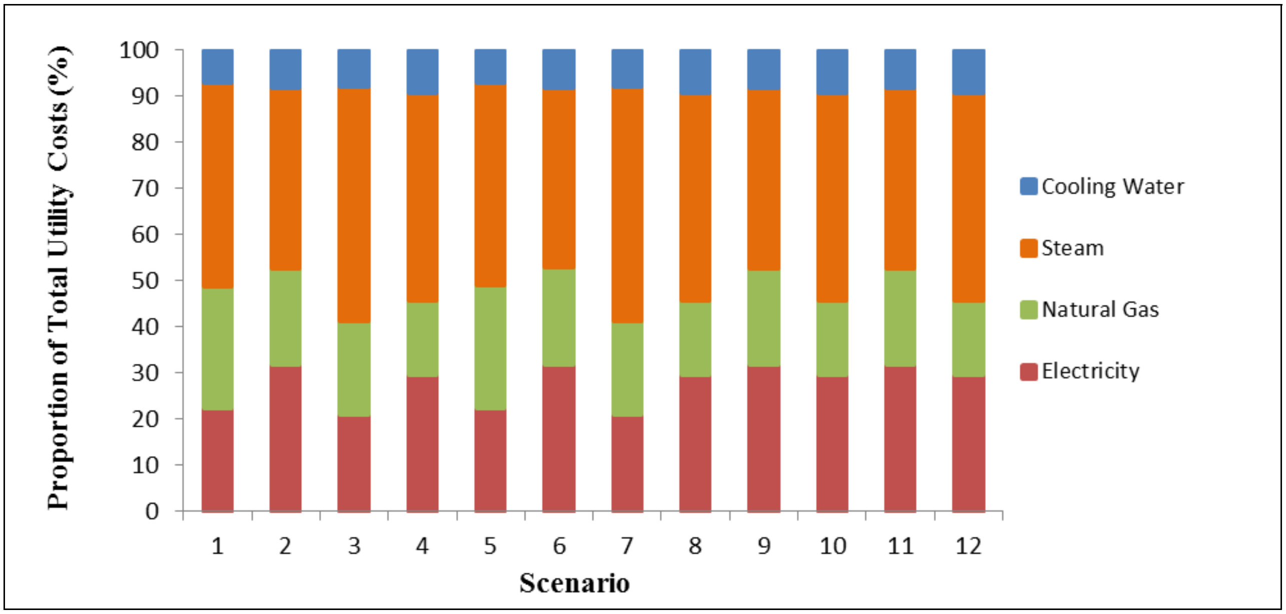

Figure 5. The effect of individual utilities on the overall price of utilities within the plant. Cooling water is the only utility that does not change in price among the 2005, 2011a, and 2011b scenarios. Scenarios 1, 3, 5, and 7 have the same utility prices; while scenarios 2, 4, 6, 8, 9, 10, 11, and 12 have the same utility prices.

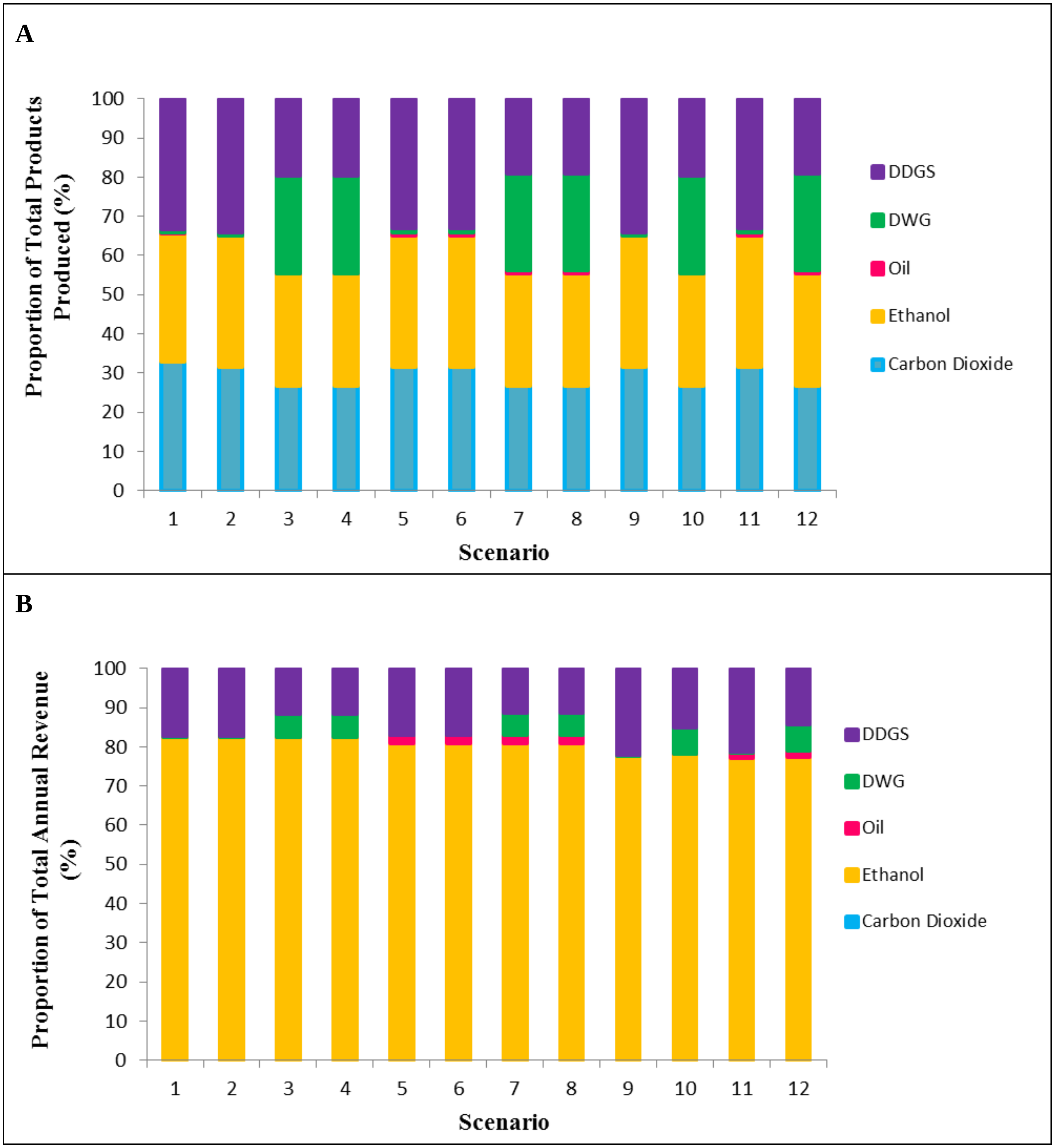

Figure 6. Partitioning of mass and revenues according to products and coproducts. A) Mass balance. B) Effects on annual revenue.

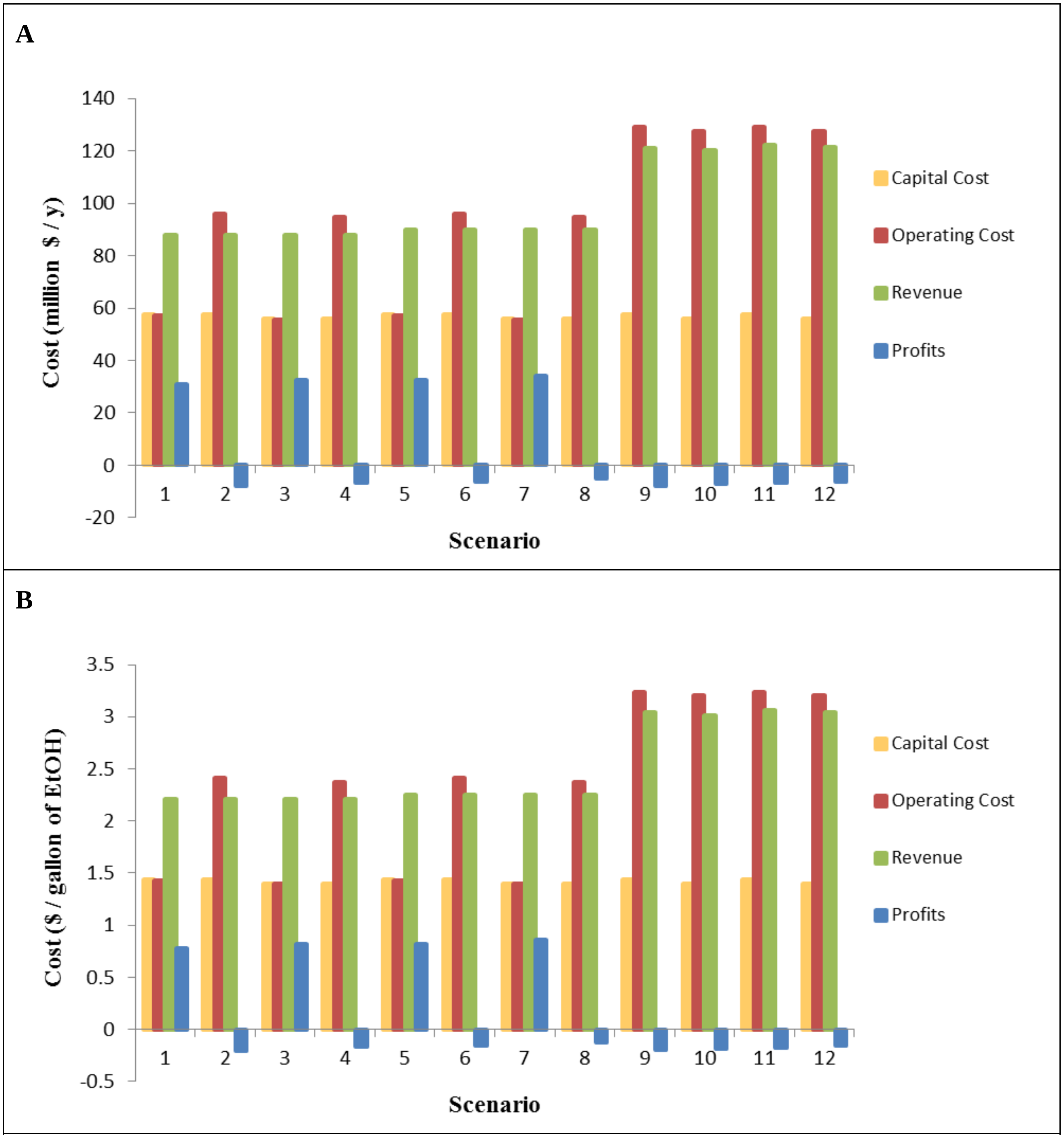

Figure 7. Comparisons of capital costs, operating costs, annual revenue, and profits for each scenario simulated. A) Costs accumulated for a year of production. B) Costs broken down according to number of gallons produced per year.

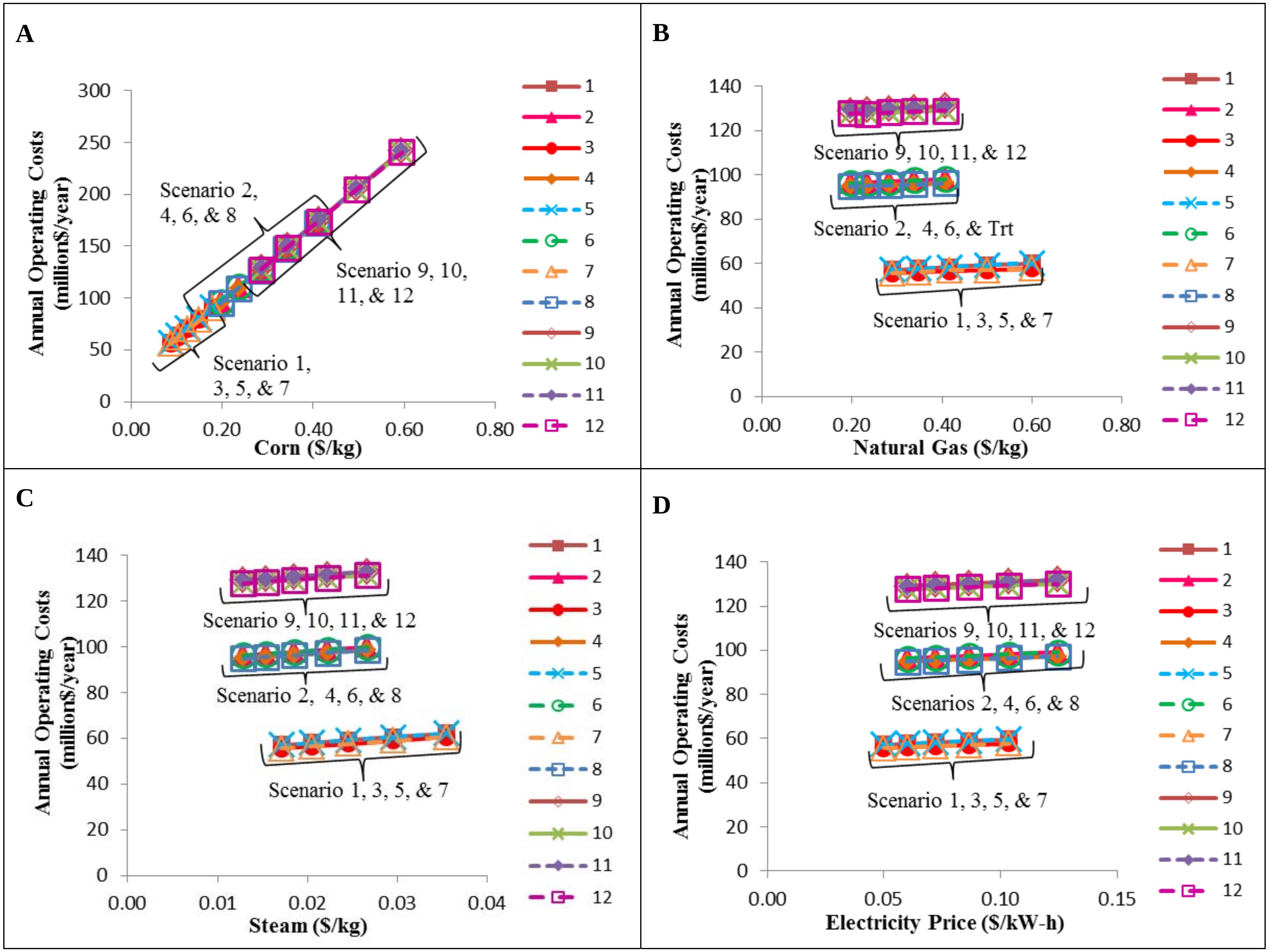

Figure 8. Sensitivities of the model to a 20% increase in corn and utility prices.

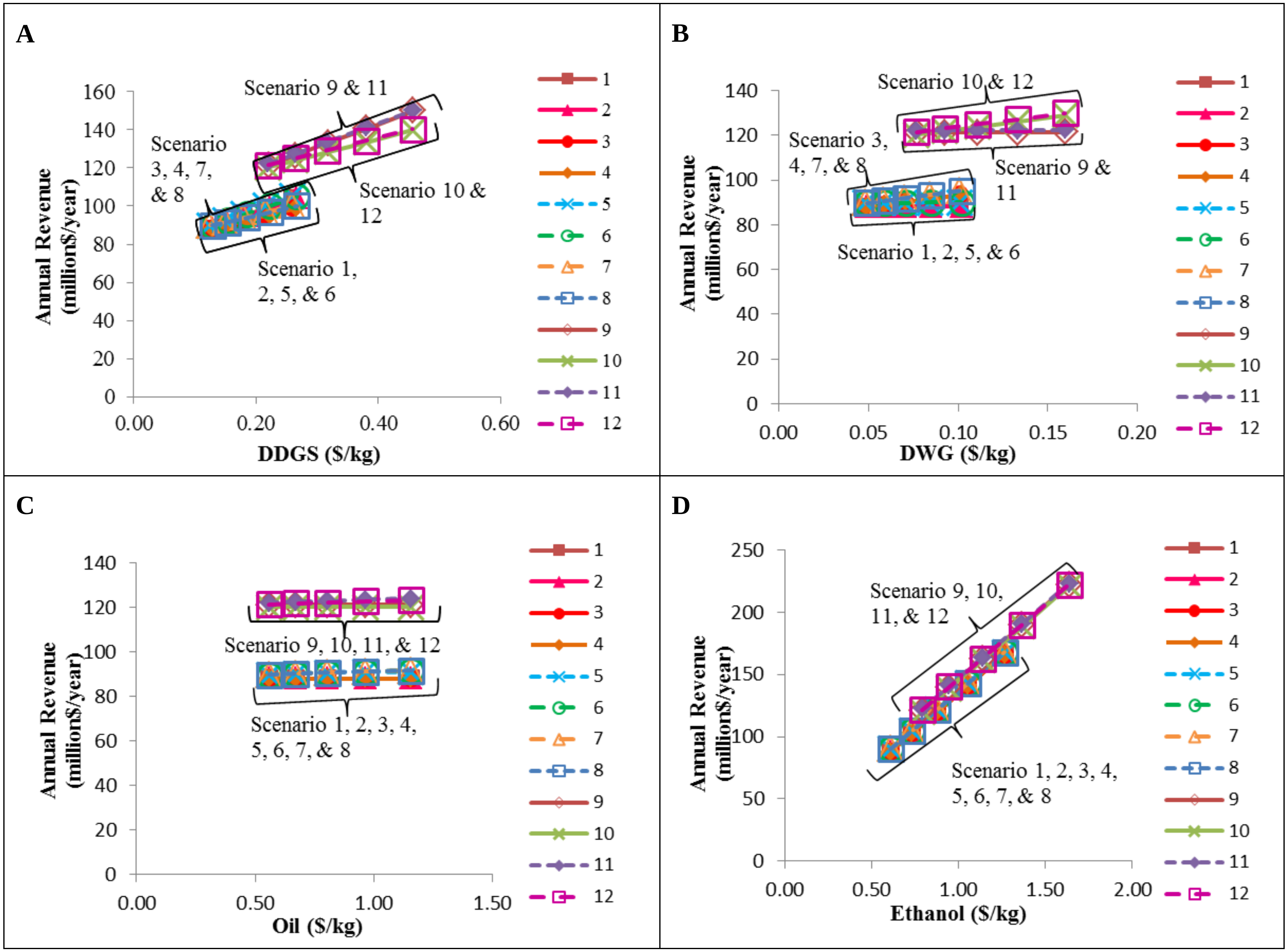

Figure 9. Sensitivities of the model to a 20% increase in product market prices.