Corn Wet Mill Improvement and Corn Dry Mill Improvement Pathways Summary Description

DOE Pathway Objectives

The Biomass Program objective for both the corn wet mill and dry mill pathways is to improve the overall operation of today's production facilities by incorporating new technologies that use residues/intermediates from the existing corn milling processes to increase yields of biofuels - defined by the Program as biomass derived liquid transportation fuels that are fungible in today's transportation fuel supply. Ethanol is the primary biofuel of this pathway.

This near-term strategy, based on demonstrating new technologies in existing facilities, will begin to lay the technical foundation and build the practical expertise for the other pathways based on lignocellulosic feedstocks. Other near term opportunities for wet mill and dry mill improvements include production of new bioproducts, improvements in plant efficiency and reductions in operating costs.

Corn ethanol production facilities are also envisioned to have a significant role in the Program's mid-term strategy of using existing agricultural residues to bridge the gap between near-term, niche, low-cost biomass supplies and long-term high-volume dedicated perennial energy crops. Initially, agricultural residue supply and conversion systems will be demonstrated in existing primary facilities, such as corn or other grain processing mills.

Pathway Overviews

Corn Wet Mill

The corn wet mill improvement pathway block flow diagram shown in Figure 1 outlines the current wet mill process steps and how new processing steps could be incorporated into the existing process. The bold lines highlight the routes to ethanol; and the dotted lines identify routes to new bioproducts. This diagram is not intended to be all inclusive. Other viable processing options should be considered for addition.

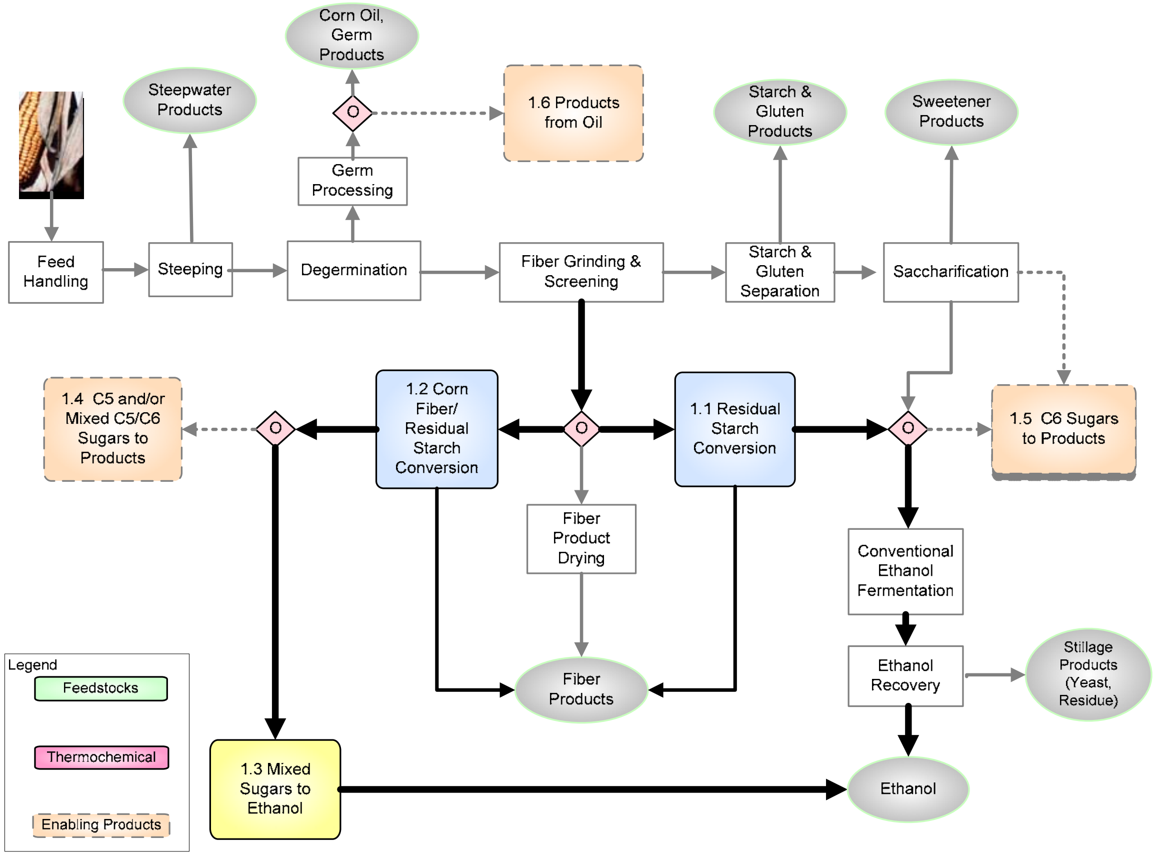

Figure 1: Wet Mill Improvements Pathway Diagram

Existing Corn Wet Mill Process[1]

Wet milling involves separating the corn kernel into its component parts (germ, fiber, protein, and starch) prior to fermentation, as illustrated by the white boxes in Figure 1. Corn is soaked in a dilute acid dilute solution, which dissolves the soluble nutrients and facilitates the separation of grain into its component parts. Germ is removed from the kernel, and the kernel is screened to remove the bran. The remaining gluten and starch is then passed through a screen, and both are separated by centrifuges. The starch is then processed into various products, such as ethanol, sweeteners or food starch. The germ is processed to produce corn oil and corn germ co-products.

Corn Wet Mill Process Improvements for Fuel Production

The corn wet mill improvements for fuel production are focused on developing and demonstrating new processes that use the residual fiber stream from the grinding/screening process to produce additional ethanol. The process improvements are described in Table 1.

[1] *How Ethanol is Made*. (2005). Renewable Fuels Association. http://www.ethanolrfa.org/resource/made/

Table 1. Corn Wet Mill Process Improvements for Fuel Production

Process Category	Process Step(s)	Description
Biomass-to-Sugars	1.1 Residual Starch Conversion	Convert residual starch stream to fermentable C6 sugars and new feed byproduct.
Biomass-to-Sugars	1.2 Corn Fiber/Residual Starch Conversion	Convert wet mill corn fiber and residual starch to C5 and/or C5/C6 mixed sugars and new feed byproduct.
Sugars-to-Fuel	1.3 Mixed Sugars to Ethanol	Convert mixed sugars from corn fiber to ethanol via fermentation; recover ethanol.

The sugars extracted from the residual starch and fiber can also be used to produce bio-products (Process Steps 1.4 and 1.5); the extracted corn oil from the germ processing step can also be converted to new bio-products (Process Step 1.6).

Corn Dry Mill

The corn dry mill improvement pathway block flow diagram shown in Figure 2 outlines the current dry mill process steps and how new processing steps could be incorporated into the existing process. The bold lines highlight the routes to ethanol; and the dotted lines identify routes to new bioproducts. This diagram is not intended to be all inclusive. Other viable processing options should be considered for addition.

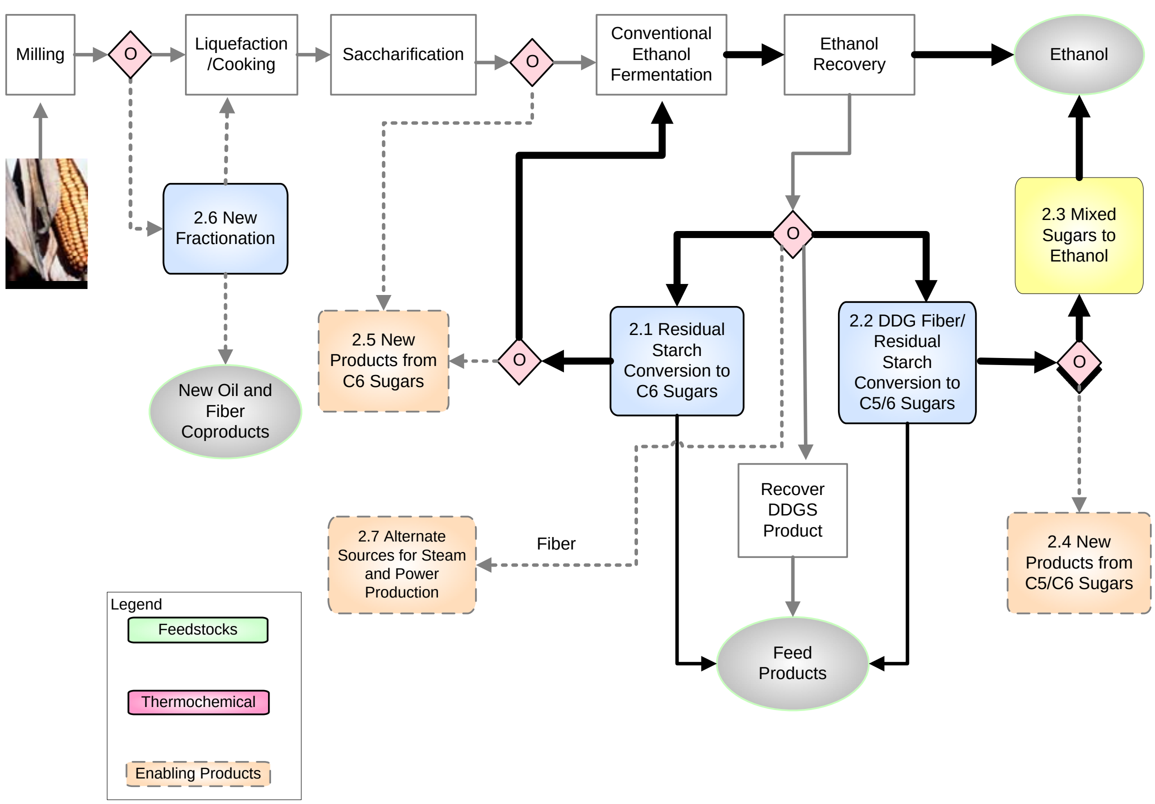

Figure 2: Dry Mill Improvements Pathway Diagram

Existing Corn Dry Mill Process[2]

The first step in the corn dry milling process is to grind the entire corn kernel into a coarse "meal", as illustrated by the white boxes in Figure 1. The meal is slurried with water to form a "mash" and enzymes are added to convert the starch to dextrose in a high-temperature cooker. The mash is cooled and transferred to fermenters where yeast is added and the sugar is converted to ethanol and carbon dioxide (CO_2). After fermentation, the resulting "beer" is transferred to distillation columns where the ethanol is separated from the remaining "stillage," dehydrated, and then blended with about 5% denaturant for sale as fuel. The stillage is sent through a centrifuge that separates the coarse grain from the solubles. The solubles are then concentrated to about 30% solids by evaporation, resulting in Condensed Distillers Solubles (CDS) or "syrup." The coarse grain and the syrup are then dried together to produce dried distillers grains with solubles (DDGS), a high quality nutritious livestock feed.

Corn Dry Mill Process Improvements for Fuel Production

The corn dry mill improvements for fuel production are focused on developing and demonstrating new processes that use the residual stream (stillage) from the ethanol recovery process to produce additional ethanol. The process improvements are described in Table 2.

Table 2. Corn Dry Mill Process Improvements for Fuel Production

Process Category	Process Step(s)	Description
Biomass-to-Sugars	2.1 Residual Starch Conversion	Convert residual starch stream to fermentable C6 sugars and new feed byproduct.
Biomass-to-Sugars	2.2 DDG Fiber/ Residual Starch Conversion	Convert dry mill corn fiber and residual starch to C5 and/or C5/C6 mixed sugars and new feed byproduct.
Sugars-to-Fuel	2.3 Mixed Sugars to Ethanol	Convert mixed sugars from corn fiber to ethanol via fermentation; recover ethanol.

The sugars extracted from the residual starch and fiber (Process Steps 2.3 and 2.4); the C6 sugars produced in the saccharification step (Process Step 2.5); and the corn meal from the initial grinding step can also be converted to new bio-products (Process Step 2.6). In addition, the residual fiber stream from the corn fiber conversion process and/or corn stover (brought into the plant specifically for this purpose) could be used to produce heat and power for the facility (Process Step 2.7).

Total Resource Potential for Corn Wet and Dry Mills

In 2005, the wet milling process accounted for about 21 percent[3], or 840 million gallons of the total U.S. fermentation ethanol capacity and the dry milling process accounted for about 79 percent[4], or 3.16 billion gallons. The percentage produced by dry mills has been increasing as new dry process mills continue to be built, while new wet mills are not because their existing product markets, except ethanol, are largely satisfied by

[2] *How Ethanol is Made*. (2005). Renewable Fuels Association. http://www.ethanolrfa.org/resource/made/
[3] From Niche to Nation: Ethanol Industry Outlook 2006. Renewable Fuels Association. http://www.ethanolrfa.org/objects/pdf/outlook/outlook_2006.pdf
[4] From Niche to Nation: Ethanol Industry Outlook 2006. Renewable Fuels Association. http://www.ethanolrfa.org/objects/pdf/outlook/outlook_2006.pdf

existing wet mill capacity. No significant expansion of the wet mill industry is expected for ethanol production. The total corn output available for biofuel production, based on information from the joint USDA/DOE Billion Ton Study[5] as well as data from a Renewable Fuels Association (RFA) report and projections from a National Corn Growers Association (NCGA) factsheet[6] , is summarized in Table 3. The "Baseline" case is Scenario 1 in the Billion Ton Study based on the National Resources Inventory for 2001. The "High Case" is the high yield increase case of Scenario 3 in the Billion Ton Study which includes perennial crops and land use change. Tables 7 and 8 provide data on all scenarios and cases evaluated in the Billion Ton Study. Other grain crops used in ethanol production, often in combination with corn, include sorghum, barley and wheat. Quantities potentially available for these additional starch crops are shown in Table 4.

Table 3. Corn Output Available for Biofuel Production [7,8,9]

Feedstock	Feedstock Case	Harvested Acreage (Million Acres)	Product Yield, Dry Tons/Acre (Bu/Acre)	Total Annual Output (Million Dry Tons)	Output Available for Biofuel Production, Million Dry Tons (Million Bushels)
Corn Grain	Baseline (2001)	68.8	3.3	227.0	13.5
	High Case	76.6	4.9	375.3	74.8
	RFA Baseline (2005)	-	3.52 (147.9)	-	34.0 (1,430)
	NCGA High Case (2015-16)	78.0	4.6	458.3	141.7
Corn Fiber	Baseline (2001)				6.2
	High Case				12.3
	RFA Baseline (2005)				9.9[10]
					1.8[11]
	NCGA High Case (2015-16)				Assumed none available[12]

[5] *Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply*. (April 2005). US Department of Energy and US Department of Agriculture. http://feedstockreview.ornl.gov/pdf/billion_ton_vision.pdf

[6] *How Much Ethanol Can Come from Corn?* (Accessed June 2006). National Corn Growers Association Factsheet. http://www.ncga.com/ethanol/pdfs/2006/HowMuchEthanolCan%20ComeFromCorn.v.2.pdf

[7] *Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply*. (April 2005). US Department of Energy and US Department of Agriculture. http://feedstockreview.ornl.gov/pdf/billion_ton_vision.pdf

[8] *From Niche to Nation: Ethanol Industry Outlook 2006*. Renewable Fuels Association. http://www.ethanolrfa.org/objects/pdf/outlook/outlook_2006.pdf

[9] *How Much Ethanol Can Come from Corn?* (Accessed June 2006). National Corn Growers Association Factsheet. http://www.ncga.com/ethanol/pdfs/2006/HowMuchEthanolCan%20ComeFromCorn.v.2.pdf

[10] RFA reports 9 million metric tons (9.9 short tons) of DDGS produced in 2005, however document is not clear whether this tonnage is on a dry or as produced basis. Checking with RFA.

[11] RFA reports 2.4 mill. metric tons (2.6 short tons) of corn gluten feed and germ meal produced in 2005. Carbohydrates most likely used for additional ethanol production are in the corn gluten feed. Assumed corn gluten feed is 70 % of the total. Is tonnage dry or as produced basis? Check with RFA.

[12] NCGA high case for ethanol production uses a yield of 3.0 gallons/bushel which includes conversion of both corn starch and a significant amount (~2/3) of the available structural carbohydrates in the corn fiber. Therefore, no additional ethanol credit from corn fiber is taken for cases where the corn fiber is a co-product of the 3.0 gallon/bushel ethanol.

Table 4: Additional Potential Starch Grain Crops Available for Biofuel Production [13]

Feedstock	Feedstock Case	Harvested Acreage (Million Acres)	Product Yield (Dry Tons/Acre)	Total Annual Output (Million Dry Tons)	Output Available for Biofuel Production (Million Dry Tons)
Sorghum	Baseline (2001)	8.6	1.4	12	0.5
	High Case	6.8	1.9	12.9	2.8
Barley	Baseline (2001)	4.3	1.2	5.2	0.2
	High Case	3.7	1.7	6.3	1.9
Wheat	Baseline (2001)	48.8	1.0	50.2	0.2
	High Case	47.3	1.5	68.9	0.0
TOTAL	Baseline (2001)				0.9
	High Case				4.7

Total Ethanol[14] Production Potential from Corn Wet and Dry Mills

The total ethanol potential of corn in wet and dry mills is summarized in Table 5. Table 6 shows the potential ethanol from sorghum, barley and wheat.

[13] *Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply*. (April 2005). US Department of Energy and US Department of Agriculture. http://feedstockreview.ornl.gov/pdf/billion_ton_vision.pdf , Appendix B.

[14] Due to the presence of the existing ethanol industry, estimates of ethanol potential have been developed for all starch grain feedstocks. This is not intended to preclude consideration of other biofuels but rather to serve as a common fuel product to evaluate the relative contribution of different feedstock types as well establish a basis for comparing other biofuel options.

Table 5. Ethanol Fuel Potential of Corn

Feedstock	Feedstock Case	Mill Type (Both, Dry, or Wet)	Output Available for Biofuel Production (Million Dry Tons)	Ethanol Yield Gallons per Dry Ton (gal/bu)	Annual U.S. Ethanol Production (Million Gallons)
Corn Grain	Baseline (2001)	Both	13.5	105 (2.5)	1,400
	High Case	Both	74.8	126 (3.0)	**9,400**
	RFA Baseline (2005)	Both	34.0	118 (2.8)	4,000
		Dry	26.9	118 (2.8)	3,100
		Wet	7.1	118 (2.8)	900
	NCGA High Case (2015-16)	Both	141.7	126 (3.0)	**17,900**
		Dry	*134.6*	*126 (3.0)*	*17,000*
		Wet	*7.1*	*126 (3.0)*	*900*
Corn Fiber	Baseline (2001)	Both	6.2	-	-
	High Case	Both	12.3	0	0
	RFA Baseline (2005)	Both	11.7		
		Dry	9.9		
		Wet	1.8		
	NCGA High Case (2015-16)	Both	0	0	0
		Dry	*0*	*0*	*0*
		Wet	*0*	*0*	*0*

Table 6: Ethanol Fuel Potential of Additional Potential Starch Grain Crops

Feedstock	Feedstock Case	Output Available for Biofuel Production (Million Dry Tons)	Ethanol Yield[15] (Gallons per Dry Ton)	Annual U.S. Ethanol Production (Million Gallons)
Sorghum	Baseline (2001)	0.5	113	57
	High Case	2.8	113	318
Barley	Baseline (2001)	0.2	102	20
	High Case	1.9	102	194
Wheat	Baseline (2001)	0.2	106	21
	High Case	0.0	106	0
TOTAL	Baseline (2001)	0.9		98
	High Case	4.7		512

Ethanol yields used in Table 6 do not assume improvement from current levels. However, even if ethanol yield improvements were assumed, these crops would be expected to provide only about 1% of the 2030 target of 60 billion gallons.

[15] *30x30: A Scenario for Supplying 30% of 2004 Motor Gasoline with Ethanol by 2030*. (6/30/06 Draft). Appendix A, Table A-4.

Billion Ton Study Resource Data for All Scenarios

Table 7: Corn and Corn Fiber Resource Quantities for Baseline and 4 Cases[16]

Feedstock	Acres Harvested	Average Yield	Total Annual Production	Feedstock used or Available for Biofuels	% of Total used for Biofuels
	(million acres)	dry tons/acre/year	million dry tons/year	million dry tons/year	%
Scenario 1: Baseline					
Corn Grain	68.8	3.3	227.0	13.5	5.9%
Corn Fiber				6.2	
Scenario 2- Case A: Moderate Crop Yield Increase, No Land Use Change					
Corn Grain	76.6	4.1	314.1	46.9	14.9%
Corn Fiber				8.6	
Scenario 3- Case A: Moderate Crop Yield Increase, With Land Use Change					
Corn Grain	76.6	4.1	314.1	46.9	14.9%
Corn Fiber				8.6	
Scenario 2- Case B: High Crop Yield Increase, No Land Use Change					
Corn Grain	76.6	4.9	375.3	74.8	19.9%
Corn Fiber				12.3	
Scenario 3 – Case B: High Crop Yield Increase, With Land Use Change					
Corn Grain	76.6	4.9	375.3	74.8	19.9%
Corn Fiber				12.3	

[16] *Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply*. (April 2005). US Department of Energy and US Department of Agriculture. http://feedstockreview.ornl.gov/pdf/billion_ton_vision.pdf , Appendix B.

Table 8: Other Potential Starch Grain Crop Resource Quantities for Baseline and 4 Cases[17]

Feedstock	Acres Harvested	Average Yield	Total Annual Production	Feedstock used or Available for Biofuels	% of Total used for Biofuels
	(million acres)	dry tons/acre/year	million dry tons/year	million dry tons/year	%
Scenario 1: Baseline					
Sorghum	8.6	1.4	12.0	0.5	4.2%
Barley	4.3	1.2	5.2	0.2	3.9%
Wheat - winter	31.3	1.1	34.4	0.2	0.6%
Wheat - spring	17.5	0.9	15.8	0.0	0.0%
Subtotal				0.9	
Scenario 2- Case A: Moderate Crop Yield Increase, No Land Use Change					
Sorghum	6.8	1.7	11.6	1.8	15.6%
Barley	3.7	1.5	5.6	0.6	10.8%
Wheat - winter	33.3	1.4	46.6	0.0	0.0%
Wheat - spring	19.0	1.1	20.9	0.0	0.0%
Subtotal				2.4	
Scenario 3- Case A: Moderate Crop Yield Increase, With Land Use Change					
Sorghum	6.8	1.7	11.6	1.8	15.6%
Barley	3.7	1.5	5.6	0.6	10.8%
Wheat - winter	33.3	1.4	46.6	0.0	0.0%
Wheat - spring	19.0	1.1	20.9	0.0	0.0%
Subtotal				2.4	
Scenario 2- Case B: High Crop Yield Increase, No Land Use Change					
Sorghum	6.8	1.9	12.9	2.8	21.7%
Barley	3.7	1.7	6.3	0.9	14.3%
Wheat - winter	33.3	1.6	53.3	2.5	4.7%
Wheat - spring	19.0	1.2	22.8	0.0	0.0%
Subtotal				6.2	
Scenario 3- Case B: High Crop Yield Increase, With Land Use Change					
Sorghum	6.8	1.9	12.9	2.8	21.7%
Barley	3.7	1.7	6.3	1.9	30.2%
Wheat - winter	30.3	1.6	48.5	0.0	0.0%
Wheat - spring	17.0	1.2	20.4	0.0	0.0%
Subtotal				4.7	

[17] *Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply*. (April 2005). US Department of Energy and US Department of Agriculture. http://feedstockreview.ornl.gov/pdf/billion_ton_vision.pdf , Appendix B.