NAICS Code: Wet Corn Milling and Starch Manufacturing (311221)

SUMMARY INFO: Wet corn milling is a vital food production sector that separates corn into various components for food, energy, and industrial purposes. Between 10 and 15 percent of American corn crops are refined in these facilities, supporting 166,000 jobs and generating $61 billion in economic output annually.[1] Wet corn milling adds significant value to American corn, with its outputs used throughout various economic sectors, including as sweeteners, biofuels, livestock feed, and industrial polymers. It is considered the most energy-intensive food processing industry, with energy costs accounting for mills' second-largest operating expense, after raw materials costs.[2]

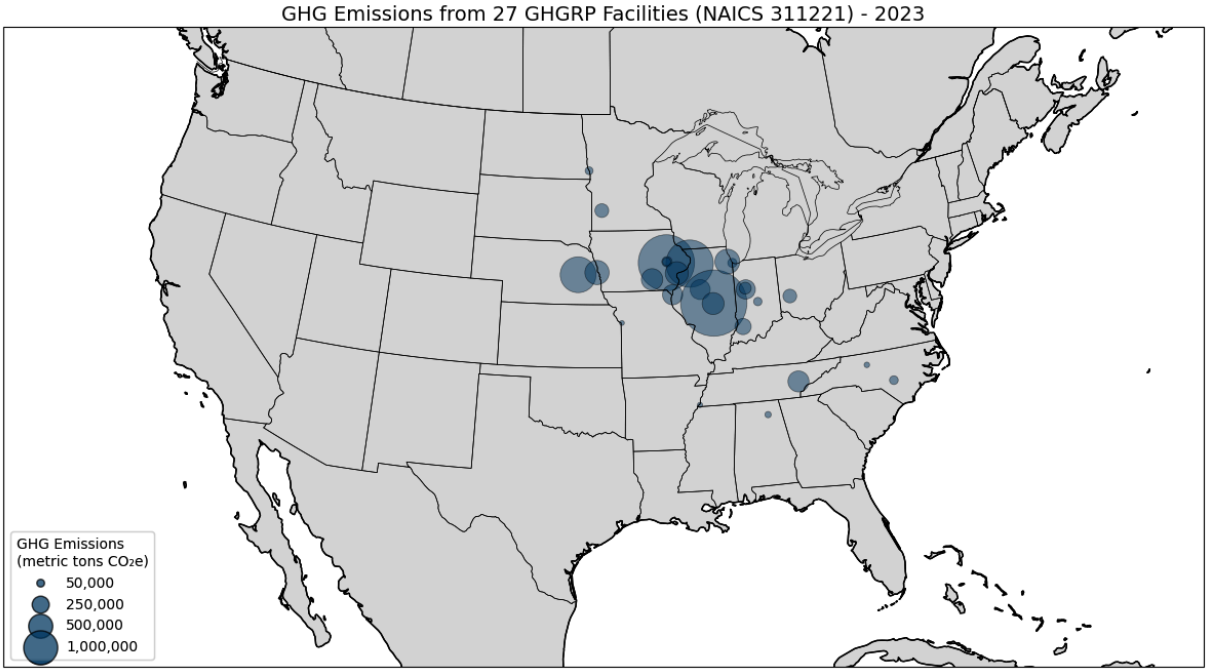
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Link to archetype code:

Archetype Name: Wet Corn Milling

Emissions and facility overview: According to the United States Census Bureau, there are 70 establishments associated with NAICS 311211 in the United States, 27 of which report annual GHG emissions in the GHGRP.[3] Reported emissions from GHGRP amounted to 14.45 Mt CO2e in 2023. The majority of GHGRP plants are concentrated in Illinois and Iowa, as depicted in the map below.



Sector outputs: NAICS code 311221 is responsible for production of corn syrup, corn sweeteners, corn oil, and other starches.[4] Unlike the 325193 sector (ethyl alcohol manufacturing), wet corn milling

[1] Corn Refiners Association. Corn Refining Industry Economic Impact.
[2] Lawrence Berkeley National Laboratory. Energy Efficiency Improvement and Cost Saving Opportunities for the Corn Wet Milling Industry. July 2003.
[3] U.S. Census Bureau. County business patterns: NAICS 311221. 2023; U.S. Environmental Protection Agency. Greenhouse Gas Reporting Program (GHGRP) data for food manufacturing. 2023.
[4] Executive Office of the President Office of Management and Budget. North American Industry Classification System. 2022.

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produces edible products. According to the Corn Refiners Association (CRA), 60% of the mass output of NAICS code 311221 is sweeteners like high fructose corn syrup and glucose.[5] 26% of mass output production are byproducts such as corn feed and germ. The remaining 12% is corn oil production.[6]

Process pathways: Wet corn milling is the process of converting bushels of corn into glucose, sweeteners, and corn byproducts. The process begins with steeping, where dry corn is soaked in hot water and mild acid to break the corn shell. Dry corn milling, used mainly in ethanol manufacturing, omits steeping and instead separates corn kernels mechanically. Wet and dry corn milling differ in their separation mechanisms, end products ratios, and energy intensities, resulting in distinct industrial pathways. In wet corn milling, steeping enhances separation of the corn kernel and is often used in food manufacturing processes to increase yield.[7] Sugar refinement is the process of converting glucose into syrups and compounds like dextrin. Our archetype models a wet corn milling process to manufacture glucose, omitting sugar refinement, because the bulk of thermal energy demand in this industry is associated with conversion to glucose.[8] Wet corn milling to glucose also simulates a process occurring at all wet corn milling facilities, avoiding discrepancies and variability from refining steps.

According to GHGRP, some wet corn milling facilities also have secondary NAICS codes 325193, meaning they also possess the pathway to produce ethyl alcohol.[9] No facilities within GHGRP have NAICS code 311221 as a secondary NAICS code. Our archetype for wet corn milling does not model ethyl alcohol manufacturing

Process overview: Figure 1 documents the conversion process of corn bushels to glucose and other byproducts. Wet corn milling begins with cleaning corn bushels, either with compressed air or water wash processing to remove dirt and debris. Then, the steeping process mixes cleaned kernels with water and dilute acid to break the kernel's harder outside shell. Steeping occurs at roughly 50 ℃ for anywhere from 6[10] to 30 hours in the steep tank.[11] In order to create acidic conditions, trace amounts of sulfur dioxide are added to aid in separation. Following steeping, the hydrated corn has nearly quadrupled in water content to 45 wt%,[12]and is separated from light steep water using a physical separator, creating two of the three major production pathways. Figure 1 documents that split at the steep tank. The hydrated corn kernels are further separated into germ and endosperm in a degerminator, creating the final production pathway to produce sugar products, corn oil and corn feed. The following process overview will document each of these production pathways.

Sugar Production Line: The main product produced in wet corn milling is sugar products produced

[5] Corn Refiners Association. 2002 Corn Annual. 2002.
[6] Lawrence Berkeley National Laboratory. Energy Efficiency Improvement and Cost Saving Opportunities for the Corn Wet Milling Industry. July 2003.
[7] Corn Refiners Association. Product Safety and Quality.
[8] Christina Galitsky et al. Energy Efficiency Improvement and Cost Saving Opportunities for the Corn Wet Milling Industry. LBNL. July 2003.
[9] U.S. Environmental Protection Agency. Greenhouse Gas Reporting Program (GHGRP) data for food manufacturing. 2023.
[10] Corn Refiners Association. 2002 Corn Annual. 2002.
[11] Lawrence Berkeley National Laboratory. Energy Efficiency Improvement and Cost Saving Opportunities for the Corn Wet Milling Industry. July 2003.
[12] Edna C. Ramirez et al. Engineering process and cost model for a conventional corn wet milling facility. January 2008.

from glucose. However, not every part of a corn kernel can be converted into sugar.[13] A corn kernel has three major components: bran, germ and endosperm. After the bran is weakened and broken in steeping, the germ is separated from the endosperm in degermination. The bran and endosperm then get sent to a grinding mill, where corn starch within the endosperm gets separated from bran (fiber) and gluten, which are dewatered and later used in corn feed production.. This is done using washing screens, centrifuges and fiber's insolubility. This occurs in the fiber dewaterer and gluten dewater process unit in Figure 1. The fiber and gluten get sent to Production Pathway 3 to generate corn feed. Starch is then purified in starch washing filters and can be further converted into glucose or refined sugar products.

Refined Oil Production Line: The germ of the corn kernel contains an oil-rich embryo, representing 10 % of the kernel's weight.[14] Following degermination in Figure 1, germ is sent to a germ dryer which operates at roughly 90 ℃. Following germ drying, corn oil is extracted from the germ. Germ only contains around 50% by weight corn oil. The remaining germ weight is separated and used to create corn oil meal following oil extraction. Oil extraction also occurs at 90 ℃.[15] The oil is then sent through centrifugal separators and filters to remove trace impurities.

Feed Byproduct Production Line**:** To avoid wasting any part of the corn kernel, the gluten, bran and suspended solids within light steep water are converted into corn feed. Following steeping, the light steep water solid content increases from 5% by weight to 47.5% to be mixed with gluten and bran. This occurs in the steep water evaporator in Figure 1. Steep water evaporation occurs at 120 ℃.[16] This produces heavy steep water, which is mixed with dewatered fiber and dewatered gluten in a feed dryer in later steps.

After fiber and gluten leave the starch production line, they get dewatered prior to returning to the corn feed production line.[17] Following dewatering, all co-products beyond sweeteners (starch) are combined into feed for industrial meat production. Feed dryers operate at 120 ℃.[18]

[13] The Andersons. Kernel growth stages.
[14] Food and Agriculture Organization of the United Nations. Maize in human nutrition. 1992.
[15] Harry L. Brown et al. Energy Analysis of 108 Industrial Processes. 1996.
[16] Ibid.
[17] Edna C. Ramírez et al. Enzymatic corn wet milling: engineering process and cost model. January 2009.
[18] Harry L. Brown et al. Energy Analysis of 108 Industrial Processes. 1996.

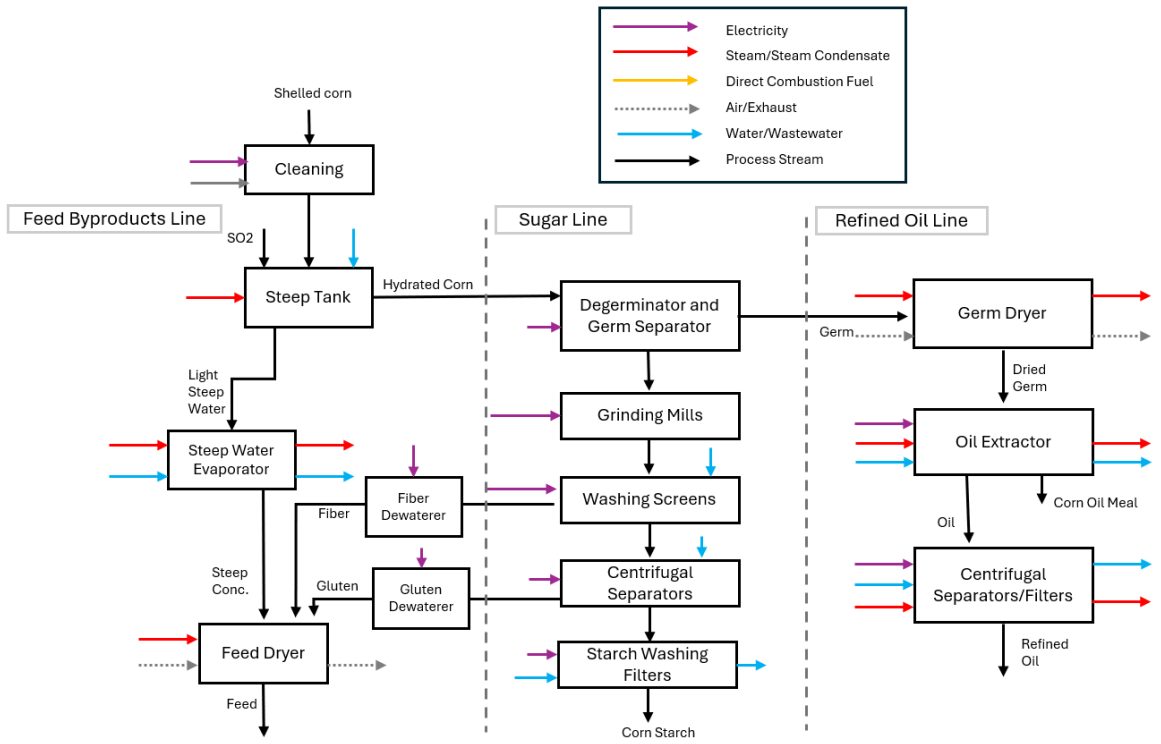


Figure 1: Wet Corn Milling Archetype Process Flow Diagram

Corn starch can be further processed beyond cleaning into dextrin, corn syrups and other products. However, the bulk of thermal energy demand in wet corn milling is associated with steeping, steep water evaporation, and feed drying. Future work should focus on extending the manufacturing process to include sugar refinement steps. These steps will vary by manufacturing facility, so special attention should be paid to facility-level production data of different refined products.

Archetype Unit Process Assumptions: Figure 1 depicts the unit processes, mass flows, and energy flows modeled in our process system archetype. Table 1 below shows the assumptions made within each unit process of the archetype. Corn has a specific heat capacity ranging from 1.5 to 2.5$\frac{kJ}{kg℃}$. Throughout the archetype, we assume a static heat capacity for corn solids of 2.42$\frac{kJ}{kg℃}$.[19]

Model comparison: In order to compare our archetype to prior studies, we compared two sources of thermal energy demand to the results of our archetype,[20] using both a thermal energy intensity per bushel of corn mass input and a thermal energy intensity per mass output of starch. We compare it to Brown et al.,[21] which represents the broadest compilation of manufacturing models and has been widely used as the industrial standard. Lawrence Berkeley National Laboratory's (LBNL)"Energy Efficiency

[19] AgEcon. Preserving Grain Quality by Aeration and In-store Drying. October 1985.
[20] Harry L. Brown et al. Energy Analysis of 108 Industrial Processes. 1996; Lawrence Berkeley National Laboratory. Energy Efficiency Improvement and Cost Saving Opportunities for the Corn Wet Milling Industry. July 2003.
[21] Harry L. Brown et al. Energy Analysis of 108 Industrial Processes. 1996.

Improvement and Cost Saving Opportunities for the Corn Wet Milling Industry"[22] represents a more recent and efficient wet corn model. We find that LBNL estimates for energy intensity are lower than Brown et al. This may be highlighting the increased efficiency in the industry over time. We also find high variation between the output basis and input basis due to discrepancies in product yield per bushel of corn. However, taking these thermal energy intensities, we find that the archetype produces heat intensities within the upper and lower estimates provided by these sources.

We find a 35% difference in overall thermal energy intensity when comparing a first principles approach to calculating thermal energy demand to the output of LBNL, with a greatest discrepancy within the feed dryer and steep liquor evaporator. These discrepancies can be largely explained by the high mechanical separation of gluten and fiber dewater and the static steam efficiency assumed within the steep liquor evaporator. Both models serve as valuable reference points, but, given their age, they may no longer represent current best practices or the efficiency levels achievable in current facilities. Our models, based on first principles, represent a more thermodynamically efficient wet corn milling process, and therefore are likely closer to industrial standards than results produced in 1996 or 2003.

Limitations and future work: This process system archetype relies on sector-average assumptions for setting parameters such as product yields per bushel of corn and steam economy of the steep-liquor evaporator. Other literature-based parameters that may not fully capture facility-level heterogeneity within NAICS 311221. This distinction is documented in Table 1. Several key inputs, including steeping residence time, corn to water ratios, dewatering moisture targets, and germ oil yield fractions, are drawn from various sources and applied uniformly, introducing uncertainty into mass and energy balances.

The model excludes downstream starch conversion and sugar refinement processes, which may generate non-negligible energy use at certain facilities. Light and heavy refinement of corn starch into high fructose corn syrup, or conversion of starch into dextrin, are two processes which are excluded from figure 1, but might occur following corn starch washing. We expect that these processes would increase overall thermal energy demand, while contributing to higher maximum steam temperatures due to heavy corn syrup unit temperatures of 115 ℃ and dextrin conversion at temperatures of 95 ℃.[23] Furthermore, this model assumes steady-state continuous operation without accounting for startup, shutdown, or batch effects. Startup and shutdown both affect thermal efficiency, leading to decreased yields and higher energy intensities overall. However,batch effects of steeping could allow for wet corn mills to pursue demand response effects, contributing to increased energy cost savings.

[22] Lawrence Berkeley National Laboratory. Energy Efficiency Improvement and Cost Saving Opportunities for the Corn Wet Milling Industry. July 2003.
[23] Harry L. Brown et al. Energy Analysis of 108 Industrial Processes

Table 1: Wet Corn Milling Archetype Unit Process Assumptions

Unit Process Name	Assumptions	Parameter Basis	Source
Cleaning	Corn Moisture Content: 15.5%	Sector Average	C. Gregg Carlson and Cheryl L. Reese. Grain Marketing – Understanding Corn Moisture Content, Shrinkage and Drying. 2019.
	Compressed Air to Dirty Corn: 1.00	Engineering judgment	
	Electricity Demand: 34.90 kW/kg	Literature-derived	Lawrence Berkeley National Laboratory. Energy Efficiency Improvement and Cost Saving Opportunities for the Corn Wet Milling Industry. July 2003.
Steep Tank	Unit Temperature and Outlet Temperature: 51 ℃	Literature-derived	Lawrence Berkeley National Laboratory. Energy Efficiency Improvement and Cost Saving Opportunities for the Corn Wet Milling Industry. July 2003. Harry L. Brown et al. Energy Analysis of 108 Industrial Processes
	Corn to water ratio: 2:3	Literature-derived	Harry L. Brown et al. Energy Analysis of 108 Industrial Processes
	SO_2 to Water ratio: 0.002	Literature-derived	Lawrence Berkeley National Laboratory. Energy Efficiency Improvement and Cost Saving Opportunities for the Corn Wet Milling Industry. July 2003.
	Hydrated Corn Moisture Content: 45%	Literature-derived	Harry L. Brown et al. Energy Analysis of 108 Industrial Processes. 1996.
	Steep water to Hydrated Corn Ratio: 0.96/1.6	Sector Average	Harry L. Brown et al. Energy Analysis of 108 Industrial Processes. 1996.
	Heat Loses: 10%	Engineering judgment	
Steep Water Evaporator	Steam economy: 2.5	Literature-derived	Bryan Hackett. The Essentials of Continuous Evaporation. May 2018.
	Moisture Content out: 0.525	Sector Average	Lawrence Berkeley National Laboratory. Energy Efficiency Improvement and Cost Saving Opportunities for the Corn Wet Milling Industry. July 2003.

	Steam Temperature: 120 ℃	Literature-derived	Harry L. Brown et al. Energy Analysis of 108 Industrial Processes
	Unit Temperature and Outlet Temperature: 93.3 ℃	Literature-derived	Harry L. Brown et al. Energy Analysis of 108 Industrial Processes
Degerminator	Electricity Demand: 0.0004559 kW/kg	Literature-derived	Lawrence Berkeley National Laboratory. Energy Efficiency Improvement and Cost Saving Opportunities for the Corn Wet Milling Industry. July 2003
	Heat Loses: 10%	Engineering judgment	
Germ Dryer	Unit Temperature and Exhaust Temperature: 90 ℃	Literature-derived	Harry L. Brown et al. Energy Analysis of 108 Industrial Processes. 1996.
	Dry Germ Moisture Content: 3%	Sector Average	Sergio O. Serna-Saldivar. Corn: Chemistry and Technology. 2019. Lawrence Berkeley National Laboratory. Energy Efficiency Improvement and Cost Saving Opportunities for the Corn Wet Milling Industry. July 2003
	Air Ratio: 3.0	Engineering judgment	
	Heat Loses: 10%	Engineering judgment	
Oil Extractor	Electricity: 23.3 kW/kg	Literature-derived	Lawrence Berkeley National Laboratory. Energy Efficiency Improvement and Cost Saving Opportunities for the Corn Wet Milling Industry. July 2003.
	Oil to Germ Ratio: 0.050/.108	Literature-derived	Harry L. Brown et al. Energy Analysis of 108 Industrial Processes. 1996.
	Heat Loses: 10%	Engineering judgment	
	Unit Temperature and Outlet Temperature: 90 ℃	Literature-derived	Harry L. Brown et al. Energy Analysis of 108 Industrial Processes. 1996.
	Cooling Water ΔT: 20 ℃	Literature-derived	Harry L. Brown et al. Energy Analysis of 108 Industrial Processes. 1996.
Oil Separator	Electricity: 965.6 kW/kg	Literature-derived	Lawrence Berkeley National Laboratory. Energy Efficiency Improvement and Cost Saving Opportunities for the Corn Wet Milling Industry. July 2003.
	Heat Loses: 10%	Engineering judgment	

	Corn Oil Heat Capacity: 1.67 kj/kg ℃	Sector Average	Don W. Green and Robert H. Perry. Perry's Chemical Engineers' Handbook. 2008.
Grinding Mills	Electricity: 32.3 kW/kg	Literature-derived	Lawrence Berkeley National Laboratory. Energy Efficiency Improvement and Cost Saving Opportunities for the Corn Wet Milling Industry. July 2003.
	Heat Loses: 10%	Engineering judgment	
Washing Screens	Water to Kernel Ratio: 0.60/1.440	Literature-derived	Harry L. Brown et al. Energy Analysis of 108 Industrial Processes
	Heat Loses: 10%	Engineering judgment	
	Electricity: 0.930 kW/kg	Literature-derived	Lawrence Berkeley National Laboratory. Energy Efficiency Improvement and Cost Saving Opportunities for the Corn Wet Milling Industry. July 2003.
Centrifugal Separators	Unit Temperature: Ambient	Engineering judgment	
	Water to Hull Ratio: .50/.64	Sector Average	Lawrence Berkeley National Laboratory. Energy Efficiency Improvement and Cost Saving Opportunities for the Corn Wet Milling Industry. July 2003.
	Electricity: 90.87 kW/kg	Literature-derived	Lawrence Berkeley National Laboratory. Energy Efficiency Improvement and Cost Saving Opportunities for the Corn Wet Milling Industry. July 2003.
	Heat Loses: 10%	Engineering judgment	
Gluten Dewaterer	Moisture Content Out: 57%	Manufacturer-derived	Alfa Laval. What we do.
Fiber Dewaterer	Moisture Content Out: 60%	Manufacturer-derived	Valmet Fiber Press.
Feed Dryer	Unit temperature: 120 ℃	Literature-derived	Harry L. Brown et al. Energy Analysis of 108 Industrial Processes. 1996.
	Exhaust Temperature: 200 ℃	Literature-derived	Harry L. Brown et al. Energy Analysis of 108 Industrial Processes. 1996.
	Feed Outlet Moisture Content: 10%	Sector Average	Bob Myer and Matt Hersom. Corn Gluten Feed for Beef Cattle.
	Heat loses: 10%	Engineering judgment	
	Air Ratio: 3.0	Engineering judgment	

Starch Washing Filter	Starch Purity: 50%	Literature-derived	Lawrence Berkeley National Laboratory. Energy Efficiency Improvement and Cost Saving Opportunities for the Corn Wet Milling Industry. July 2003.
	Electricity: 69.24 kW/kg	Literature-derived	Lawrence Berkeley National Laboratory. Energy Efficiency Improvement and Cost Saving Opportunities for the Corn Wet Milling Industry. July 2003.
	Water to Starch: 1.5/.84	Literature-derived	Harry L. Brown et al. Energy Analysis of 108 Industrial Processes. 1996.
	Heat lose: 10%	Engineering judgment	