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The 2035 Initiative

NAICS Code:Beet Sugar Manufacturing (311313)

SUMMARY INFO: Beet sugar manufacturing produces over half of American sugar by processing harvested sugarbeets between the fall and spring months. Beet sugar manufacturing adds significant profit value to beet crops and promotes agricultural diversification, especially in the upper midwest. Sugar beets are a vital rotation crop for farmland regions, controlling disease and pests impacting other crops like corn and wheat. Beet sugar facilities process over 30 million tons of sugar beets annually, grown on over 1.1 million acres of farmland.[1] Farmer cooperatives own the vast majority of the sector, ensuring that beet sugar profits go back into agricultural communities. Beet sugar manufacturing employs about 151,000 Americans, with an annual economic impact of approximately $23 billion.[2]

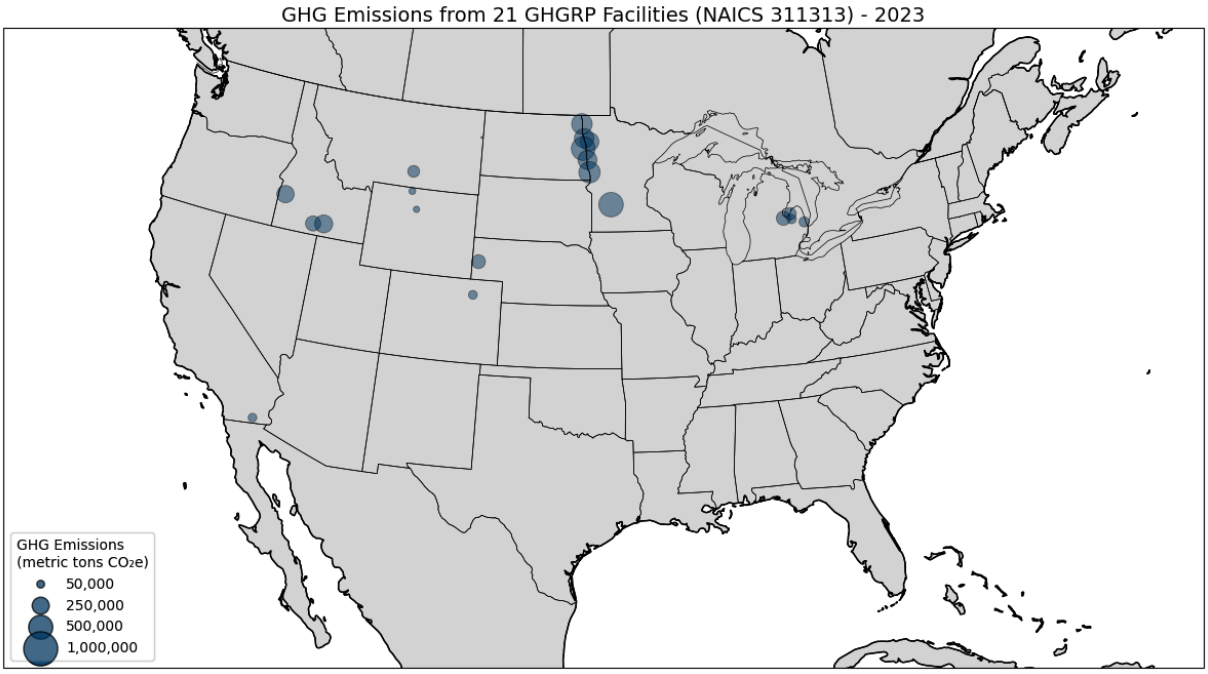
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Authors: Jason Ye, Antoine Merlo, Madeline Ranalli, and Eric Masanet

Link to archetype code:
https://github.com/ISALGroup/archetypes/blob/main/archetypes_list/archetype_beet_sugar.py

Archetype Name: Beet Sugar Manufacturing

Emissions and facility overview: According to the United States Census Bureau, there are 29 manufacturing plants associated with NAICS 311313 in the United States, 21 of which report annual GHG emissions in the GHGRP.[3] Reported emissions from GHGRP amounted to 3.05 MMT of CO2e in 2023. The majority of these plants in the US are concentrated in the northern states, as summarized in the map below.



[1] American Sugarbeet Growers Association. Sugarbeet History.
[2] American Sugarbeet Growers Association. How Sugarbeets Affect Our Nation's Economy.
[3] U.S. Census Bureau. 311313: Beet Sugar Manufacturing. 2023; U.S. Environmental Protection Agency. Greenhouse Gas Reporting Program (GHGRP).

Sector outputs: The beet sugar manufacturing sector produces sugar, mainly in the form of sucrose, from beet harvested as raw materials.[4] Pulp is also obtained as a byproduct during the extraction of sugar from beet.

Process pathways: Upon initial diffusion, sugar and pulp are separated from beet. Sugar then undergoes a series of purification steps, including carbonation, evaporation and crystallization. Molasses are separated from the main sugar product and are often also recycled to the pulp processing units. Sugar is then cooled and dried prior to packing and shipping. Meanwhile, pulp is pressed, dried and pelletized for uses such as animal feed.

Process Overview:

EPA's "Emission Factor Documentation for AP-42"[5] and "Sugar Beet Cultivation, Management and Processing" by Misra, Srivastava and Mall[6] were the main sources consulted for obtaining the parameters and assumptions used in the beet sugar model. As per the diagram below, carbonation is a key process used to remove impurities within the juice from which final sugar is recovered. GHGRP shows that the calcination of lime used in this process is often a significant source of carbon dioxide emissions to the atmosphere, due to carbon dioxide being produced alongside calcium oxide during the manufacturing of calcium oxide as lime. Thus, all beet sugar facilities that report to GHGRP show Subpart S on GHGRP, which tracks details on this lime manufacturing process such as byproduct formation.

The beet sugar manufacturing process begins with washing solid particles such as soil, stone and organic matter from beet in the so-called fluming stage. Beet composition prior to fluming is obtained from Krajnc, Mele and Glavic,[7] and Gruska et al.[8] after fluming. The beet, now composed mainly of sucrose, pulp and water, is sliced into strips known as cossettes. Electricity is the main energy involved in these two initial processes, and these processes alone can consume over a quarter of the total electricity throughout the process.

In the diffusion or extraction stage, the sugar (mainly sucrose) component of cossettes, known as juice, is extracted from the pulp byproduct through immersion in hot water. Both the juice and the pulp streams that result from this extraction are composed of over 80% water.[9] This water must be removed through subsequent process units for the sugar and pulp to be sellable. Extraction is the only part of the beet sugar manufacturing process that makes use of hot water as a utility. Moreover, its steam usage amounts to around 20% of the steam usage throughout the manufacturing process.

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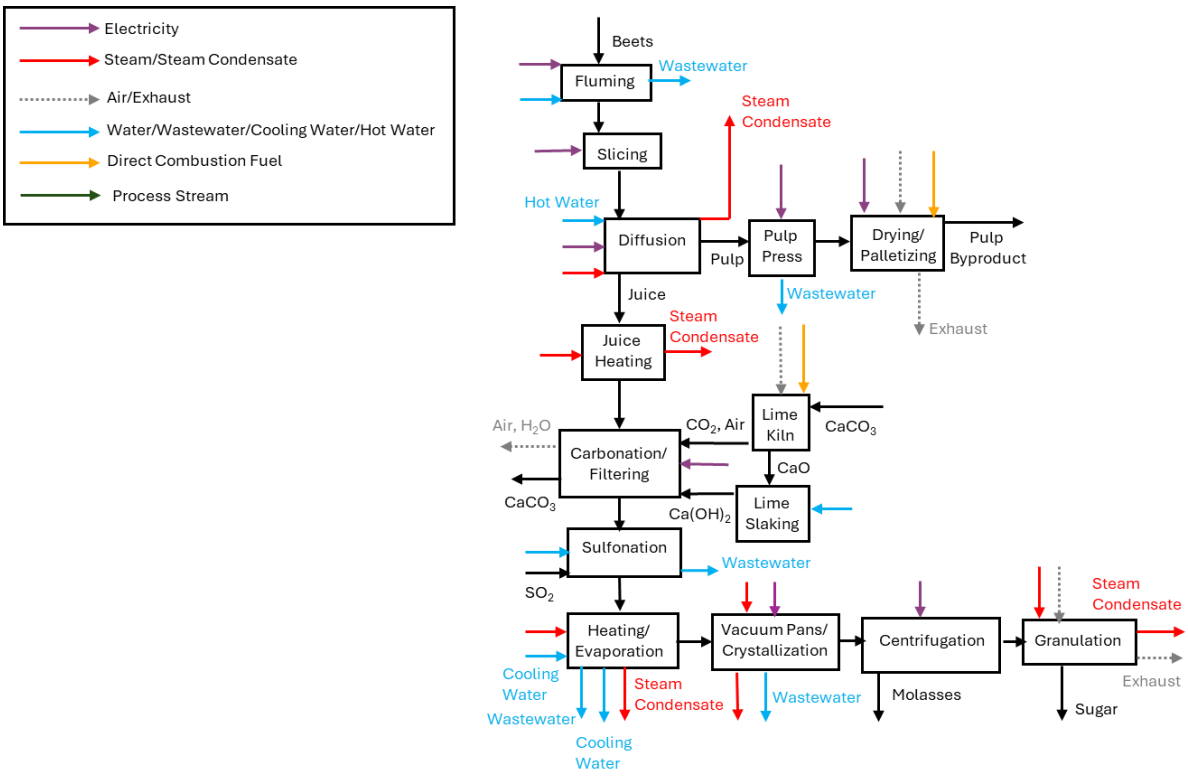
[4] U.S. Census Bureau. 311313: Beet Sugar Manufacturing. 2023.
[5] U.S. Environmental Protection Agency. Sugarbeet Processing. 1997.
[6] Varucha Misra et al. Sugar Beet Cultivation, Management and Processing. 2022.
[7] Damjan Krajnc et al. Improving the economic and environmental performances of the beet sugar industry in Slovenia: increasing fuel efficiency and using by-products for ethanol. 2007.
[8] Radosław Michał Gruska et al. Fresh and Stored Sugar Beet Roots as a Source of Various Types of Mono- and Oligosaccharide. August 2022.
[9] Yi Zheng et al. Integrating sugar beet pulp storage, hydrolysis and fermentation for fuel ethanol production. May 2012; James BeMiller. Carbohydrate Chemistry for Food Scientists. 3 - Oligosaccharaides. 2019.

The mixture – known as “raw juice” – is composed mostly of water and sugar at this stage. It is first heated to 85 C using steam. It then undergoes a series of chemical reactions, known as carbonation, for further purification. Calcium oxide is used and is usually sourced onsite.

In the first stage, limestone enters a lime kiln unit in the form of calcium carbonate and dissociates into calcium oxide and carbon dioxide through the calcination process. The calcium oxide then enters a lime slaker, where it is mixed with water to form calcium hydroxide or milk of lime in a highly exothermic reaction.[10] Though some of the carbon dioxide from calcination is often emitted to the atmosphere, most of this carbon dioxide reacts with the calcium hydroxide (whose temperature is obtained from Pesce et al.[11]) to reform calcium carbonate crystals in a carbonation tank. Specifically, these crystals form first from the reaction of carbon dioxide and water from the juice that produces carbonic acid, i.e., $CO_2 + H_2O <-> H_2CO_3$. The carbonic acid intermediate then reacts with calcium hydroxide to reform calcium carbonate, i.e., $H_2CO_3 + Ca(OH)_2 <-> CaCO_3 + 2H_2O$.[12]

The slaking mixture is fed in the carbonation tank and most of the remaining impurities from the sugar juice then adsorb onto these calcium carbonate crystals. If further juice purification is needed, carbon dioxide and calcium hydroxide can further react in this way, so that new calcium carbonate crystals can reform to allow for more adsorption. These resulting crystals are then filtered, leaving the resulting juice, known as thin juice, almost exclusively composed of water and sugar. The reaction temperature can be as high as 900 °C.[13]

[10] Matt Radaker. Lime slaking 101. January 2022.
[11] Cecilia Pesce et al. (2023). Effects of sucrose on fresh-state and setting properties of air lime. August 2023.
[12] Varucha Misra et al. Sugar Beet Cultivation, Management and Processing. 2022.
[13] Valerio Colombari. Lime's crucial role in sugar production: innovation for efficiency and sustainability.



Prior to evaporating most of the water from the thin juice, elemental sulfur is added to inhibit reactions that darken the juice.[14] The juice is then sent to a multi-effect evaporator composed of five stages of evaporation that typically occur at decreasing temperature and pressure.[15] As the name suggests, the evaporator removes most of the water from the juice to result in a thick juice mixture composed of around 72% sucrose.[16] To determine the amount of steam needed to perform this evaporation, a steam economy of 3 is assumed.[17] Even so, this typically results in around 60% of steam used throughout the manufacturing process being dedicated to the evaporator alone.

After evaporation, the thick juice undergoes crystallization in vacuum pans to allow the sugar to grow to a desired size through supersaturation. The resulting mixture, known as massecuite, has a sugar purity of around 92%.[18] Crystallization accounts for around 15% of the total steam usage throughout the manufacturing process. The massecuite is then sent to a centrifuge to separate the desired sugar stream from a syrup stream, known as molasses. Molasses also contains a substantial amount of sucrose and can, thus, be used as animal feed upon being recycled to the pulp stream that the extraction stage produces. Centrifugation is powered mainly by electricity, whose usage amounts to around 15% of the total electricity usage across the manufacturing process.

[14] U.S. Environmental Protection Agency. Sugarbeet Processing. 1997.
[15] Dhara Shah and C.G. Bhagchandani (2012). Design, modelling and simulation of multiple effect evaporators. July 2012.
[16] Varucha Misra et al. Sugar Beet Cultivation, Management and Processing. 2022.
[17] R. Paul Singh. Energy in Food Processing. 1986.
[18] Varucha Misra et al. Sugar Beet Cultivation, Management and Processing. 2022.

At this stage, the main sugar stream composed of around 99% sugar (mainly sucrose), is fed to a combination of drying and cooling units known as granulator. The granulator allows the sugar stream to achieve a dry content of 99.7% to 99.95%[19] through steam whose usage typically accounts for <1% of the total steam usage in the entire process.

Meanwhile, the pulp produced by the extraction unit is first pressed to decrease its concentration in water from around 80% to around 50%. The electricity involved amounts to around 13% of the total electricity usage across the manufacturing process. Finally, prior to being pelletized and sent off as animal feed, the resulting pulp stream is dried until it reaches around 98% pulp by mass.[20] This process uses both electricity and fuel such as natural gas, where electricity usage amounts to around 15% across the manufacturing process and fuel usage.[21] By electrifying this drying process, despite an increase in the electricity usage, the need for fuel combustion would be eliminated. This would reduce the amount of harmful emissions to the atmosphere that the exhaust stream produces.

Archetype Unit Process Assumptions: Figure 1 depicts the unit processes, mass flows, and energy flows modeled in our process system archetype. Assumptions made in the model have been described in writing.

Model comparison: Numerical outputs from this beet sugar model have been compared extensively against various literature. The model states that every 48,562 kg/hr of beet yields 8401 kg/hr of sugar, which is a sugar to beet ratio of 0.173 by mass. The latest USDA report (May 2025) states this ratio as 0.151. 0.25 tons of limestone is needed for the lime kiln to produce every ton of sugar from beet.[22] The model shows that 1820 kg/hr of limestone is needed for every 8401 kg/hr of final sugar product, so that this mass ratio of limestone to sugar is predicted as 0.217. Overall, these results demonstrate that the mass and energy outputs from the beet sugar model are all within the same order of magnitude as reported in literature.

Limitations and future work: Various simplifying assumptions have been made in this model. For instance, as mentioned, molasses is usually recycled to the pulp byproduct processing part of the beet sugar manufacturing process upon production from the centrifuge. To minimize the number of such recycle flows, this recycling of molasses is neglected in the model. This is not expected to yield overly drastic errors, since the main focus of beet sugar manufacturing is the production of sugar rather than pulp. However, future work can still add back such details as molasses recycle stream into the model.

Simplifying assumptions were also made on the compositions of streams throughout the manufacturing process. For instance, the sugar recovered from beet is often composed of not just sucrose, but also other forms of sugar such as glucose. However, since sucrose is typically the main sugar of interest yielded from beet, this model assumes sugar to take only the form of sucrose. In the future, more in-depth research can be done on the composition of beet, so that more details can be obtained from the

[19] Koen Dillen et al. Bred for Europe but grown in America: the case of GM sugar beet. January 2013.
[20] Regiane Alves de Oliveira et al. A Simple Biorefinery Concept to Produce 2G-Lactic Acid from Sugar Beet Pulp (SBP): A High-Value Target Approach to Valorize a Waste Stream. April 2020.
[21] Arne Sloth Jensen and Bernard Morin. Energy and the environment in beet sugar production. 2015.
[22] Ahmet Görgülü. Elevating sugar beet by-products into healthier, natural, and functional ingredients. February 2025.

beet sugar model on the exact components of sugar recoverable from a beet mixture. This can also result in a more detailed composition of the molasses stream that, as with the main final sugar stream at present, is assumed to be composed of only sucrose and water.

Finally, the removal of impurities from beet happens not only in the initial fluming stage, but also in later stages such as during carbonation that occurs in the liming process. However, it is the fluming stage that removes most of the impurities such as soil, stone and organic matter. Thus, this model accounts only for the removal of these impurities during fluming. Future work can account for carbonation's process of removing impurities as well by depicting the process of remaining impurities not removed through fluming being adsorbed onto the surface of the calcium carbonate crystals that form during carbonation. This would further enhance the granularity of the model.