DECARBONIZATION TECHNOLOGIES ANALYSIS

For Energy and Emissions Intensive Sectors in California

February, 2024

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Introduction

The following document explains the approach utilized to obtain the energy use and cost implications for various decarbonization technologies in the manufacturing sub-sector, namely food and beverage manufacturing, pulp and paper manufacturing, cement manufacturing, iron and steel manufacturing, and glass manufacturing sub-sectors. The technologies and their energy use impacts pertain to the manufacturing facilities listed within the 2022 Mandatory Reporting of GHG Emissions (MRR).[1] However, these technologies may apply to similar facilities across the manufacturing sector in the U.S.

Manufacturing Energy Consumption Survey Data

To consider the decarbonization opportunities of various sub-sectors, it is important to understand their energy-consuming end-uses, such as boilers, process heating equipment, machine drives, combined heat and power (CHP), and HVAC units, among others. We employed data from the 2018 Manufacturing Energy Consumption Survey (MECS) published by the U.S. Energy Information Administration (U.S. EIA).[2] U.S. EIA gathers information from manufacturing facilities using online surveys and releases the compiled data once every four years. The 2018 MECS involved around 15,000 establishments, encompassing 97% to 98% of the total manufacturing energy consumption. The survey provides distinct assessments of energy usage across 21 manufacturing subsectors and 79 industry groups. The data is published at the national level, though there is limited disaggregation by the U.S. Census Regions. A typical MECS data for the food manufacturing sector is given in Table 1. It disaggregates the total energy consumption into various industrial end-use processes, such as steam, boilers, process cooling, and so on.

Table 1: MECS Energy Consumption Data for the U.S. Food and Beverage Manufacturing Sector (in TBtu/yr)

End-Use	Total
Offsite Steam	46
Conventional Boilers	236
CHP/Cogeneration	305
Process Heating	194
Process Cooling	4
Other Process Uses	20
Machine Drives	15
HVAC	61
Other Facility Support	24
Onsite Transportation	3
Other Non-process	1
Total	**909**

[1] "Mandatory GHG Reporting - Electric Power Entities | California Air Resources Board." Accessed February 1, 2024. https://ww2.arb.ca.gov/mrr-epe.

[2] "U.S. Energy Information Administration - EIA - Independent Statistics and Analysis." Accessed February 1, 2024. https://www.eia.gov/consumption/manufacturing/data/2018/.

California Energy Balance

For each subsector in the CARB MRR 2022 data, the energy consumption estimates from MECS were broken down into California energy consumption estimates through the application of assumptions provided by the California energy balance update and decomposition analysis for the industry and buildings.[3] The work estimates California Energy Balance (CALEB) and the proportion of MECS energy consumption data that is utilized by the manufacturing facilities in California. For example, it estimates that 6.5% of total food manufacturing energy usage as per MECS 2006 data is within the California food manufacturing facilities. Similar estimates were provided for other manufacturing subsectors in question. It should be noted that the analysis was carried out for MECS 2006 data, and the estimates may not be completely relevant to MECS 2018 data; however, the paucity of such estimates led us to employ the estimates generated from MECS 2006 data.

Table 2: Proportion of Energy Consumption by California Industries as compared to U.S. Manufacturing Sector Energy Consumption from 2018 MECS Data

Manufacturing Subsector	Percentage
Food	8%
Pulp and Paper	1.9%
Cement	6.3%
Glass	6.3%
Metals	2%

Employing the percentages identified in Table 2, we estimated the energy consumption of the relevant sub-sectors in California. An example of such a breakdown for the food manufacturing sector is presented below:

Table 3: Energy Consumption Assumption for California Food Manufacturing Sector (in TBtu/yr)

End-Use	Total
Conventional Boiler Use	4
CHP and/or Cogeneration Process	19
Process Heating	24
Process Cooling and Refrigeration	16
Machine Drive	0.3
Electro-Chemical Processes	2
Other Process Use	1
Facility HVAC (f)	5
Facility Lighting	2
Other Facility Support	0.2
Onsite Transportation	0.1
Total	**74**

[3] Hasanbeigi, Ali, Stephane de la Rue du Can, and Jayant Sathaye. "Analysis and Decomposition of the Energy Intensity of California Industries." Energy Policy 46 (July 1, 2012): 234–45. https://doi.org/10.1016/j.enpol.2012.03.056.

Energy and Carbon flow

The Manufacturing Energy and Carbon Footprints illustrate the distribution of energy supply, demand, losses, and greenhouse gas (GHG) emissions across various manufacturing sectors in the United States.[4] These footprints data are published and maintained by the U.S. DOE. They rely on data from the U.S. EIA MECS and the U.S. Environmental Protection Agency (EPA) to depict the utilization and wastage of energy in manufacturing, along with the corresponding emissions from combustion and industrial processes.[5] Each footprint visually represents the energy flow (in the form of fuel, electricity, or steam) to key manufacturing end uses such as boilers, combined heat and power generation, process heaters, process coolers, machine-driven equipment, and facility HVAC. Additionally, the footprints also map the GHG emissions linked to energy generation and end-use processes. An example of such a depiction is illustrated in Figure 1. The flow of fuel and carbon emissions are displayed for all end-uses within the sector.

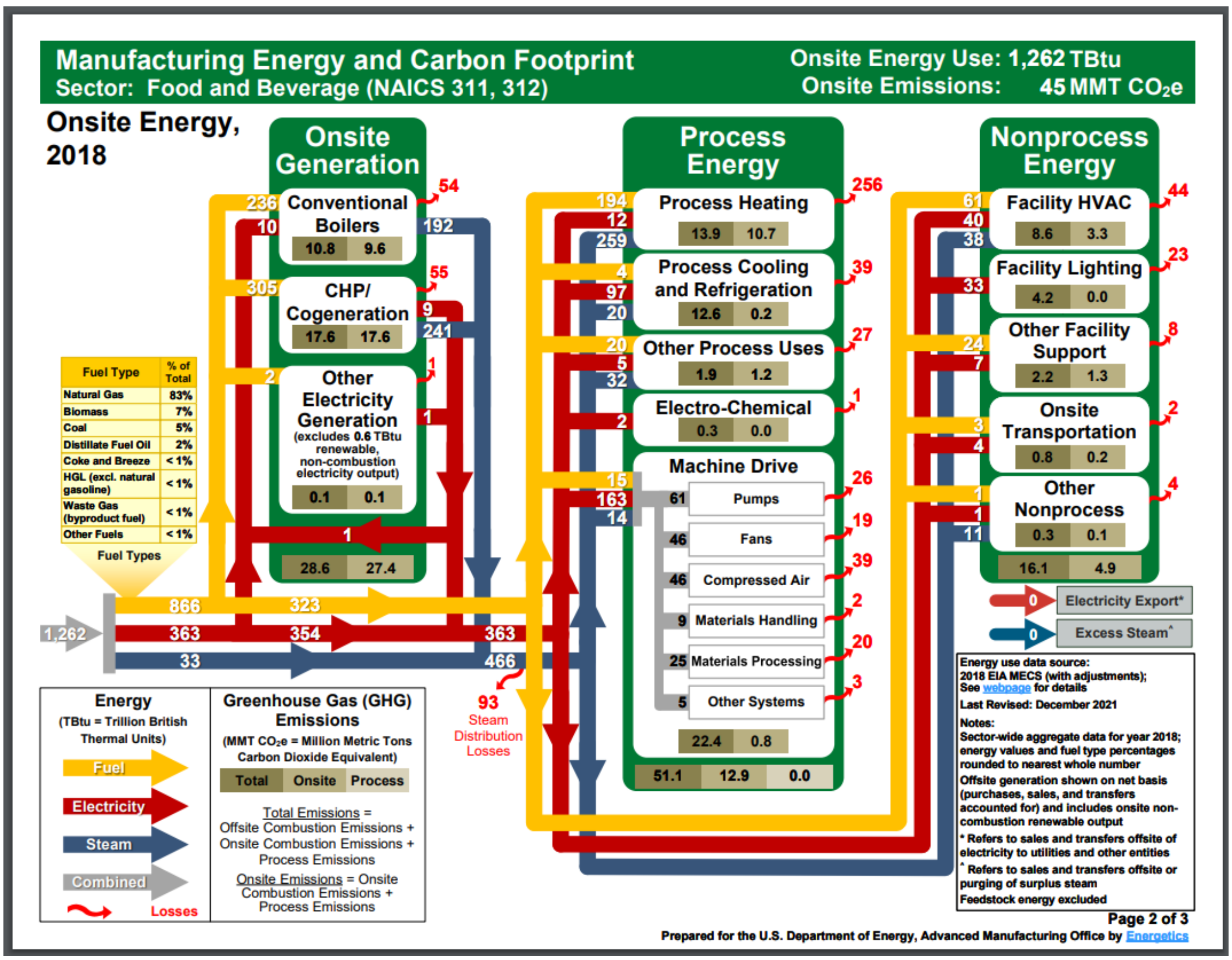

Figure 1: MECS Energy and Carbon Flow for U.S. Food and Beverage Manufacturing Sector [4]

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[4] DOE, US. "Energetics,"Manufacturing Energy and Carbon Footprints (2018 MECS)," Energy. gov, 2022."

[5] US EPA, OAR. "Inventory of U.S. Greenhouse Gas Emissions and Sinks." Reports and Assessments, February 8, 2017. https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks.

With the assistance of such breakdowns, we estimated the energy consumption and GHG emissions by the California manufacturing facilities. We performed this exercise to understand the energy consumption by unique end-uses. Through such an understanding, it would be possible to propose decarbonization measures relevant to each sub-sector with minimum generalization. For example, if a subsector is abundantly utilizing hot water, it would make sense to propose hot water heat pumps. Whereas, in cases where there is high energy consumption from refrigeration, improving motor efficiency and utilizing newer, premium efficiency measures would yield higher energy use and carbon emissions reduction. Table 4 estimates the California Food and Beverage manufacturing sectors' energy and carbon flows by end-use. It is prevalent that the sector utilizes a significant proportion of energy to generate steam and hot water through offsite steam, conventional boilers, and cogeneration. This helps us to streamline relevant decarbonization technologies for this sub-sector. Further, 20% of fuel is employed for process heating end-uses which covers end-uses such as drying and concentration through fuel combustion. Relevant forms of electrification could decarbonize such end-uses. In short, the breakdown of energy and carbon flow helps us prioritize decarbonization efforts for the energy and carbon hotspot end-uses.

Table 4: Estimation of California Food and Beverage Energy Use and Carbon Emissions by End-use

End-Use Type	Fossil Fuel Usage (TBtu/yr)	Annual CO2e Emissions ($MTCO_2e/yr$)	% Fuel Usage	% Emissions
Offsite Steam	4	192,000	5%	5%
Conventional Boilers	19	768,000	26%	20%
CHP/Cogeneration	24	1,408,000	34%	37%
Process Heating	16	856,000	21%	23%
Process Cooling	0.3	16,000	0%	0%
Other Process Uses	2	96,000	2%	3%
Machine Drives	1	64,000	2%	2%
HVAC	5	264,000	7%	7%
Other Facility Support	2	104,000	3%	3%
Onsite Transportation	0.2	16,000	0%	0%
Other Non-process	0.1	8,000	0%	0%
Total	**74**	**3,792,000**	**100%**	**100%**

Documentation of Decarbonization Technologies

In this section, we document the technologies and their calculations performed in all the Excel sheets that were produced for CARB analysis. The documentation includes methodologies for the estimation and calculation of energy and carbon implications concerning the identified technologies, grouped with all the relevant references and sources from the literature.

We assume that the fossil fuel utilized for the sector is natural gas unless mentioned otherwise, which is billed at $11.13/MMBtu of natural gas. [6] The electricity rate assumed for this exercise is $0.19/kWh of the facility's electricity consumption. [7] California purchased electricity CO_2e emissions factor is estimated approximately 0.000218 MTCO_2e/kWh of site-purchased electricity[8], whereas for natural gas, it is 0.05311 MTCO_2e/MMBtu. [9] Annual operating hours are estimated to be 8,760 hours per year. Finally, we also assume California's Carbon Emissions cost in the exercise at $39/ton of CO_2 emission. [10] The equipment lifetime and discount rates are considered 20 years and 6%, respectively, unless stated otherwise. Using these two variables, the capital recovery factor (CRF) is calculated as 0.087.

Food Manufacturing Sector (NAICS 311)

The food manufacturing sector primarily utilizes low-temperature steam, hot water, and hot air for combustion purposes. The sector is diverse due to producing a wide range of food products such as dairies, bakeries, canned foods, meat, sugar, snacks, and beverages. MRR 2022 data identifies 31 food and beverage facilities in California that, in total, emit 1,582,387 MTCO_2e/yr. The sources of these emissions are through combustion, process, venting, and suppliers. The sub-section below explains the approach taken to identify and quantify decarbonization technologies for the food and beverage manufacturing sector. The proportion of fossil fuel employed in the sector to generate steam, hot water, and hot combustion air is 50%, 25%, and 25%, respectively. [11] We utilize these estimates to allocate the technologies relevant to the decarbonization of steam, hot water, and process heating.

The calculations are done by disaggregating the food and beverage sector into the dairy sector, fruit and vegetable sector, and other remaining food and beverage manufacturing sectors. The breakdown of energy use for these sub-sectors was derived from MECS 2018 data as the U.S. EIA also publishes energy use by sub-sectors up to the four-digit NAICS Code. Four-digit NAICS code pertains to sub-sectors such as grain and oilseed milling, dairy, fruit and vegetables, sugar, animal slaughtering and processing, and beverage and tobacco manufacturing.

Hot Water Heat Pump

Through the utilization of the hot water energy proportion from the aforementioned paragraph, we calculate the overall fossil fuel required to generate hot water in the dairy sector as 1.15 TBtu/yr, resulting in annual CO_2e emissions of 61,256 metric tons for 8 dairy facilities listed in the CARB MRR 2022 data. Consequently, an average dairy facility would utilize 0.14 TBtu/yr of fossil fuel, thereby emitting 7,660 MTCO_2e/yr.

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[6] Forecasted 2025-2030 rate from AEO natural gas price (https://www.eia.gov/outlooks/aeo/tables_ref.php) and scaling using a ratio of average 2020-2021 CA prices to US prices.

[7] Average 2025-2030 rate from CEC Electricity Rate Forecast (https://efiling.energy.ca.gov/GetDocument.aspx?tn=253591&DocumentContentId=88826)

[8] CARB GHG Inventory: Table 12: 2000-2021 GHG Emission Trends (https://ww2.arb.ca.gov/sites/default/files/2023-12/2000-2021_ghg_inventory_trends_figures.xlsx). 2017-2021 prices are relatively flat so we think the 2021 values is an accurate assumption for the next 5 years.

[9] https://portfoliomanager.energystar.gov/pdf/reference/Emissions.pdf

[10] 2023 November Auction Settlement Price from CARB Website

[11] "Summary Table" Tab from the spreadsheet; The proportion are derived from LBNL's existing work with U.S. DOE's Industrial Roadmap Report

Assuming an operating schedule of 8,760 hours per year, we estimate the per facility (or equipment) average energy use of 16 MMBtu/hr (4,690 kW). We have to assume that each facility utilizes one piece of equipment because of a lack of facility-level operations data. Based on the average energy use of 16 MMBtu/yr (NG use), a facility would spend approximately $1,605,000/yr in natural gas usage costs.

For hot water heat pumps (HWHPs), we assume a nominal Coefficient of Performance (COP) of 3. Based on the COP of 3, the electrical energy required to operate HWHPs is estimated as:

HWHP Electricity Consumption = Existing Fuel Usage/COP

= 16 MMBtu/hr/3

= 5.33 MMBtu/hr

= 5.33 MMBtu/hr x 293.071 kW/MMBtu/hr

= 1,562 kW

We can calculate the annual electricity consumption and electric usage costs from the HWHP electricity consumption as follows:

HWHP Annual Electricity Usage Costs = 1,562 kW x 8,760 hrs/yr x $0.19/kWh

= $2,600,386/yr

We also utilize the cap and trade auction costs in the abated carbon emissions and the final levelized costs; however, for simplicity purposes, we are not including the cap and trade-related costs in this documentation. We will simply apply the cap and trade auction costs of $39/ton in the final $/ton number in this documentation. This approach is used throughout this document.

Based on the existing fossil fuel and proposed electricity usage costs for the heat pumps, the annual energy usage cost savings (AEUCS) is calculated as:

AEUCS = Existing Fossil Fuel Usage Costs – HWHP Annual Electricity Usage Costs

= $1,605,000 - $2,600,386

= $-995,386/yr

The negative value indicates that annual energy costs will increase.

The annual electricity-related CO_2e can be calculated as:

Proposed CO_2e emissions = 1,562 kW x 8,760 hrs/yr x 0.000218 $MTCO_2e$/kWh

= 2,983 $MTCO_2e$/yr

The annual carbon abatement is calculated as:

Annual CO_2e abatement = Existing CO_2e emissions – Proposed CO_2e emissions

= 7,660 $MTCO_2e$/yr – 2,983 $MTCO_2e$/yr

= 4,677 $MTCO_2e$/yr

The capital cost for the HWHP is based on its rated capacity. The capital costs are bounded by the power curve equation as shown below: [12]

Capital cost $= \left(1{,}658\, x\, (Rated\ kWoutput^{-0.174})\right) x\ Rated\ kW$ output

$= \left(1{,}658\, x\, (4{,}690^{-0.174})\right) x\ 4{,}690$

= $1,786,378

Levelized Cost of Abated Carbon $= \frac{Capital\ costs\ x\ CRF - AEUCS}{Annual\ CO2e\ Abatement}$

$= \frac{1{,}786{,}378\ x\ 0.087 + 995{,}386}{4{,}677}$

= $246/ton of avoided CO_2e

Using the $30/ton of cap and trade auction costs, the overall cost of avoided carbon is calculated to be $207/ton of avoided CO_2e.

Steam Generating Heat Pump

Through the utilization of the steam generation energy proportion, we calculate the overall fossil fuel required to generate steam in the dairy sector as 4.6 TBtu/yr, resulting in annual CO_2e emissions of 245,024 metric tons for the 8 dairy facilities in California's MRR 2022 data. Consequently, an average dairy facility would utilize 0.58 TBtu/yr of fossil fuel, thereby emitting 30,630 $MTCO_2e$/yr.

Assuming an operating schedule of 8,760 hours per year, we estimate the per facility (or equipment) average energy use of 66 MMBtu/hr (19,350 kW). We have to assume that each facility utilizes one piece of equipment because of a lack of facility-level operations data; however, in reality, facilities could be using multiple equipment in multiple buildings. Based on the average energy use of 66 MMBtu/yr (NG use), a facility would spend approximately $6,419,000/yr in natural gas usage costs.

For steam-generating heat pumps (SGHPs), we assume a nominal Coefficient of Performance (COP) of 2. Higher COPs can be achievable if the facility has a waste heat source for the heat pumps. Based on the COP of 2, the electrical energy required to operate SGHPs is estimated as:

SGHP Electricity Consumption = Existing Fuel Usage/COP

= 66 MMBtu/hr/2

= 33 MMBtu/hr

= 33 MMBtu/hr x 293.071 kW/MMBtu/hr

= 9,671 kW

We can calculate the annual electricity consumption and electric usage costs from the SGHP electricity consumption as follows:

[12] Alstone, Peter, Evan Mills, Jerome Carman, and Alejandro Cervantes. "Toward carbon-free hot water and industrial heat with efficient and flexible heat pumps." Schatz Energy Research Center, Arcata, CA (2021).

SGHP Annual Electricity Usage Costs = 9,671 kW x 8,760 hrs/yr x $0.19/kWh

= $16,100,087/yr

Based on the existing fossil fuel and proposed electricity usage costs for the heat pumps, the annual energy usage cost savings (AEUCS) is calculated as:

AEUCS = Existing Fossil Fuel Usage Costs – SGHP Annual Electricity Usage Costs

= $6,419,000 - $16,100,087

= $-9,681,087/yr

The annual electricity-related CO_2e can be calculated as:

Proposed CO_2e emissions = 9,671 kW x 8,760 hrs/yr x 0.000218 $MTCO_2e$/kWh

= 18,469 $MTCO_2e$/yr

The annual carbon abatement is calculated as:

Annual CO_2e abatement = Existing CO_2e emissions – Proposed CO_2e emissions

= 30,630 $MTCO_2e$/yr – 18,469 $MTCO_2e$/yr

= 11,981 $MTCO_2e$/yr

The capital costs for the SGHP are based on its rated capacity. The capital costs are bounded by the power curve equation as shown below: [13]

$$\text{Capital costs} = \left(445\ x\ (Rated\ kWoutput^{-0.105})\right) x\ Rated\ kW\text{output}$$

$$= \left(445\ x\ (19{,}350^{-0.105})\right) x\ 19{,}350$$

= $3,054,495

$$\text{Levelized Cost of Abated Carbon} = \frac{Capital\ costs\ x\ CRF - AEUCS}{Annual\ CO2e\ Abatement}$$

$$= \frac{3{,}054{,}495\ x\ 0.087 + 9{,}681{,}087}{11{,}981}$$

= $830/ton of avoided CO_2e

Using the $30/ton of cap and trade auction costs, the overall cost of avoided carbon is calculated to be $791/ton of avoided CO_2e.

[13] Zühlsdorf, B., Poulsen, J. L., Dusek, S., Wilk, V., Krämer, J., Rieberer, R., ... & Arpagaus, C. (2023). High-Temperature Heat Pumps. Task 1– Technologies.: Task Report.

Electric Boilers

For electric boilers, we assume a nominal efficiency of 99%, whereas it is assumed to be 75% for fossil fuel-fired boilers. [14] Based on the efficiencies, the electrical energy required to operate electric boilers is estimated as:

Electric boiler Electricity Consumption = Existing Fuel Usage x fossil fuel boiler efficiency/electric boiler efficiency

= 66 MMBtu/hr x (0.75/0.99)

= 50 MMBtu/hr

= 50 MMBtu/hr x 293.071 kW/MMBtu/hr

= 14,654 kW

We can calculate the annual electricity consumption and electric usage costs from the electric boiler electricity consumption as follows:

Electric boiler Annual Electricity Usage Costs = 14,654 kW x 8,760 hrs/yr x $0.19/kWh

= $24,395,686/yr

Based on the existing fossil fuel and proposed electricity usage costs for the heat pumps, the annual energy usage cost savings (AEUCS) is calculated as:

AEUCS = Existing Fossil Fuel Usage Costs – Electric Boiler Annual Electricity Usage Costs

= $6,419,000 - $24,395,686

= $-17,976,686/yr

The annual electricity-related CO_2e can be calculated as:

Proposed CO_2e emissions = 14,654 kW x 8,760 hrs/yr x 0.000218 $MTCO_2$e/kWh

= 27,984 $MTCO_2$e/yr

The annual carbon abatement is calculated as:

Annual CO_2e abatement = Existing CO_2e emissions – Proposed CO_2e emissions

= 30,630 $MTCO_2$e/yr – 27,984 $MTCO_2$e/yr

= 2,646 $MTCO_2$e/yr

The capital costs for the electric boiler are based on its rated capacity. The capital costs are bounded by the power curve equation as shown below: [15]

Capital costs = $\left(2{,}835\ x\ (Rated\ kWoutput^{-0.361})\right) x\ Rated\ kW$ output

[14] Zuberi, Jibran, Ali Hasanbeigi, and William R. Morrow. "Electrification of boilers in US manufacturing." (2021).

[15] Zuberi, Jibran, Ali Hasanbeigi, and William R. Morrow. "Electrification of boilers in US manufacturing." (2021).

$$= \left(2{,}835\ x\ (14{,}654^{-0.361})\right) x\ 14{,}654$$

$$= \$1{,}301{,}964$$

Levelized Cost of Abated Carbon $$= \frac{Capital\ costs\ x\ CRF - AEUCS}{Annual\ CO2e\ Abatement}$$

$$= \frac{1{,}301{,}964\ x\ 0.087 + 17{,}976{,}686}{2{,}646}$$

$$= \$6{,}837/\text{ton of avoided } CO_2e$$

Using the \$30/ton of cap and trade auction costs, the overall cost of avoided carbon is calculated to be \$6,798/ton of avoided CO_2e.

Biofuel Boilers

Biofuel boiler's calculations are very similar to that of the electric boilers. The only differences are the capital costs, biogas (RNG) costs, boiler efficiencies, and their carbon emission factors. The capital costs for typical biofuel boilers follow the power curve equation which is shown below; these boilers have typically combustion efficiencies of up to 80%: [16]

Biofuel boiler capital costs $$= \left(17{,}002\ x\ (Rated\ kWoutput^{-0.462})\right) x\ Rated\ kW \text{output}$$

Similarly, the cost of biogas per MMBtu is assumed to be approximately \$16/MMBtu. [17] The carbon emissions from the biogas are considered to be 0, thereby resulting in a favorable \$/ton value of \$79/ton of abated carbon. With the inclusion of cap and trade auction costs, it is around \$40/ton of avoided CO_2e.

Solar Thermal Steam

We estimate the available floor space area for solar panels from U.S. EIA's MECS 2018 data. [18] The majority of the assumptions for this measure have been referenced from NREL's System Advisor Model (NREL SAM). [19]

The floor space area for a typical dairy plant is estimated as 9,100 m^2 from[17]. The number is discounted by 25% to account for any space that may already be in use through equipment such as chillers and cooling towers.

The solar thermal system estimated for this purpose is a parabolic trough CSP. In these systems, the sun's energy is focused through reflectors with a parabolic curve onto a receiver pipe – the heat absorber tube – positioned approximately one meter above the curved mirror surface. The heat transfer fluid, typically thermal oil, flowing through the pipe experiences a temperature increase from 560°F to 740°F. Subsequently, the generated heat energy is utilized in the thermal power block to produce steam.

[16] Malico, Isabel, Ricardo Nepomuceno Pereira, Ana Cristina Gonçalves, and Adélia M. O. Sousa. "Current Status and Future Perspectives for Energy Production from Solid Biomass in the European Industry." Renewable and Sustainable Energy Reviews 112 (September 1, 2019): 960–77. https://doi.org/10.1016/j.rser.2019.06.022.

[17] IEA. "Sustainable Supply Potential and Costs – Outlook for Biogas and Biomethane: Prospects for Organic Growth – Analysis." Accessed February 2, 2024. https://www.iea.org/reports/outlook-for-biogas-and-biomethane-prospects-for-organic-growth/sustainable-supply-potential-and-costs.

[18] https://www.eia.gov/consumption/manufacturing/data/2018/pdf/Table9_1.pdf

[19] Blair et al. (2018), System Advisor Model (SAM) General Description (Version 2017.9.5), NREL/TP-6A20-70414

A field of trough solar collectors consists of multiple parallel rows of these parabolic trough-shaped mirrors.

The heat sink power estimate for the collector is approximately 0.19 kW of heat output/m^2 of solar thermal module area. Based on this, the solar thermal heat sink power is estimated as:[18]

Solar thermal heat-sink power = 0.19 x 9,100 m^2

= 1,735 kW

To produce 1,735 kW of heat sink power, the target receiver thermal power capacity should at least be:

Target receiver thermal power = 1,735 kW/ Efficiency

= 1,735 kW/40%[18]

= 4,340 kW

The capital costs for solar thermal systems are based on the size of the target receivers. The capital costs and O&M costs are estimated at $560/kW and $8/kW, respectively.

Capital costs = $560/kW x 4,340 kW

= $2,430,400

O&M costs = $8/kW x 4,340 kW

= $34,720/yr

Based on the heat sink energy potential, the amount of fossil-fuel-fired boiler steam that can be replaced from the CSP system is:

Replaced steam = 1,735 kW/ 293.071 MMBtu/hr/kW

= 6 MMBtu/hr

AEUCS = 6 MMBtu/hr x 8,760 hrs/yr x $11.03/MMBtu

= $579,737/yr

Abated CO_2e emissions = 6 MMBtu/hr x 8,760 hrs/yr x 0.05311 $MTCO_2e$/MMBtu

= 2,791 $MTCO_2e$/yr

The carbon abatement cost is calculated as:

Levelized Cost of Abated Carbon $= \frac{Capital\ costs\ x\ CRF - AEUCS}{Annual\ CO2e\ Abatement}$

$= \frac{2{,}430{,}400\ \ x\ 0.087 - 579{,}737}{2{,}791}$

= $-132/ton of avoided CO_2e

Using the $30/ton of cap and trade auction costs, the overall cost of avoided carbon is calculated to be $-171/ton of avoided CO_2e.

Microgrid (PV + Battery Storage)

The floor space area for a typical dairy plant is estimated as 9,100 m^2 [17]. The module area to kW-DC system capacity is estimated as 0.19 kW_{DC}/m^2 of PV module area. Whereas, the DC-AC conversion ratio is 1.15. [18] The capacity of the PV modules based on the area available for a typical dairy processing plant is calculated as:

PV Module kW-DC Capacity = Available area x Conversion Factor

= 9,100 m^2 x 0.19 kW_{DC}/m^2

= 1,729 kW-DC

We assume the battery storage capacity to be similar to the PV modules' kW-DC nameplate capacity based on NREL SAM assumptions. [18] The capital costs of the entire system, which includes the PV Module, Inverter, Battery, Balance of system equipment, Labor, Overhead, Contingency, Permitting, Engineering & developer overhead cost, is estimated as $2,380/kW-DC. Whereas, the annual O&M costs are estimated to be 2.5% of the capital costs. These costs are calculated below:

Capital Costs = kW_{DC} Nameplate Capacity x Conversion Factor

= 1,729 kW_{DC} x $2,380/$kW_{DC}$

= $4,115,020

Annual O&M Costs = Capital Costs x 2.5%

= $4,115,020 x 0.025

= $102,876/yr

The annual electricity yield for a typical plant in California is calculated next. We assume the annual daily average solar irradiation in California at 5.40 kW/m^2/day. [18]

Annual Electricity Yield = (kW_{DC} x 8,760 hrs/yr)/ (DC-to-AC Conversion Ratio x 5.40 kW/m^2/day)

= (1,729 kW_{DC} x 8,760 hrs/yr)/ (1.15 x 5.40 kW/m^2/day)

= 2,438,976 kWh/yr

AEUCS = Annual Electricity Yield x Unit Electricity Cost

= 2,438,976 kWh/yr x $0.19/kWh

= $463,405/yr

Abated CO_2e emissions = Annual Electricity Yield x Purchased Electricity Grid Emissions Factor

= 2,438,976 kWh/yr x 0.000218 $MTCO_2e$/kWh

= 5,317 $MTCO_2e$/yr

The carbon abatement cost is calculated as:

Levelized Cost of Abated Carbon $= \frac{Capital\ costs\ x\ CRF - AEUCS}{Annual\ CO2e\ Abatement}$

$$= \frac{4{,}115{,}020 \, x \, 0.087 - 463{,}405 + 102{,}876}{5{,}317}$$

= $-0.47/ton of avoided CO_2e

Using the $30/ton of cap and trade auction costs, the overall cost of avoided carbon is calculated to be $-30.5/ton of avoided CO_2e.

Advanced Electro-heating Technologies

These technologies include heating and drying methods such as microwave heating, infrared drying, and ohmic heating. Based on various literature sources, the average energy use reduction from these innovating processes is estimated as 57%. Please refer to the "Economic Parameters" tab within the "1 – Food sector analysis for CARB.xlsx" spreadsheet for all the references. For the capital costs, we could not estimate the capital costs of industrial-grade advanced electro-heating technologies. Therefore, the calculations for this analysis only include the annual energy costs and CO_2e emissions savings. The existing fuel usage for process heating per equipment for the dairy sector is estimated as 32 MMBtu/hr in the spreadsheet's "CA Food Facilities (MRR 2022)" tab.

Proposed Electricity Consumption = Existing Fuel Usage x (1-Energy Use Reduction)

= 32 MMBtu/hr x (1-0.57)

= 14 MMBtu/hr

= 14 MMBtu/hr x 293.071 kW/MMBtu/hr

= 4,103 kW

We can calculate the annual electricity consumption and electric usage costs from the advanced electro-heating equipment electricity consumption as follows:

Proposed Annual Electricity Usage Costs = 4,103 kW x 8,760 hrs/yr x $0.19/kWh

= $6,829,033/yr

Based on the existing fossil fuel and proposed electricity usage costs, the annual energy usage cost savings (AEUCS) is calculated as:

AEUCS = Existing Fossil Fuel Usage Costs – Electric Boiler Annual Electricity Usage Costs

= 32 MMBtu/hr x 8,760 hrs/yr x $11.13/MMBtu - $6,829,033/yr

= $3,119,962- $6,829,033

= $-3,709,071/yr

The annual electricity-related CO_2e can be calculated as:

Proposed CO_2e emissions = 4,103 kW x 8,760 hrs/yr x 0.000218 $MTCO_2e$/kWh

= 7,835 $MTCO_2e$/yr

The annual carbon abatement is calculated as:

Annual CO_2e abatement= Existing CO_2e emissions – Proposed CO_2e emissions

=32 MMBtu/hr x 8,760 hrs/yr x 0.05311 $MTCO_2e$/MMBtu– 7,835 $MTCO_2e$/yr

= 7,053 $MTCO_2e$/yr

Levelized Cost of Abated Carbon $= \frac{-AEUCS}{Annual\ CO2e\ Abatement}$

$= \frac{3{,}709{,}071}{7{,}053}$

= \$526/ton of avoided CO_2e

Pulp and Paper Manufacturing Sector (NAICS 322)

The pulp and paper manufacturing sector primarily utilizes boilers and cogeneration systems to generate steam for use in pulping, evaporation, papermaking, and other operations. [20] The sector produces various products such as printing and writing paper, paper and paperboard, wrapping and packaging paper, household and sanitary paper, and newsprint. MRR 2022 data identifies 5 paperboard manufacturing facilities in California that, in total, emit 655,149 $MTCO_2e$/yr. The sources of these emissions are through combustion, process, vented, and suppliers. The sub-section below explains the approach taken to identify and quantify decarbonization technologies for this sector. The majority of energy usage is to generate steam; the section below identifies decarbonization technologies for steam and process heat generation. The breakdown of energy use for these subsectors was derived from MECS 2018 data.

Solar Thermal Steam/Process Heat

Please refer to the "Food Manufacturing Sector" Section.

Microgrid (PV + Battery Storage)

Please refer to the "Food Manufacturing Sector" Section.

Biogas (Biofuel) Boilers

Please refer to the "Food Manufacturing Sector" Section.

Steam Generating Heat Pump

Please refer to the "Food Manufacturing Sector" Section. The only difference is that for the pulp and paper manufacturing sector, we assume that the source heat for industrial heat pumps is between 100-200°C, thereby achieving a CoP of up to 4. [21] Based on the same source, we also estimate the amount of waste heat supply potential for the pulp and paper manufacturing sector in the United States. Unlike other sectors, waste heat sources will be available in the future for this sector despite electrification, primarily, because of the utilization of biomass such as wood, tree bark, hog fuel, and black liquor.

Electric Boiler

Please refer to the "Food Manufacturing Sector" Section.

[20] Kramer, Klaas Jan, Eric Masanet, and Ernst Worrell. "Energy efficiency opportunities in the US pulp and paper industry." Energy engineering 107, no. 1 (2010): 21-50.

[21] Kosmadakis, George. "Estimating the Potential of Industrial (High-Temperature) Heat Pumps for Exploiting Waste Heat in EU Industries." Applied Thermal Engineering 156 (June 25, 2019): 287–98. https://doi.org/10.1016/j.applthermaleng.2019.04.082.

Glass Manufacturing Sectors (NAICS 3272)

The glass manufacturing sector primarily utilizes furnaces to generate process heat for melting raw materials such as sand (silica), soda, limestone, clarifying agents, coloring, and recycled glass cullet. [22] The sector produces various products such as flat glass, container glass, and mineral wool. MRR 2022 data identifies 9 paperboard manufacturing facilities in California that, in total, emit 681,932 $MTCO_2e$/yr. The sources of these emissions are through combustion, process, vented, and suppliers. The sub-section below explains the approach taken to identify and quantify decarbonization technologies for this sector. The majority of energy usage is to generate heat for raw materials melting; the section below identifies decarbonization technologies for process heat generation. The breakdown of energy use for these subsectors was derived from MECS 2018 data.

Solar Thermal Steam/Process Heat

Please refer to the "Food Manufacturing Sector" Section.

Microgrid (PV + Battery Storage)

Please refer to the "Food Manufacturing Sector" Section.

Biogas (Biofuel) Boilers

Please refer to the "Food Manufacturing Sector" Section.

Hydrogen as a Fuel

Hydrogen, as a fuel, could be blended with natural gas or RNGs up to 15-20% without significant changes in the equipment and piping systems. The benefit of doing so is the reduction in carbon emissions through the existing natural gas usage. The section assumes a blend of up to 15% hydrogen in the existing natural gas pipes for combustion. Since we assume the boilers utilize the same piping systems, there are no significant capital costs related to this measure. However, as the blend percentage of hydrogen increases, the existing burners and pipes will need to be replaced as per the standards required to combust and transport the hydrogen gas, respectively.

The cost of hydrogen gas per MMBtu is assumed to be approximately $37/MMBtu. [23] The carbon emissions from the hydrogen gas are considered to be 0. The existing natural gas usage for the production of the glass melting process by the glass manufacturing facilities in CA is estimated at 10 TBtu/yr, resulting in an average facility-wide energy usage of 127 MMBtu/hr.

Assuming a blend percentage of 15%, the effective cost of the fuel is calculated as:

Proposed Fuel Cost = 85% of NG Cost + 15% of H_2 Cost

= 0.85 x $11.13/MMBtu + 0.15 x $37/MMBtu

= $15.01/MMBtu

The annual energy usage cost savings are calculated below:

AEUCS = 127 MMBtu/hr x 8,760 hrs/yr x ($11.13-$15.01)/MMBtu

[22] https://in.saint-gobain-glass.com/knowledge-center/glass-manufacturing-process

[23] https://www.energy.gov/eere/fuelcells/hydrogen-shot

= $-4,316,578/yr

Assuming a blend percentage of 15%, the effective CO_2e emission factor for the resulting fuel is calculated as:

Proposed CO_2e Emission Factor = 85% of NG Emission Factor + 15% of H_2 EF

= 0.85 x 0.05311 $MTCO_2e$/MMBtu + 0.15 x 0

= 0.04514 $MTCO_2e$/MMBtu

The annual CO_2e emission reduction is calculated below:

Emissions Reduction = 127 MMBtu/hr x 8,760 hrs/yr x (0.05311-0.04514) $MTCO_2e$/MMBtu

= 8,867 $MTCO_2e$/yr

LCAC is calculated as follows:

$$\text{Levelized Cost of Abated Carbon} = \frac{-AEUCS}{Annual\ CO2e\ Abatement}$$

$$= \frac{4{,}316{,}578}{8{,}867}$$

= $487/ton of avoided CO_2e

With the inclusion of cap and trade auction costs, it is around $448/ton of avoided CO_2e.

All Electric Heating Furnace

The existing natural gas usage for the production of the glass melting process by the glass manufacturing facilities in CA is estimated at 10 TBtu/yr, resulting in an average facility-wide energy usage of 127 MMBtu/hr.

Electric Heating Furnaces reduce the energy consumption of the equipment because electric heaters do not have thermal and combustion-related losses that are prevalent in fossil fuel-fired boilers. In short, they reduce energy consumption by up to 30%. [24]

The proposed electricity consumption of the electric heating furnace is calculated below:

Proposed electricity consumption = 127 MMBtu/hr x (1 – 30%)

= 89 MMBtu/hr

= 89 MMBtu/hr x 293.071 kW/MMBtu/hr

= 26,083 kW

The annual energy usage cost savings can then be calculated as:

AEUCS = Existing Fuel Usage Cost – Proposed Electricity Usage Cost

= (127 MMBtu/hr x $11.13/MMBtu – 26,083 kW x $0.19/kWh) x 8,760 hrs/yr

[24] https://issuu.com/quartzmetals/docs/glass_international__july_august_20

= $-31,030,198/yr

The annual CO_2e emission reductions can be calculated as follows:

Annual CO_2e reduction = (127 MMBtu/hr x 0.05311MTCO$_2$e/MMBtu – 26,083 kW x 0.000218 MTCO$_2$e /kWh) x 8,760 hrs/yr

= 9,276 MTCO$_2$e/yr

The relationship between the energy usage of furnaces and the amount of glass production per day is given below:[25]

Glass production = 0.13 tons of glass per MMBtu/hr of furnace capacity

= 0.13 x 127 MMBtu/hr x 24 hrs/day

= 396 ton/day

= 300 tons/day[26]

The capital costs for an electric heating furnace are governed by the equation as shown below. The capital costs for such a system are also calculated below:

Capital Costs = (-22,100 x ln(Ton of glass production per day) + 166,204) x ton/day production

= (-22,100 x ln(300) + 166,204) x 300

= $13M *(the price was converted from euros to dollars; hence, the cost is $13M instead of 12M euros)*

The levelized cost of abated carbon can be calculated as:

$$LCAC = \frac{Capital\ costs\ x\ CRF - AEUCS}{Annual\ CO2e\ Abatement}$$

$$= \frac{13{,}000{,}000\ x\ 0.087 + 31{,}030{,}198}{9{,}276}$$

= $3,467/ton of avoided CO_2e

Using the $30/ton of cap and trade auction costs, the overall cost of avoided carbon is calculated to be $3,428/ton of avoided CO_2e.

Please note that for the glass sector, CCS and Thermal Batteries could also be viable options. Though not calculated for this analysis, please refer to the Cement Manufacturing Sector section for calculation methodologies.

Cement Manufacturing Sectors (NAICS 3273)

The cement manufacturing sector primarily utilizes calcining and pre-calcining kilns to generate process heat for decomposing limestone (calcium carbonate) into clinker (calcium oxide + silicates + aluminates + ferrites) and CO_2. MRR 2022 data identifies 14 facilities in California that, in total, emit 7,723,464 MTCO$_2$e/yr. The sources of these emissions are through combustion, process, vented, and suppliers. The

[25] Levine, Elliott, Michael Greenman, and Keith Jamison. "The development of a next generation melting system for glass production: Opportunities and progress." In ACEEE Summer Study on Energy Efficiency in Industry. Washington, DC, USA: ACEEE, 2003.

[26] Electric heaters are available up to 300 ton/day capacities, therefore, capping the capacity at 300 ton/day

sub-section below explains the approach taken to identify and quantify decarbonization technologies for this sector. The majority of energy usage is to generate heat for kiln operations; the section below identifies decarbonization technologies for process heat generation. The breakdown of energy use for these subsectors was derived from MECS 2018 data.

Solar Thermal Steam/Process Heat

Please refer to the "Food Manufacturing Sector" Section.

Microgrid (PV + Battery Storage)

Please refer to the "Food Manufacturing Sector" Section.

Coal to NG or Biomass waste

Please refer to the "Food Manufacturing Sector" Section.

Carbon Capture and Storage

Approximately 56% of the carbon emissions in the cement manufacturing sector originate from the process emissions during the calcination of limestone into lime and CO_2. [27] CCS could be a viable technology to capture process emissions along with combustion-related emissions. The fuel usage for kiln operation in the sector in California sees a substantial quantity of coal and coke. Therefore, decarbonizing the kiln operations will yield tremendous CO_2 emission reductions.

Out of the 14 facilities, 7 facilities are cement manufacturers emitting 7,437,393 $MTCO_2e$/yr. Facility level emissions are estimated as 1,062,485 $MTCO_2e$/yr (7,437,393 $MTCO_2e$/yr/7).

The carbon emissions resulting from the calcination reaction can be calculated below:

CO_2 from calcination = Total CO_2 emissions from cement facilities x 56%

= 7,437,393 x 0.56

= 4,164,940 $MTCO_2e$/yr

Average calcination per facility = 4,164,940/7 facilities

= 594,991 $MTCO_2e$/yr

As per reference [26], CCS could capture and store 95% of the facility's emissions. The captured CO_2 is calculated as:

Captured Carbon = 594,991 $MTCO_2e$/yr x 0.95

= 565,241 $MTCO_2e$/yr

CCS also employs compressors and pumps for compressing the captured CO_2 and transportation of captured CO_2, solvents, and steam, respectively. This typically increases the electricity consumption by up to 50%. The existing CO_2e emissions from purchased electricity are estimated as 97,748 $MTCO_2e$/yr.

[27] https://www.energy.gov/sites/default/files/2023-11/Industry%20Guide%20to%20CCS%20at%20Cement%20Plants_Nov%2029%202023_0.pdf

Reference [26] mentions that the electricity usage of a cement manufacturing plant is approximately 9.2% of total facility-wide emissions.

Proposed increase in electricity-related emission = 97,748 $MTCO_2e/yr$ x 1.5 – 97,748

= 48,874 $MTCO_2e/yr$

Total abated carbon is calculated as:

Annual Abated Carbon = Captured Carbon – Increased electricity-related emissions

= 565,241 – 48,874

= 516,367 $MTCO_2e/yr$

The capital cost of the entire CCS is approximated as \$220/ton of CO_2 captured. Whereas, the annual O&M costs are approximately 10% of capital costs. [28] See the calculations below:

Capital costs = \$220/ton of CO_2 captured x Captured Carbon

= 220 x 565,241

= \$124,353,020

Annual O&M Costs = 10% of Capital Costs

= 0.1 x \$124,353,020

= \$12,435,302/yr

The levelized cost of abated carbon is calculated as:

$$LCAC = \frac{Capital\ costs\ x\ CRF - AEUCS}{Annual\ CO2e\ Abatement}$$

$$= \frac{124{,}353{,}020\ x\ 0.087 + 12{,}435{,}302}{565{,}241}$$

= \$41/ton of avoided CO_2e

Calcined Clay Supplementary Cementitious Materials (SCMs)

The existing clinker percentage in the cement is 95%, whereas, the remaining 5% is mostly gypsum. In this measure, we propose the substitution of limestone material with calcined clay supplementary cementitious materials (SCMs) to reduce the process emissions during the calcination process. Calcined clay can be a low-carbon substitute for conventional Portland cement, offering the potential to decrease CO_2 emissions associated with cement production. This is achieved by substituting a portion of the clinker with limestone and calcined clays. [29] It can be adopted on a wide scale due to the abundant

[28] Panja, Palash, Brian McPherson, and Milind Deo. "Techno-Economic Analysis of Amine-Based CO2 Capture Technology: Hunter Plant Case Study." Carbon Capture Science & Technology 3 (June 1, 2022): 100041. https://doi.org/10.1016/j.ccst.2022.100041.

[29] Srinivasan, Pavitra, Ali Hasanbeigi, and Nora Esram. "Adoption of Limestone Calcined Clay Cement and Concrete in the US Market in the Drive to Net Zero," 2023.

availability of its raw materials, limestone, and calcined clay. This sets it apart from other frequently utilized SCMs like fly ash or slag.

We decrease the content of the clinker in our analysis from 95% to 70%, thereby reducing it by 25%. We utilize calcined clay and limestone at 17% and 8%, respectively. Calcined clay acts as an SCM and contributes to the pozzolanic reactions that improve the cement's strength and durability. Limestone, on the other hand, helps reduce the overall clinker content in the cement, leading to a lower carbon footprint. Based on research, the ratio is optimal at 2:1.

Proposed process emissions after reducing the clinker percentage to 70% can be calculated as:

Proposed process emissions = Facility Emissions x process emissions % x proposed clinker %

= 1,062,485 x 40% x 70%

= 446,244 $MTCO_2e/yr$

The reduction of limestone in the calcination process by 8% and re-addition after the calcination process will reduce the fuel usage during the calcination process by 8%. The proposed fuel emissions can be calculated as:

Proposed fuel related emissions= Facility Emissions x fuel emissions % x (1 - limestone percentage)

= 1,062,485 x 0.4 x (1-0.08)

= 390,994 $MTCO_2e/yr$

Abated emissions = 1,062,485 – 446,244 – 390,994

= 225,247 $MTCO_2e/yr$

The fossil fuel and clinker intensity is assumed as 3.75 MMBtu/ton of clinker production. [24] The cost parameters for the clinker, limestone, and calcined clay are $40/ton, $40/ton, and $35/ton, respectively. [30,31,32,33]

The existing fossil fuel emissions can be calculated by dividing the fossil fuel-related emissions by their respective emission factor. We estimate a weighted-average emission factor because the CA fuel mix for cement manufacturing is heavily outweighed by coal and coke energy use. The calculations to estimate the weighted average emission factor are shown in the "Limestone Calcined Clay Cements" Tab within the "1 - Cement Manufacturing Sector Analysis for CARB.xlsx" spreadsheet. The weighted average

[30] Gálvez-Martos, José-Luis, Roneta Chaliulina, Ammar Elhoweris, Jonathan Mwanda, Amer Hakki, and Yousef Al-horr. "Techno-Economic Assessment of Calcium Sulfoaluminate Clinker Production Using Elemental Sulfur as Raw Material." *Journal of Cleaner Production* 301 (June 10, 2021): 126888. https://doi.org/10.1016/j.jclepro.2021.126888.

[31] https://thundersaidenergy.com/downloads/cement-costs-and-energy-economics/#:~:text=The%20breakdown%20of%20costs%2C%20in,ton%20for%20electricity%3B%20and%20%2420%2F

[32] Glenk, Gunther, Kelnhofer Anton, Rebecca Meier, and Stefan Reichelstein. "Cost-Efficient Pathways to Decarbonizing Portland Cement Production," 2023.

[33] Scrivener, Karen, Fernando Martirena, Shashank Bishnoi, and Soumen Maity. "Calcined Clay Limestone Cements (LC3)." *Cement and Concrete Research*, Report of UNEP SBCI WORKING GROUP ON LOW-CO2 ECO-EFFICIENT CEMENT-BASED MATERIALS, 114 (December 1, 2018): 49–56. https://doi.org/10.1016/j.cemconres.2017.08.017.

emission factor is 0.0998 $MTCO_2e$/MMBtu of fossil fuel consumption. The total fossil fuel consumption is calculated as:

Fossil fuel consumption = Fossil fuel emissions/Weighted average emission factor

= (1,062,485 x 0.4)/0.09989

= 4,254,620 MMBtu/yr

Proposed fuel consumption = Proposed fuel emissions/Weighted average emission factor

= 390,994/0.09989

= 3,914,246 MMBtu/yr

Based on the fossil fuel consumption and the relationship between the fuel energy use and clinker production, the clinker usage can be estimated as:

Existing Clinker Use = Existing Fossil fuel use/ Fossil fuel and clinker intensity

= 4,254,620/3.75

= 1,134,565 tons of clinker/yr

The proposed limestone, calcined clay, and clinker usages are calculated based on the proposed proportion of these materials in the cement. These are calculated as:

Proposed limestone use = Existing clinker use x limestone use %

= 1,134,565 ton of clinker x 8%

= 90,765 tons of limestone/yr

Proposed calcined clay use = Existing clinker use x calcined clay use %

= 1,134,565 ton of clinker x 17%

= 192,876 ton of calcined clay/yr

Proposed clinker use = Existing clinker use x proposed clinker use %

= 1,134,565 ton of clinker x 70%

= 794,196 tons of clinker/yr

The fuel usage is diverse, thereby resulting in many fuel costs. We calculated the weighted average fuel costs based on the existing percentage of fuel type in the mix. The weighted average fuel costs were estimated at \$4.03/MMBtu (See “Limestone Calcined clay cements” Tab). The reduction in fuel usage can be calculated as:

Fuel cost savings = Fuel Use Reduction x \$4.03/MMBtu

= (4,254,620 – 3,914,246) x 4.03

= \$1,371,707/yr

Similarly, the materials usage cost implication due to changes in the amount of materials used can be calculated by:

Material cost savings = Clinker use reduction x \$40/ton of clinker – limestone use x \$40/ton of limestone – calcined clay use x \$35/ton of calcined clay

= (1,134,565-794,196) x 40 – 90,765 x 40 – 192,876 x 35

= \$3,233,500/yr

Total cost savings can be calculated as:

AEUCS = Material cost savings + fuel cost savings

= \$3,223,500/yr + \$1,371,707/yr

= \$4,595,207/yr

The levelized cost of abated carbon is calculated as:

$$LCAC = \frac{-AEUCS}{Annual\ CO2e\ Abatement}$$

$$= \frac{-4{,}595{,}207}{225{,}247}$$

= \$-20/ton of avoided CO_2e

Recycled Carbonated Fines SCMs

Please refer to the "Limestone Calcined Clay Cements" section. Apart from the cost of recycled carbonated fines, the calculations are similar.

Thermal Batteries Storage

This decarbonization measure could support the existing kilns by providing process heat that is stored in graphite blocks that are heated by electricity when the grid electricity usage costs are low or through off-grid electricity such as solar or wind power. The capital costs for the graphite blocks are relatively low; however, to be cost competitive with natural gas kilns, the facility will need to source their electricity from off-grid cheaper renewables that are preferably owned by them as well. This is because grid-purchased electricity is significantly more expensive than natural gas, presumably making it cost-prohibitive. More information on the thermal batteries could be explored in this source. [34] The battery can deliver heat at 1,500 to 1,700°C, hot enough to meet at least 93% of the industrial heat demand that is currently supplied by combustible fuels.

As per the MRR 2022 data for the cement manufacturing facilities in California, the process heating fossil fuel energy uses 28 TBtu/yr for 14, which can be converted into 226 MMBtu/hr (66 MWh) of energy use by individual facilities.

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[34] Rissman, Jeffrey, and Eric Gimon. "Industrial Thermal Batteries: Decarbonizing U.S. Industry While Supporting a High-Renewables Grid." Energy Innovation, 2023. https://energyinnovation.org/wp-content/uploads/2023/07/2023-07-13-Industrial-Thermal-Batteries-Report-v133.pdf.

The source [33] assumes a 15 MWh thermal battery that has a storage capacity of up to 84 hours of energy storage. We assume a 10 MWh thermal battery to be conservative. Based on the capacity of the thermal battery, the percentage of facility heat that can be supplied is as follows:

% of facility heat that can be supplied = 10 MWh/66 MWh

= 15%

The levelized cost of energy for the measure in California was estimated to be $62/MWh by the source. [33] Based on the levelized cost of energy, the annualized capital costs can be calculated as:

Annualized capital costs = LCOE x Installation Capacity x Operation Hours

= 62 x 10 x 8,760

= $5,431,200/yr

The lifetime span and discount factor used for this technology are different from the others in our analysis because this technology is at a lower TRL of 6. So, we use a higher discount factor of 7%, and a lower lifetime span of 10 years, resulting in the CRF of 0.142. Based on the CRF, the capital costs for the technology can be estimated as:

Capital costs = Annualized capital costs/CRF

= 5,431,200/0.142

= $38,247,887

Annual fossil fuel use cost savings can be calculated as follows:

Fossil fuel use cost savings = Capacity of Thermal battery x 3.412 MMBtu/MWh x Operational hours x NG Cost per MMBtu

= 10 x 3.412 x 8,760 x 11.13

= $3,326,659/yr

Annual CO_2e abatement can be calculated as follows:

Emission Reduction Annual = (Capacity of Thermal battery/Plant process heat requirement)/per facility fuel emissions

= (10/66) x (2,400,879 annual CO_2e emissions for process heating/14 facilities) [35]

= 15,874 $MTCO_2$e/yr

Levelized Costs of carbon abatement can be calculated as:

LCAC $= \frac{Capital\ Costs\ x\ CRF - AEUCS}{Annual\ CO2e\ Abatement}$

[35] See "CA Cement Facilities (MRR2022)" Tab: Cells E24 and C20

$$= \frac{5{,}431{,}200 - 3{,}326{,}659}{15{,}874}$$

$$= \$133/\text{ton of avoided } CO_2e$$

Metal Processing Sector (NAICS 321 and 332)

The metals processing sector, in California, primarily processes iron blocks in foundries and forging. Two secondary aluminum smelting facilities recycle aluminum from used materials and smelt them for further use. In short, the state does not smelt the elements from their ores, or they do not do primary smelting. MRR 2022 data identifies 8 facilities in California that, in total, emit 372,839 $MTCO_2e$/yr. The sources of these emissions are through combustion, process, vented, and suppliers. The sub-section below explains the approach taken to identify and quantify decarbonization technologies for this sector. The majority of energy usage is to generate heat for kiln and heating operations; the section below identifies decarbonization technologies for process heat generation. The breakdown of energy use for these subsectors was derived from MECS 2018 data.

Hot Water Heat Pump

See the Food Manufacturing Sector

Electrification of Hot rolling/Reheating Furnace

See the Glass manufacturing sector's "All Electric Heating Furnace" for more information. Some key differences are that the efficiencies of existing and proposed reheating furnaces are estimated at 58% and 74%, respectively. [36]

The capital costs for the electric reheating furnace were not available in the literature for industries as per the authors' knowledge. It should also be noted that the capacities of electric furnaces may be substantially lower than existing fossil fuel-fired furnaces.

Solar Thermal Process Heat

Please refer to the food manufacturing sector.

Microgrid (PV + Battery Storage)

Please refer to the food manufacturing sector.

15% Hydrogen Process Heating

Please refer to the Glass manufacturing sector.

Biogas Process heating with RNG

Please refer to the food manufacturing sector.

[36] Schmitz, N., L. Sankowski, F. Kaiser, C. Schwotzer, T. Echterhof, and H. Pfeifer. "Towards CO2-Neutral Process Heat Generation for Continuous Reheating Furnaces in Steel Hot Rolling Mills – A Case Study." *Energy* 224 (June 1, 2021): 120155. https://doi.org/10.1016/j.energy.2021.120155.