# Climate Technology Review

An Assessment of Opportunities to Reduce Greenhouse Gas Emissions at Stationary Sources in the Bay Area

October 2018

Bay Area Air Quality Management District

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## PREFACE

The Bay Area Air Quality Management District (Air District) commissioned this research effort (contract number 2018.011) to perform an assessment evaluating opportunities to reduce greenhouse gas emissions at stationary sources of air pollution in the Bay Area (e.g. refineries, natural gas power plants, manufacturing facilities, waste management facilities, residential and commercial buildings, etc.). Mitigation measures may include equipment, software, smart/connected technologies, or other innovations that reduce use of non-renewable energy, reduce emissions, or optimize energy efficiency. These technology options will be evaluated on technology readiness, costs, benefits, and barriers to development, demonstration, and deployment.

As per the scope of work for this project, the top recommended measures focus on early stage and less well-known commercial opportunities for greenhouse gas reductions. Common renewable sources of distributed generation, such as solar and wind power, therefore are not included in the assessment.

## ACKNOWLEDGEMENTS

Jonathan Rogers of Energetics Incorporated managed this project and is lead author of this report. Christopher Gillespie and Harrison Schwartz, also of Energetics, supported this effort. They identified relevant literature sources, conducted interviews with technology developers, identified mitigation measures, and populated the measure assessment matrix. Thomas Finamore provided valuable document production support to prepare this report for final publication.

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The mitigation measures in this report were selected based on the best available and most recent literature that could be identified. This report is not expected to be an exhaustive list of mitigation options but attempts to be as complete as possible. All estimates are intended for guidance at a high-level and those pertaining to emissions abatement, economics, barriers, and otherwise should not be misconstrued to infer the suitability of an individual mitigation measure at a specific plant or facility. Before implementation, mitigation measures of interest should be evaluated on a case-by-case basis with additional input from facility operations staff, technology vendors, and other knowledgeable stakeholders.

# Executive Summary

According to the Bay Area Air Quality Management District's (Air District) 2017 Clean Air Plan, industrial stationary sources accounted for 26% of 2015 Bay Area greenhouse gas (GHG) emissions. If contributions from energy (14%), buildings (10%), waste (3%), and agriculture (1%) are added, the result totals more than half of all Bay Area GHG emissions.

The 2017 Clean Air Plan lays the groundwork for a long-term effort to reduce Bay Area GHG emissions 40 percent below 1990 levels by 2030 and 80 percent below 1990 levels by 2050.[1] To understand opportunities to achieve these goals, the Air District is assessing mitigation measures to reduce GHG emissions at stationary sources of air pollution in the Bay Area. The effort described in this report identifies 188 emissions mitigation measures that span the most emissions intensive industries in the Air District.

Table ES-1 shows the number of identified mitigation measures organized by industry and industry subsector. Although power generation is listed, low carbon power generating technologies such as solar photovoltaics and wind were largely out of scope for this effort. Renewable power generation plus energy storage may greatly accelerate the decarbonization of U.S. electric grids. However, an assessment of those technologies is not included in this report.

This assessment evaluated the identified mitigation measures across an array of key comparison variables:

- **Emissions Mitigation**
  - Industry Subpart-Process emissions impact
  - District emissions impact
  - National emissions impact
- **Economics**
  - Investment Scale (per individual deployment)
  - Cost Relative to Baseline
  - Return on Investment
- **Maturity**
  - Technology Readiness Level
  - Measure Provider Maturity
- **Barriers**
  - Technical Barriers
  - Economic/Market Barriers
  - Policy Barriers

Resources used to evaluate the mitigation measures across the key comparison variables include technology roadmaps, regulatory agency reports, academic literature, vendor brochures, vendor interviews, and more.

Table ES-1. Number of Mitigation Measures by Industry Sector

| Industry | Subsector | Measures |
|---|---|---|
| Agriculture | Soil Management | 5 |
| | Enteric Fermentation | 1 |
| | Manure Management | 5 |
| Buildings | Commercial | 35 |
| | Residential | 19 |
| Electronics | Semiconductors | 10 |
| Petroleum Systems | Natural Gas Compression | 1 |
| | Refining - Combustion | 8 |
| | Refining - Other | 18 |
| Metals | Iron and Steel Production | 6 |
| Minerals | Cement Production | 14 |
| Power Generation | Batteries | 2 |
| | Combined heat and power | 6 |
| | Fuel Cells/Electrolyzers | 1 |
| | Power Plants | 1 |
| Waste | Composting | 8 |
| | Landfills/Combustion | 15 |
| | Wastewater | 12 |
| Other | Asphalt Drying | 3 |
| | Carbon Capture | 1 |
| | Food Processing | 8 |
| | Glass Production | 8 |
| | Industrial Gas Suppliers | 1 |
| | **Total** | **188** |

Figure ES-1 summarizes the three especially promising mitigation measures for each sector. These measures are prioritized based on those that demonstrate high cost effectiveness and high ease of adoption. Many of the measures listed represent those that can be implemented at low cost and that require minimal process changes.

Following the results of this assessment, the Air District has three key strategies it can employ for a given technology: (1) **Regulate** and enforce the adoption of the technology; (2) **Incentivize** the adoption of the technology with financial support; and (3) **Educate** and encourage adoption of the technology with relevant stakeholders. Figure ES-1 suggests one key strategy for each measure, but other strategies may also be employed in parallel.

For measures where regulation is possible, the technology is generally commercially available and cost effective for facilities to implement, resulting in long-term energy or cost savings without the need for market incentives. The Air District will evaluate the feasibility of developing rules around these measures.

[1] "Final 2017 Clean Air Plan. Spare the Air, Cool the Climate: A blueprint for clean air and climate protection in the Bay Area." Bay Area Air Quality Management District. Adopted April 19, 2017. baaqmd.gov/~/media/files/planning-and-research/plans/2017-clean-air-plan/attachment-a_-proposed-final-cap-vol-1-pdf.pdf

There is an opportunity for the Air District and other financing authorities to provide incentives for technologies that have demonstrated high potential for reducing emissions at a reasonable capital investment, but are still in the demonstration phase, have a limited number of customers, or are otherwise not yet widely commercially available. In these cases, financial intervention could make the difference in accelerating the adoption of new technologies and supporting these technologies to become more widespread and cost-effective.

For technologies that are readily commercially available, or which may apply to sectors with robust existing financing opportunities, the Air District will conduct outreach to stakeholders to make sure they are aware of the opportunities. For example, some of the building technologies in Figure ES-1 may qualify for existing incentive programs for energy efficiency.

Each industry faces unique circumstances and barriers to deployment. The information in this report is to be interpreted as high-level guidance. Each measure should be evaluated on a case-by-case basis to determine suitability for real-world deployment, with input from facility operations staff, technology vendors, and other knowledgeable stakeholders.

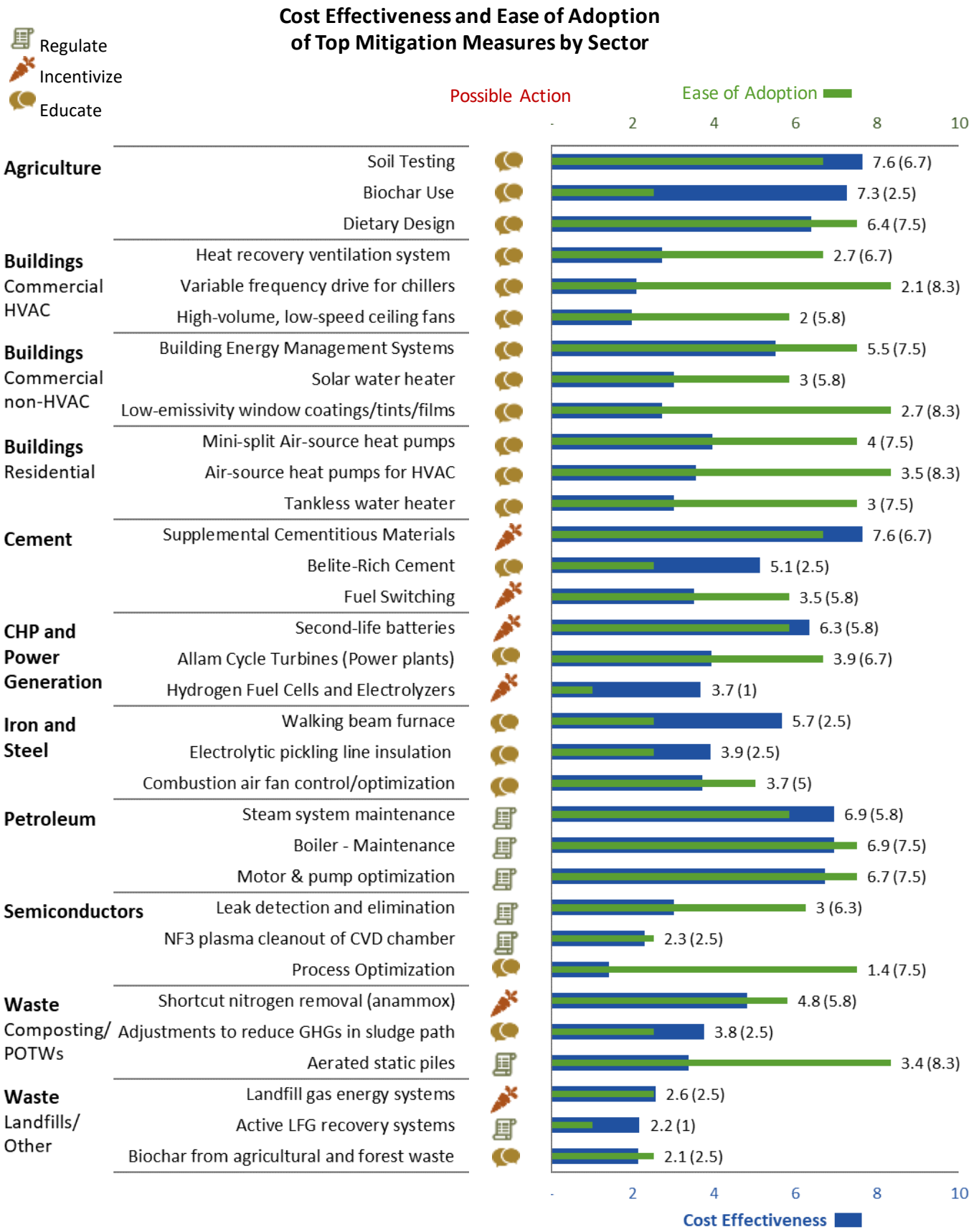


Figure ES-1. Cost Effectiveness, Ease of Adoption, and Possible Action for Top Mitigation Measures by Sector

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# 1 | Introduction

In 2017, the Bay Area Air Quality Management District (Air District) adopted a Clean Air Plan, a multi-pollutant strategy to reduce ozone, particulate matter, toxic air contaminants, and greenhouse gases (GHG). The strategy includes proposed regulations, grant and incentive programs, public education and outreach, and partnerships with other agencies and stakeholders. [2]

As part of the Clean Air Plan's vision for a post-carbon Bay Area by 2050, the Air District established the Technology Implementation Office (TIO) in 2016 to scale up technologies that reduce GHG emissions. The TIO plans to incentivize stationary sources of GHG emissions to incorporate low-carbon intensity practices across Bay Area industries. The TIO also supports deployment of zero emissions energy generation, zero emissions vehicles and infrastructure, efficiency technologies, and new smart/connected technologies.

This report describes an assessment of opportunities to reduce GHG emissions at stationary sources of air pollution in the Air District (e.g. refineries, natural gas power plants, manufacturing facilities, waste management facilities, residential and commercial buildings, etc.), as well as opportunities to scale up technologies beyond the Bay Area. Figure 1-1 compares contributions to Bay Area and national emissions from major stationary sources of air pollution.[2,3] The assessment identifies and evaluates emissions mitigation measures across a variety of key comparison variables including emissions impact potential, technology readiness, costs, and barriers to development, demonstration, and deployment.

**Relevant Emissions and Global Warming Potentials**

| Greenhouse Gas | 100 yr GWP |
|---|---|
| Carbon dioxide ($CO_2$) | 1 |
| Methane ($CH_4$) | 34 |
| Nitrous oxide ($N_2O$) | 298 |
| Hydrofluorocarbons (HFC) | 155 to 13,856 |
| Black Carbon (BC) | 1,055 to 2,240 |
| Perfluorocarbons (PFC) | 6,500 to 12,340 |
| Sulfur hexafluoride ($SF_6$) | 26,087 |

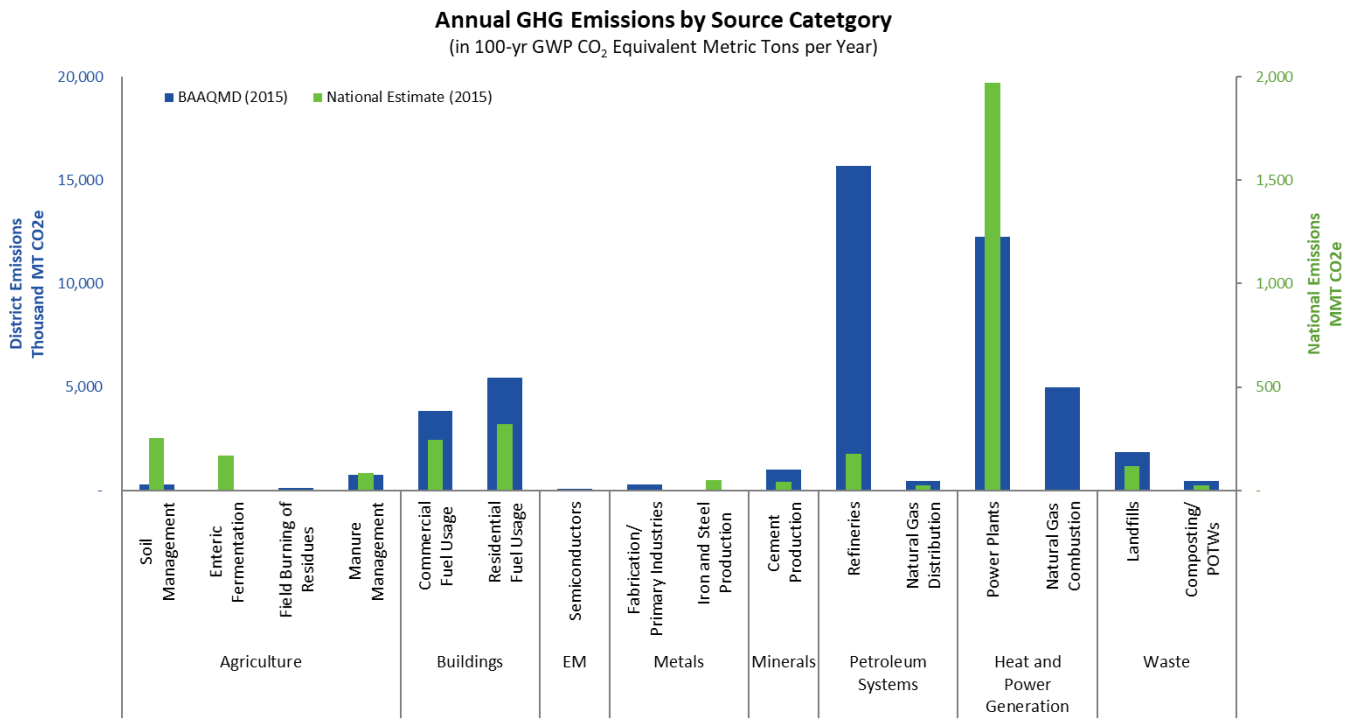



Figure 1-1. Annual GHG Emissions by Source Category

Air District estimates obtained from Table 3-2 of the 2017 Clean Air Plan and the 2015 Air District emissions inventory data set
National estimates obtained from the 2018 US EPA, "Inventory of U.S. Greenhouse Gas Emissions and Sinks"
EM = Electronics Manufacturing
POTW = Publicly Owned Treatment works

[2] "Final 2017 Clean Air Plan. Spare the Air, Cool the Climate: A blueprint for clean air and climate protection in the Bay Area." Bay Area Air Quality Management District. Adopted April 19, 2017. baaqmd.gov/~/media/files/planning-and-research/plans/2017-clean-air-plan/attachment-a_-proposed-final-cap-vol-1-pdf.pdf

[3] "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016." U.S. EPA. 2018. epa.gov/sites/production/files/2018-01/documents/2018_complete_report.pdf

# 2 | Results

This assessment identified 188 emissions mitigation measures that span the most emissions-intensive industries in the Air District. For each industry, this assessment identified three mitigation measures that were especially promising, given the Air District's goal to encourage the scale-up of emerging technologies that reduce greenhouse gas emissions (Figure 2-1).

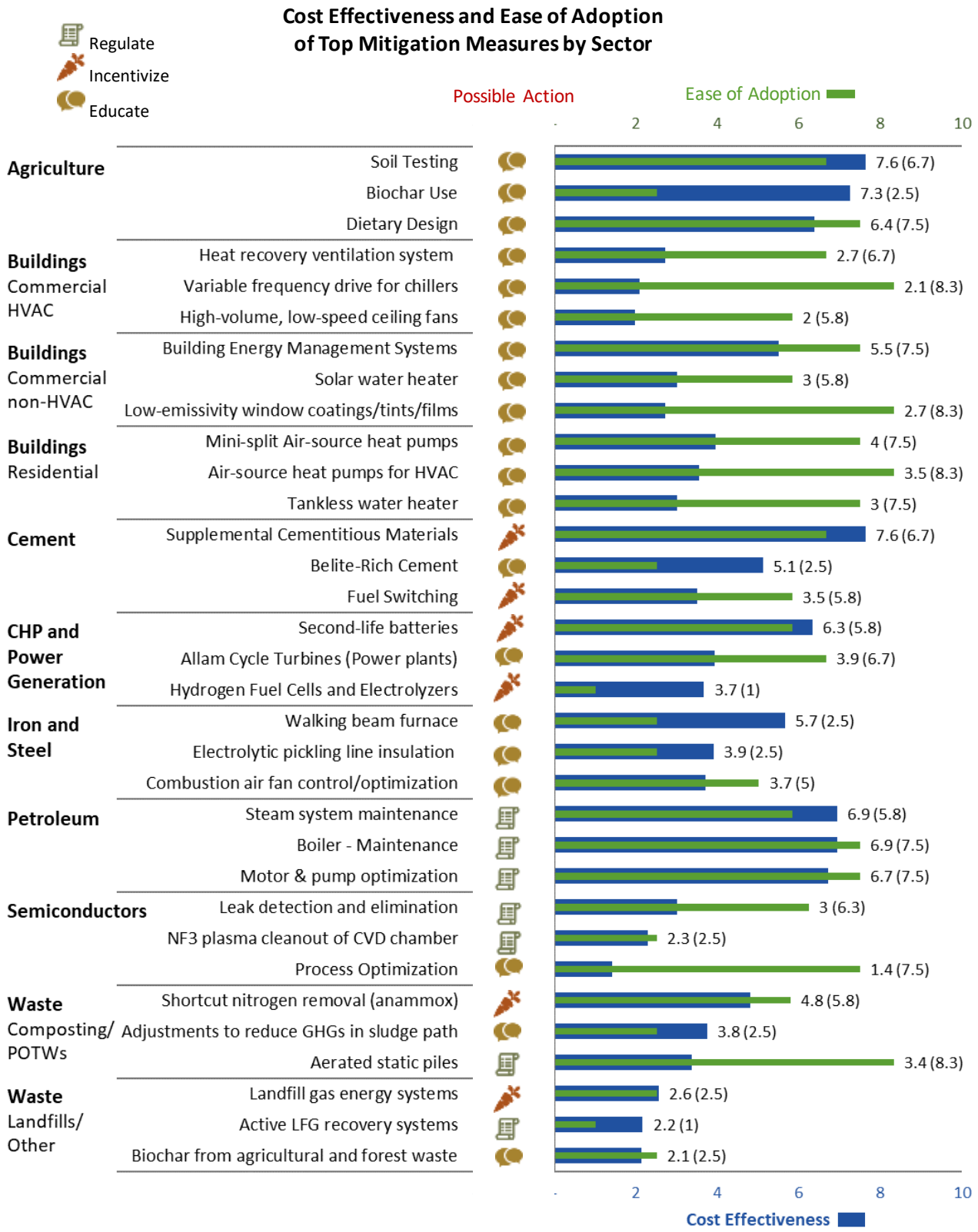



Figure 2-1. Cost Effectiveness, Ease of Adoption, and Possible Action for Top Mitigation Measures by Sector

Measures were evaluated and scored across several key comparison variables, listed below. The Cost Effectiveness score incorporates emissions reduction potential and economic viability; the Ease of Adoption score considers current technical, economic, market, and policy barriers to widespread adoption of a measure.

- **Emissions Mitigation**
  - Industry Subpart-Process emissions impact
  - District emissions impact
  - National emissions impact
- **Economics**
  - Investment Scale (per individual deployment)
  - Cost Relative to Baseline
  - Return on Investment
- **Maturity**
  - Technology Readiness Level
  - Measure Provider Maturity
- **Barriers**
  - Technical Barriers
  - Economic/Market Barriers
  - Policy Barriers

Figure 2-2 compares the technology readiness of the identified mitigation measures by industry sector. Some earlier stage technologies measures are included in this assessment; however, these are more likely to be missing cost estimates or other information. This report summarizes the results of a comprehensive MS Excel technology assessment matrix, which contains additional detail for each measure. The contents of the matrix are described in Section 4 of this report.

Many of the identified technologies have applications across several industries. For example, mitigation measures in the category of CHP and Power Generation may be highly relevant in sectors such as Petroleum and Commercial Buildings. While this report organizes measures by sector, it is also useful to compare them by technology type.

Figure 2-3 organizes the identified measures into technology categories and compares each category by the number of measures and the average cost effectiveness score for measures within that category.[4] The cost effectiveness of a mitigation measure category may vary dramatically between industries. Nevertheless, some interesting insights can be gained from reviewing the aggregate results of this assessment. For example, the emerging technologies related to cooling and heating, distributed generation, and energy storage have promising cost effectiveness scores, even relative to the emerging measures identified in energy and process efficiency. Considering the robust cost-saving and financing options that currently exist for efficiency improvements as an example, there may be opportunities for similar cost savings and incentives in other emerging categories.

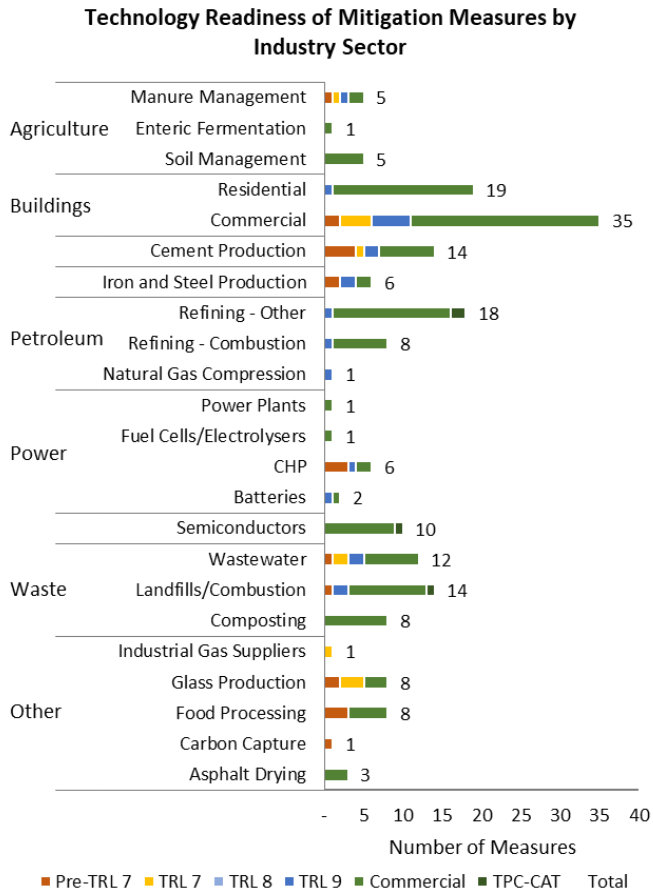
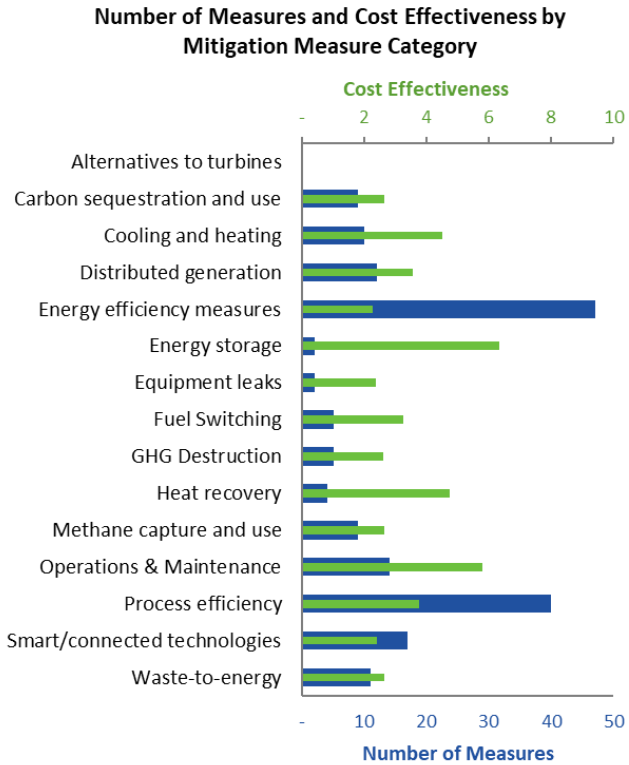



Figure 2-2. Technology Readiness of Measures by Industry Sector




[4] See section 3.3 for details on how cost effectiveness is calculated.

Following the results of this assessment, the Air District has three key strategies it can employ to promote a technology or measure: (1) **Regulate** and enforce the adoption of the technology; (2) **Incentivize** the adoption of the technology with financial aid; and (3) **Educate** and encourage adoption of the technology by performing outreach to relevant stakeholders.

Table 2 summarizes the mitigation measures that could be appropriate for regulation. These may be measures that fall within the Air District's regulatory authority and are more commercially available. Generally, these measures are highly cost effective for facilities to implement, resulting in long-term energy or cost savings without the need for market incentives. The Air District will evaluate the feasibility of developing rules around these measures.

Table 2. Mitigation Measures with Possible Regulation Action

| Mitigation Measure | Possible Action | Industry Sector |
|---|---|---|
| Aerated static piles | Regulate | Waste: Composting & POTWs |
| Active LFG recovery systems | Regulate | Waste: Landfills/Other |
| Steam trap & system maintenance | Regulate | Petroleum |
| Boiler maintenance | Regulate | Petroleum |
| Motor & pump optimization | Regulate | Petroleum |
| Leak detection and elimination | Regulate | Semiconductors |
| NF3 plasma cleanout of CVD chamber | Regulate | Semiconductors |

Table 3 identifies mitigation measures that may be appropriate for the Air District and/or partner agencies and organizations to support by providing financial incentives. Generally, these technologies have demonstrated high potential for reducing emissions at a reasonable capital investment, but are still in the demonstration phase, have a limited number of customers, or are otherwise not yet widely commercially available.

Table 3. Mitigation Measures with Possible Incentivization Action

| Mitigation Measure | Possible Action | Industry Sector |
|---|---|---|
| Shortcut nitrogen removal (anammox) | Incentivize | Waste: Composting & POTWs |
| Landfill gas energy systems | Incentivize | Waste: Landfills/Other |
| Battery backup systems | Incentivize | CHP and Power Generation |
| Hydrogen fuel cells and electrolyzers | Incentivize | CHP and Power Generation |
| Supplemental cementitious materials | Incentivize | Cement |
| Fuel switching | Incentivize | Cement |

Table 4 lists mitigation measures that the Air District may promote by conducting outreach to relevant stakeholders. These technologies tend to be readily commercially available, may already be eligible for existing robust financing opportunities, or may be a better fit for partner agency programs and authorities. For example, some of the building technologies in this list may qualify for existing incentive programs for energy efficiency.

Figure 2-3. Number of Measures and Cost Effectiveness by Category

Table 4. Mitigation Measures with Possible Education Action

| Mitigation Measure | Possible Action | Industry Sector |
|---|---|---|
| Adjustments to reduce GHGs in sludge path | Educate | Waste: Composting & POTWs |
| Biochar from agricultural and forest waste | Educate | Waste: Landfills/Other |
| Allam cycle turbines (power plants) | Educate | CHP and Power Generation |
| Belite-rich cement | Educate | Cement |
| Process optimization | Educate | Semiconductors |
| Heat recovery ventilation system | Educate | Buildings: Commercial HVAC |
| Variable frequency drive for chillers | Educate | Buildings: Commercial HVAC |
| High-volume, low-speed ceiling fans | Educate | Buildings: Commercial HVAC |
| Building Energy Management Systems | Educate | Buildings: Commercial non-HVAC |
| Solar water heaters | Educate | Buildings: Commercial non-HVAC |
| Low-emissivity window coatings/tints/films | Educate | Buildings: Commercial non-HVAC |
| Mini-split air-source heat pumps | Educate | Buildings: Residential |
| Air-source heat pumps for HVAC | Educate | Buildings: Residential |
| Tankless water heater | Educate | Buildings: Residential |
| Soil testing | Educate | Agriculture |
| Biochar use | Educate | Agriculture |
| Dietary design | Educate | Agriculture |
| Walking beam furnace | Educate | Iron and Steel |
| Electrolytic pickling line insulation | Educate | Iron and Steel |
| Combustion air fan control/optimization | Educate | Iron and Steel |

While the preceding tables suggest one key strategy for the listed measures, other strategies may also be employed in parallel. For example, it would make sense for the Air District to promote both incentives and awareness for technologies such as battery backup systems. For more measures that are more complex to implement, it may also make sense to conduct outreach on the technology while also supporting implementation with incentives along the way.

The following subsections discuss each industry and the identified mitigation measures in greater detail. Each section compares the associated mitigation measures by emissions reduction potential, economic viability, technology readiness, and technical, economic, and policy barriers.

## 2.1 | Agriculture

The agriculture end-use sector includes a variety of processes, including enteric fermentation in domestic livestock, livestock manure management, and agricultural soil management. In 2016, agricultural soil management was the largest source of $N_2O$ emissions, and enteric fermentation was the largest source of $CH_4$ emissions in the United States.[5] In 2016, the Agriculture sector was responsible for emissions of 562.6 MMT $CO_2$-e, or 8.6 percent of total U.S. GHG emissions. Methane emissions from enteric fermentation and manure management represent 25.9 percent and 10.3 percent of total $CH_4$ emissions from anthropogenic activities, respectively.[6]

The Bay Area currently has more than 8,500 agricultural operations that produce a diversity of fruits, vegetables, meat, dairy products and wines. Methane emissions from animal waste in the form of enteric fermentation and manure management account for the majority (62 percent) of GHG emissions from the agriculture sector.[7]

### Agriculture

| Prominent GHG Type(s) | $CH_4$, $N_2O$ |
|---|---|
| **Annual Emissions** | **2015** |
| **Bay Area Emissions** | (Thousand MT $CO_2$e) |
| Total | 1,390 |
| Animal waste and agriculture | 760 |
| Agriculture (other) | 630 |
| **National Process Emissions** | (MMT $CO_2$e) |
| Total | 522.3 |
| Agricultural Soil Management | 251.3 |
| Enteric Fermentation | 166.5 |
| Manure Management | 84.0 |
| Other | 20.5 |

From the 2015 BAAQMD Emissions Inventory and the 2016 U.S. EPA Emissions Inventory

### Mitigation Measure Comparison

This assessment identified 11 mitigation measures related to agriculture. Figure 2-4 compares the cost effectiveness and overall ease of adoption of the identified measures. The top measures described in this section are emerging technologies that have high potential for implementation and emissions reductions. A complete list of the identified agricultural measures and their weighted rankings across the key comparison variables is shown in Appendix C.

The top recommended measures for agriculture include soil testing, biochar use, and dietary design for livestock. These measures could help to address significant sources of agricultural emissions in the Bay Area and nationally. They

[5] "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016." U.S. EPA. 2018. epa.gov/sites/production/files/2018-01/documents/2018_complete_report.pdf

[6] 2016 emissions values from the 2016 U.S. EPA Emissions Inventory. The published report and the downloadable MS Excel tables have slightly different values, likely attributed to rounding.

[7] "Final 2017 Clean Air Plan. Spare the Air, Cool the Climate: A blueprint for clean air and climate protection in the Bay Area." Bay Area Air Quality Management District. Adopted April 19, 2017. baaqmd.gov/~/media/files/planning-and-research/plans/2017-clean-air-plan/attachment-a_-proposed-final-cap-vol-1-pdf.pdf

have relatively small initial cost and have a positive return on investment. Biochar use faces the highest barriers to deployment but could help to sequester carbon and produce higher crop yields if successfully demonstrated and applied.

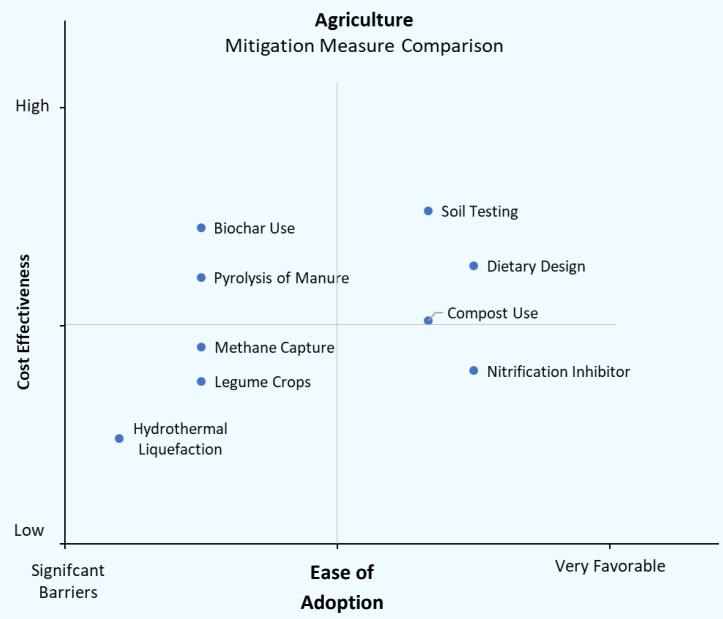



Figure 2-4. Agriculture—Mitigation Measure Comparison

2 measures not shown. See Appendix C.

## Details on Top Recommended Measures

### Soil Testing

Soil testing provides a method to monitor and optimize nitrogen and other nutrient levels. Overuse of agricultural chemicals results in runoff and leads to fugitive emissions and other adverse environmental impacts.

*Emissions:* It's estimated that the use of nitrogen fertilizers could be reduced by as much as 30% and that $N_2O$ emissions from all agricultural sources could be reduced by 3.3% with soil testing.[8] Excluding dairy farms, $N_2O$ emissions range from less than a pound per acre per year to 10 pounds per acre per year. The Bay Area emits approximately 4,600,000 pounds of $N_2O$ or 2,300 tons annually, assuming 2 pounds per acre per year over 2.3 million acres of farm land. A 30% reduction results in 690 tons of avoided $N_2O$ emissions or approximately 205,620 tons of $CO_2e$.

*Economics:* Soil testing can be done for around $10 per test or $150 per acre. The total cost depends on the size of the farm. Testing can help to reduce overapplication of fertilizer, which saves on fertilizer costs. Fertilizer cost savings can provide a rapid return on investment for testing. Testing is commercially available from established vendors.

*Barriers:* Soil testing is an established technology with low technical barriers. Testing poses no risk to farm operations and can help optimize chemical applications. Although costs can be low for testing, it can add up on larger farms which may present a barrier for some farmers. Additionally, each farmer may have different practices they are comfortable with and some may be hesitant to change. If testing is not done properly and fertilizer and chemical applications are not optimized, it could result in unintended downstream economic effects. Activities that can help to minimize nutrient runoff are supported by California policy.

### Biochar Use

Biochar is bio-derived charcoal used as a soil amendment. Biochar has a high-carbon content and therefore sequesters carbon when used as a soil amendment. It has been shown to increase agricultural productivity and increase the soil fertility of acidic soils.

*Emissions:* The most important factors contributing to avoided emissions from biochar are carbon stored as biochar in soil and fossil-fuel offset from coproduction of energy. A large benefit is also obtained due to avoided $CH_4$ emissions from biomass decomposition.[9]

*Economics:* Biochar costs approximately $30 per cubic foot and can range from $300 a ton when bought in bulk to $900 a ton for small loads. Biochar is typically applied at around 2 tons per acre. Biochar is more expensive than fertilizer and is not a direct replacement. However, it can improve soil productivity, reduce irrigation demands, and reduce fertilizer requirements which can provide an eventual return on investment.

*Barriers:* Although biochar is commercially available from established vendors, it has not been broadly used and faces several barriers to deployment. The multi-season timeframe required to observe benefits of biochar use may deter farmers. Pilot and demonstration projects may be necessary to convince farmers to change their behaviors and incorporate biochar use. Additionally, biochar availability is relatively small, and markets may be unable to rapidly respond to increases in demand. Modern, high-yield, low-emission pyrolysis technology is necessary to produce high-quality biochar. Biochar produced from traditional charcoal kilns or smoldering slash piles may negate some or all the carbon-sequestration benefits.

### Dietary Design

Enteric fermentation occurs when $CH_4$ is produced in the rumen (a multi-chambered stomach found in mammals such

[8] Verhoeven, Elizabeth, et al. "N2O emissions from California farmlands: A review." California Agriculture 71.3 (2017): 148-159. calag.ucanr.edu/Archive/?article=ca.2017a0026

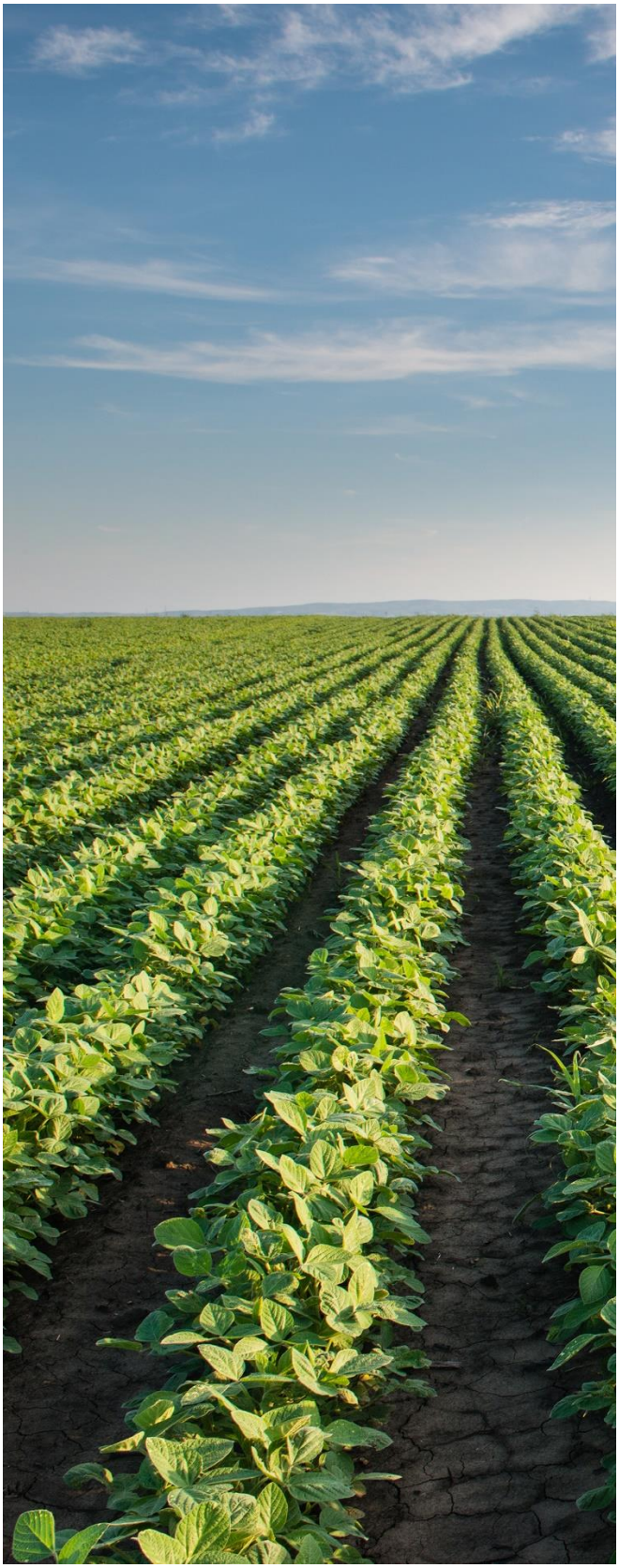
[9] Woolf, Dominic, et al. "Sustainable biochar to mitigate global climate change." Nature communications 1 (2010): 56. nature.com/articles/ncomms1053

as cattle) as microbial fermentation takes place. Dietary design for livestock can help to reduce methane and manure production.

*Emissions:* In some cases, up to a 22% reduction in $CH_4$ emissions has been demonstrated with dietary design.[10] Roughly 225 kg of methane is emitted per cow each year. The Bay Area has approximately 260,000 cows that produce 65,000 tons $CH_4$ from both enteric fermentation and manure annually. A 22% reduction could lower emissions by 14,300 tons $CH_4$ (486,000 tons $CO_2e$).[11]

*Economics:* Feed costs are the greatest expense associated with raising heifers. It follows that a reduction in feed costs could significantly contribute to decreasing the overall costs of raising dairy heifers. Dietary design could help to lower feed volumes and costs; however, it is important to ensure that there are no adverse effects on livestock health.[12]

*Barriers:* Dietary design must maintain animal nutrition. While amounts of protein and other nutrient requirements for livestock are well understood, ranchers will still need to be convinced to try dietary design approaches and may be quick to dismiss them. If dietary design can reduce livestock production costs as reported, there should be an economic incentive for ranchers to use climate-friendly feedstocks.



[10] Nampoothiri, Vinu M., et al. "Influence of Diet on Methane and Nitrous Oxide Emissions from cattle Manure." Asian Journal of Atmospheric Environment 9.3 (2015): 187-193.

[11] Fischer, Marc, and Seongeun Jeong. "Evaluating Bay Area Methane Emission Inventory." Lawrence Berkeley National Laboratory. (2016). eta.lbl.gov/sites/all/files/publications/lbnl-1006297.pdf

[12] Hill, M. et al. "Heifer Nutrition Modifications to Reduce Manure Production." PennState Extension. 2006. extension.psu.edu/heifer-nutrition-modifications-to-reduce-manure-production

## 2.2 | Buildings

Buildings generate emissions through energy use for heating, cooling, and operating the building, and from the materials used in building construction and maintenance. Energy use in buildings typically includes electricity—often produced elsewhere—as well as natural gas combustion in building furnaces, boilers, water heaters, and appliances. In addition to direct emissions from gas combustion, the buildings sector also accounts for a major share, 64 percent, of regional electricity consumption. [13]

Direct emissions from the buildings sector accounted for approximately 10 percent of Bay Area GHG emissions in 2015. Almost 70 percent of the housing units in the Bay Area were built prior to 1980, meaning that most residential structures in the Bay Area are not required to meet even the earliest energy efficiency standards. [13]

The residential and commercial end-use sectors accounted for 19 and 17 percent, respectively, of direct $CO_2$ emissions from fossil fuel combustion in 2016. Both sectors relied heavily on electricity for meeting energy demands, with 69 and 73 percent, respectively, of their emissions attributable to electricity use for lighting, heating, cooling, and operating appliances. The remaining emissions were due to the consumption of natural gas and petroleum for heating and cooking.[14]

**Buildings**

| Prominent GHG Type(s) | $CO_2$ |
|---|---|
| **Annual Emissions** | **2015** |
| **Bay Area Emissions** | (Thousand MT $CO_2e$) |
| Total | 9,270 |
| Residential | 5,450 |
| Commercial | 3,820 |
| **National Emissions** | (MMT $CO_2e$) |
| Total | 565.8 |
| Residential Fuel Usage | 319.6 |
| Commercial Fuel Usage | 246.2 |

From the 2015 BAAQMD Emissions Inventory and the 2016 U.S. EPA Emissions Inventory

### Mitigation Measure Comparison

This assessment identified 54 mitigation measures related to buildings. Figure 2-5 and Figure 2-6 compare the cost effectiveness and overall ease of adoption of the identified measures, organized by commercial and residential. The top measures described in this section are emerging technologies that have high potential for implementation and emissions reductions. A complete list of the identified

[13] "Final 2017 Clean Air Plan. Spare the Air, Cool the Climate: A blueprint for clean air and climate protection in the Bay Area." Bay Area Air Quality Management District. Adopted April 19, 2017. baaqmd.gov/~/media/files/planning-and-research/plans/2017-clean-air-plan/attachment-a_-proposed-final-cap-vol-1-pdf.pdf

[14] "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016." U.S. EPA. 2018. epa.gov/sites/production/files/2018-01/documents/2018_complete_report.pdf

building measures and their weighted rankings across the key comparison variables is shown in Appendix C.

The buildings measures are divided into commercial (non-HVAC and HVAC separately) and residential. The Top recommended commercial (non-HVAC) measures include building energy management systems, low-emissivity window coatings/tints or films, and solar water heating. Commercial HVAC is the most significant source of building energy consumption. Top measures to reduce energy consumption and associated emissions for commercial HVAC include heat recovery ventilation (HRV) system, variable frequency drive (VFD) for chillers, and high-volume, low-speed (HVLS) ceiling fans. Top identified measures to address residential emissions include mini-split air-source heat pumps (ASHP), ASHPs for HVAC, and tankless water heaters.

Buildings mitigation measures offer relatively small savings in terms of percent reduction of overall building energy usage. However, due to the scale of emissions from the buildings sector, these measures can result in very large emissions reductions. Many identified measures are commercially available and proven technologies with energy savings that can pay back up-front capital investments. There is a plethora of technologies available that can make a meaningful impact on buildings energy consumption and emissions. It may require a case-by-case evaluation of a building location and owner preference to determine which measure is best suited to a given application.

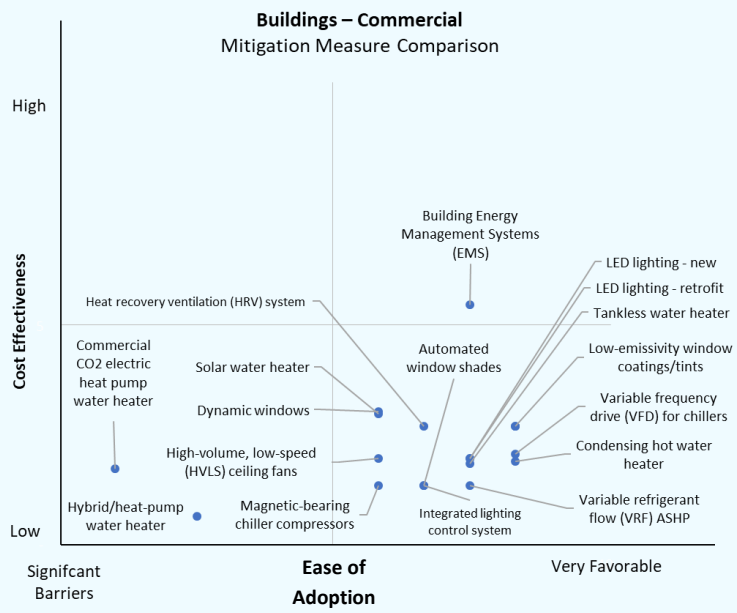



Figure 2-5. Commercial Buildings—Mitigation Measure Comparison

17 commercial building measures not shown. See Appendix C.

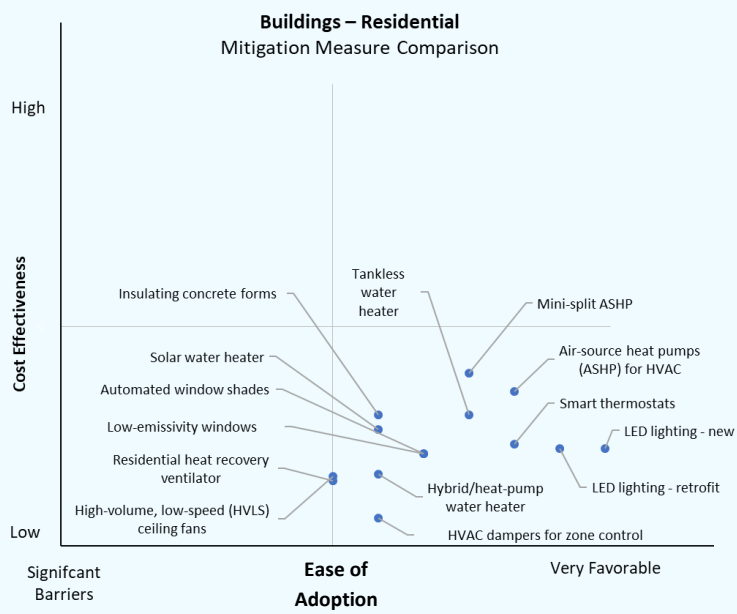



Figure 2-6. Residential Buildings—Mitigation Measure Comparison

5 residential building measures not shown. See Appendix C.

## Details on Top Recommended Commercial (non-HVAC specific) Measures

In line with the scope of work for this project, the top recommended measures focus on less well-known opportunities for emissions reductions. LED lighting, however, deserves note as a highly common and effective mitigation measure. Although not described in greater detail in the subsequent sections, LED lighting can reduce energy consumption and indirect emissions and provide a rapid return on investment for building owners. LED lighting should always be considered as a best practice for new buildings and energy retrofits.

### Building Energy Management Systems (EMS)

Building energy management systems (EMS) use a comprehensive suite of sensors and monitoring; utility, lighting, and temperature controls; building envelope thermal models; and active software controls to maximize the efficiency of building systems that use energy and reduce the net energy load across day/night, week/end, and seasonal cycles.

*Emissions:* EMS for artificial lighting systems has the highest saving effect up to 39% in average. For HVAC and other equipment, energy saving effects are around 14% and 16%

respectively.[15] These energy savings can reduce emissions from electricity generation and natural gas usage.

*Economics:* EMS costs range from $2.50-$7 per sqft. Assuming an average building size of 14,000 sqft, system costs can range from $35k-$98k. Energy savings can enable a rapid return on investment.

*Barriers:* EMS are commercially competitive, with various scopes of implementation (i.e., HVAC, lighting, refrigeration, water, process equipment, and combinations thereof). Rented spaces have a disincentive to upgrade unfortunately, as there is a disconnect between who pays for the system and who receives the benefits of lower energy costs. EMS can be difficult for small businesses and commercial spaces to implement due to the high upfront costs. In general, existing policy creates a favorable environment for EMS.

### Low-emissivity window coatings/tints or films

Low-emissivity window coatings/tints or films reduces the transmittance of solar heat radiation through a window either by reflecting infrared radiation and/or by reducing the infrared emissivity of window glass. This be achieved with window coating (sputtered or pyrolytic) or tints (bronze or other inorganics added to glass) applied directly during manufacture or glazing, or with tinted plastic films applied as a retrofit measure.

*Emissions:* Window coatings/tints or films can reduce HVAC load by up to 21%, which is significant considering that HVAC load can be 34% or more of building energy use.[16] These energy savings can indirectly reduce emissions from electricity generation and natural gas usage.

*Economics:* Coatings and tints applied directly during manufacturing can add 12-14% in cost compared to standard window glass.[16] Films can cost about $5/sqft or $70k for a 14,000 sqft building.[17] Energy savings can enable a rapid return on investment.

*Barriers:* Like EMS, window coatings/tints, or films are commercially available from robust vendors. Windows can easily be selected for new builds or retrofitted on existing buildings. There is also an economic incentive for building owners to implement the measure. Also, like EMS, that incentive may be lesser or non-existent for rented spaces.

### Solar water heating

Solar water heaters help to minimize energy use by pre-heating intake water using exterior heat panels.

*Emissions:* Solar water heaters can achieve up to a 50% reduction in building water heating load.[18] Water heating can account for 10% of building energy use, which for a 14,000 sqft building can equate to approximately 30 MWh/yr.[19] Energy savings from solar water heating can reduce emissions from electricity generation and natural gas usage.

*Economics:* Solar water heating comes at a cost premium over a standard gas tank water heater. The solar water heater may provide small annual operational savings. However, the savings may not offset the higher upfront system costs assuming a product lifetime of 24 years.

*Barriers:* Solar water heating can be widely deployed, however there may be limitations due to solar resource availability by geography. The measure is a relatively low-cost investment, but due to a lack of return on investment may be difficult to convince a building owner to deploy.

## Details on Top Recommended Commercial (HVAC specific) Measures

HVAC systems account for about 34.2% of commercial building energy use.[19] Mitigation measures that focus specifically on addressing HVAC systems can help to indirectly reduce emissions from electricity generation and directly from natural gas usage.

### Heat recovery ventilation (HRV) system

HRV saves energy by using a heat exchanger to pre-heat or cool fresh exterior air using interior air as it's exhausted.

*Emissions:* HRV energy reduction potential is reported across a broad range, with about a 30% reduction in building HVAC emissions as the median.[20]

*Economics:* HRV systems vary in cost depending on the size of unit and can range from $1,900 - $12,000. The systems are commercially available from robust companies. Properly sized and implemented systems should enable an eventual return on investment.

*Barriers:* Proper sizing and design is the main barrier to greater deployment of HRV systems. Buildings have an economic incentive to adopt the mitigation measure, however the incentive may be lesser for rented spaces.

### Variable frequency drive (VFD) for chillers

VFDs allows chiller compressor to run at variable speeds. This helps to optimize chiller performance for thermal loads and reduces waste.

[15] Lee, Dasheng, and Chin-Chi Cheng. "Energy savings by energy management systems: A review." Renewable and Sustainable Energy Reviews 56 (2016): 760-777.

[16] Culp, TD and Cort, KA. "Energy Savings of Low-E Storm Windows and Panels across US Climate Zones." Pacific Northwest National Laboratory. October 2015.

[17] Debusk, S. "New Low-e Glass or Window Film? A Comparison to Help You Decide." Buildings.com. June 25, 2012.

[18] Wentzel, B. "Water Heating for Commercial & Industrial Facilities." UGI. (2013). ugi.com/wp-content/uploads/2015/08/2013_CommercialWaterHeaterWebinar.pdf

[19] "Commercial Buildings Energy Consumption Survey (CBECS). U.S. Energy Information Administration. (2012). eia.gov/consumption/commercial/data/2012/

[20] Quinell, J. "Energy Recovery in Minnesota." Center for Energy and Environment. April 2017. mn.gov/commerce-stat/pdfs/card-report-cee-erv-practical.pdf

*Emissions:* VFDs can reduce cooling energy use by up to 30%.[21] Cooling load accounts for about 6.7% of building energy use.[19]

*Economics:* VFDs are commercially available from robust companies. Depending on the building, VFDs can achieve significant energy and cost savings. In one implementation, a $45,000 VFD installed in a 100,000 square foot facility realized a payback period of 1 year.[22] Assuming linear scaling of costs, a VFD for a 14,000 sqft commercial building may cost about $6,300, including installation.

*Barriers:* VFDs have low barriers to market and are seeing rapid deployment in new buildings. Commercial buildings have an economic incentive to adopt VFDs. In general, existing policy creates a favorable environment for VFDs.

### High-volume, low-speed (HVLS) ceiling fans

HVLS ceiling fans are high-efficiency ceiling fans that increase comfort through air movement, reducing HVAC loads and creating energy savings. They can vary in size and are best suited to large open spaces such as warehouses, gyms, stadiums, and airports.

*Emissions:* According to some vendors, HVLS ceiling fans can reduce building HVAC load by up to 30%.[23]

*Economics:* Costs can range from $3,000-$9,000 per fan.[23] Two fans can provide coverage for a large, open, 14,000 sqft space at about $10,000 in total cost.

*Barriers:* HVLS fans have moderate barriers to deployment as they are limited to large, open spaces. In the right applications they can provide an economic incentive for adoption.

## Details on Top Recommended Residential Measures

### Mini-split air-source heat pumps (ASHP)

Mini-split ASHPs allow the efficiency of ASHP cooling/heating to be retrofitted into older residential applications. Mini-splits allow for cooling and heating of individual zones, which can improve operations efficiency for intermittent loads.

*Emission:* Residential heating and cooling accounts for about 28% and 5% of residential energy use respectively.[24] Mini-split ASHPs can achieve a 50% reduction in heating energy compared to traditional electric resistance heating such as furnaces and baseboard heaters,[25] and a 30% reduction in cooling energy use.[26]

*Economics:* Mini-split ASHPs are cost competitive to traditional heat pumps. They can provide compelling energy and cost savings to residential home owners.

*Barriers:* Mini-split ASHPs are commercially available but are not very common. They are becoming an increasingly available and deployed technology.

### Air-source heat pumps (ASHP) for HVAC

ASHPs are a well-established technology for cooling and heating. They use exterior condenser units and interior air handlers to cool (or heat) interior air. Ducted systems distribute air throughout the home. ASHPs offer improved efficiency over window unit air conditioning.

*Emissions:* ASHPs can achieve more than 46% GHG emissions performance savings compared to baseline heating technologies.[27]

*Economics:* ASHPs are available in the Bay Area at a cost premium (~$6,450) over a traditional furnace ($4,800).[28] However, they provide energy and cost savings to residential home owners that may incentive the investment.

*Barriers:* Barriers to ASHP deployment are low. ASHPs are commercially widespread provide an economic incentive for home owners.

### Tankless water heaters

Tankless water heaters improve energy efficiency by heating water on demand, rather than relying on a storage tank of preheated water. Efficiency gains depend on the building situation and are greatest with intermittent water demand.

*Emissions:* Water heating accounts for about 10% of building energy use.[24] Tankless water heaters can achieve a 20% reduction in building water heating load.[29]

*Economics:* Tankless water heaters have a cost premium of about $950 vs standard gas tank water heater. They can achieve operational savings of about $100 per year and avoid the need for costly replacements.

*Barriers:* Tankless water heaters are commercially widespread and have low barriers to deployment. Some utilities even offer incentives for homes to switch to tankless water heaters.

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[21] "Chiller Best Practices VSD." Johnson Controls. Published in Chiller and Cooling Best Practices. (2017). johnsoncontrols.com/buildings/hvac-equipment/chillers/variable-speed-drives/chiller-best-practices-vsd

[22] "Improve Chiller Performance with Variable Frequency Drives." Hoosier Energy. members.questline.com/Article.aspx?articleID=28514&accountID=196000&nl=18197

[23] "HVLS Fans: Energy Efficiency & Occupant Comfort." MarcroAir. 2016. pdfs.semanticscholar.org/presentation/8d37/32e65abbedfdf7e11ce1397f63400558ef4d.pdf

[24] "Residential Energy Consumption Survey (RECS)." U.S. DOE Energy Information Administration. eia.gov/consumption/residential/data/2015/

[25] "Heat Pump Systems." U.S. Department of Energy. energy.gov/energysaver/heat-and-cool/heat-pump-systems

[26] "Ductless Mini-Split Air Conditions." U.S. Department of Energy. energy.gov/energysaver/ductless-mini-split-air-conditioners

[27] Ryan, W. "Carbon Emission Comparison Between Residential Heating and Cooling Options." Energy Solutions Center. energysolutionscenter.org/assets/1/Page/GHP_Position_Paper_and_apndx_031710.pdf

[28] "How much do heat pumps cost to install or replace?" Home Advisor. homeadvisor.com/cost/heating-and-cooling/install-a-heat-pump/#cost

[29] Ries, R. et al. "Assessing the Energy Savings of Tankless Water Heater Retrofits in Public Housing." U.S. DOE. (2013). nrel.gov/docs/fy13osti/55623.pdf

## 2.3 | Cement Production

Cement production involves kilns at facilities that manufacture Portland cement, which is the basic ingredient of concrete, mortar, stucco, and most non-specialty grout. During the cement production process, calcium carbonate ($CaCO_3$) (usually from limestone and chalk) is combined with silica-containing materials (such as sand and shale) and is heated, or calcined, in a cement kiln at a high temperature. The calcination process produces $CO_2$ as a by-product, and the $CO_2$ is released to the atmosphere.[30]

$CO_2$ emitted from cement production is the second largest source of industrial $CO_2$ emissions in the United States. [31] There is one cement manufacturing facility in the Bay Area. The kiln at the facility in the Air District is heated using a combination of coke (92% of combustion emissions) and natural gas.[32]

**Cement**

| Prominent GHG Type(s) | $CO_2$ |
|---|---|
| **Annual Emissions** | **2015** |
| **Bay Area Emissions** | (Thousand MT $CO_2e$) |
| Total | 990 |
| Process Emissions | ~626 |
| Combustion Emissions | ~382 |
| **National Process Emissions** | (MMT $CO_2e$) |
| Total | 39.9 |

From the 2015 BAAQMD Emissions Inventory and the 2016 U.S. EPA Emissions Inventory. 2015 emissions values from the BAAQMD published report are less than the combined process emissions and combustion emissions provided as part of this project.

### Mitigation Measure Comparison

This assessment identified 14 mitigation measures related to cement production. Figure 2-7 compares the cost effectiveness and overall ease of adoption of the identified measures. The top measures described in this section are emerging technologies that have high potential for implementation and emissions reductions. A complete list of the identified cement production measures and their weighted rankings across the key comparison variables is shown in Appendix C.

The top recommended measures for cement production include supplemental cementitious materials (SCM), belite-rich cement, and fuel switching. These measures could help address a significant source of emissions in the Bay Area. Any process changes will need to be implemented in close collaboration with the one operating cement production facility in the Air District.

[30] "GHGRP Minerals Sector Industrial Profile." U.S. EPA. 2012. epa.gov/ghgreporting/ghgrp-minerals-sector-industrial-profile

[31] 2016 emissions values from the 2016 U.S. EPA Emissions Inventory. The published report and the downloadable MS Excel tables have slightly different values, likely attributed to rounding.

[32] "Final 2017 Clean Air Plan. Spare the Air, Cool the Climate: A blueprint for clean air and climate protection in the Bay Area." Bay Area Air Quality Management District. Adopted April 19, 2017. baaqmd.gov/~/media/files/planning-and-research/plans/2017-clean-air-plan/attachment-a_-proposed-final-cap-vol-1-pdf.pdf

## Details on Top Recommended Measures

### Supplemental Cementitious Materials (SCM)

(either Fly Ash SCM and Slag SCM)

Several materials, especially fly ash and ground granulated blast furnace slag are increasingly being used as partial substitutes for Portland cement in many concrete applications.

*Emissions:* SCMs have been touted for enabling a cement system with a virtually zero carbon footprint, 95% reduction in the use of virgin resources.[33] Fly ash can be used as a replacement for Portland cement at a rate of 15% to 40% by mass.[34]

*Economics:* Portland cement costs can vary from around $150-250 per ton. This compares to lower for fly ash at approximately $50 and slag at around $35 per ton. SCMs will typically have added transportation costs but may still be economically viable for cement producers to incorporate.

*Barriers:* SCMs present low technical barriers to deployment. They have been used as a supplemental material for various applications for decades. However, widespread use requires cement producers to be willing to explore the viability of incorporating SCM into their processes. Fly ash supply may decrease in the future if electric power utilities continue to transition away from coal. Likewise, slag supply relies on steel manufacturing and cement producers largely rely on international suppliers.

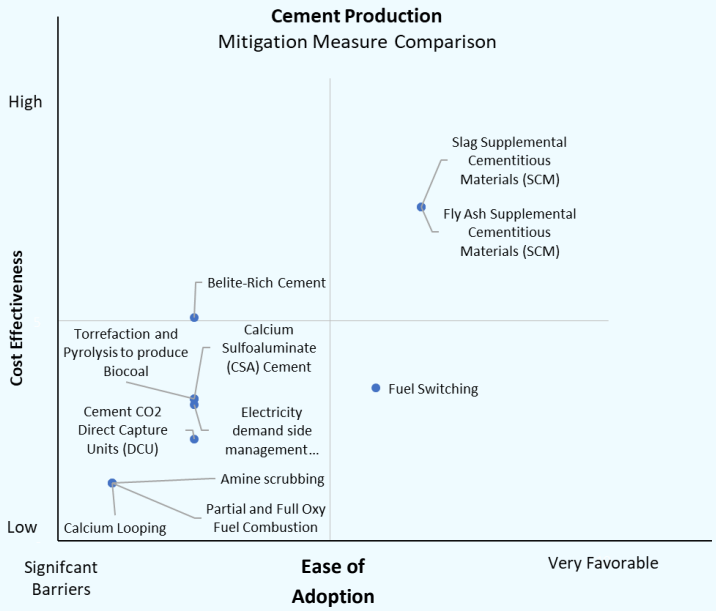



Figure 2-7. Cement Production—Mitigation Measure Comparison

2 measures not shown. See Appendix C.

### Belite-Rich Cement

Calcium silicate phases, alite and belite, are among the main components of modern Portland cement. Alite reacts rapidly and allows the construction industry to work quickly. Belite is less reactive than alite cement at early ages but can contribute appreciably to strength at later ages.

*Emissions:* The manufacture of cements with higher alite contents produces higher associated $CO_2$ emissions from calcination. Cements with higher belite contents can be manufactured at lower temperatures and with a reduced environmental impact. According to one study, belite-only cement can reduce emissions by around 10% compared to traditional processes.[35]

*Economics:* Prices vary based on exact make-up of the cement. Belite-rich cements that use most of the same materials as traditional cement require less heat and obtain lower costs. Belite-rich cements with material additives, such as calcium sulfoaluminate (CSA), can be more expensive than traditional cement products.

*Barriers:* Belite-rich cements have high barriers to deployment. They have been used in some notable projects such as the Three Gorges Dam. However, belite-rich cement can slow construction operations and the economics may vary on a case-by-case basis, which may limit broader use.

### Fuel Switching

Most cement manufacturers use coal or other heavily polluting fuels in their kilns. Switching to natural gas, biogas, or other alternative clean burning replacements can help to reduce emissions from cement production.

*Emissions:* Switching from coal to natural gas can help to reduce emissions by as much as 40%. Coal and petroleum coke account for nearly three quarters of total heat supply for cement production in the United States.[36]

*Economics:* There may be an economic incentive to switch fuels depending on the available fuel resources. However, coal tends to be the cheapest fuel available in geographies without a cost on carbon.

*Barriers:* Fuel switching presents a low risk to cement producers. Adverse changes to product performance or process reliability are unlikely due to fuel switching. However, fuel switching may require some process reconfiguration or equipment changes.

[33] "CeraTech Establishes New Standard for Green Sustainable Cement." Market Wired. (2014) marketwired.com/press-release/ceratech-establishes-new-standard-green-sustainable-cement-epd-verifies-lowest-carbon-1880280.htm

[34] Hanson, K. "SCMSs in Concrete." National Precast Concrete Association. (2017). precast.org/2017/03/scms-in-concrete/

[35] "Eco-efficient cements: Potentially economically viable solutions for a low-$CO_2$ cement-based materials industry." UN environment. (2017). wedocs.unep.org/bitstream/handle/20.500.11822/25281/eco_efficient_cements.pdf?sequence=1&isAllowed=y

[36] "2013 Minerals Yearbook." USGS. (2013) minerals.usgs.gov/minerals/pubs/commodity/cement/myb1-2013-cemen.pdf

## 2.4 | CHP and Power Generation

Electricity generators used 33 percent of U.S. energy from fossil fuels and emitted 36 percent of the $CO_2$ from fossil fuel combustion in 2016. Electric power accounted for the second largest portion (28.4 percent), while emissions from industry accounted for the third largest portion (21.6 percent) of total U.S. GHG emissions in 2016.[37]

The energy sector currently accounts for an estimated 14 percent of total Bay Area GHG emissions. The GHGs emitted by the energy sector are dominated by $CO_2$, representing approximately 99 percent of all GHGs emitted by the sector, with $CH_4$ and $N_2O$ emitted in far smaller quantities.[38]

### Mitigation Measure Comparison

This assessment identified 10 mitigation measures related to CHP and power generation. Figure 2-8 compares the cost effectiveness and overall ease of adoption of the identified measures. The top measures described in this section are emerging technologies that have high potential for implementation and emissions reductions. A complete list of the identified measures and their weighted rankings across the key comparison variables is shown in Appendix C.

Common renewable sources of distributed generation, such as solar and wind power, were out of scope for this assessment. It is worth noting that renewable resources have seen large cost reductions and performance improvements in recent years. Energy storage systems are also improving rapidly. Renewable power generation plus storage may greatly accelerate the decarbonization of U.S. electric grids.

As per the scope of work for this project, the top recommended measures focus on emerging opportunities

**Power Generation**

| Prominent GHG Type(s) | $CO_2$ |
|---|---|
| **Annual Emissions** | **2015** |
| **Bay Area Emissions** | (Thousand MT $CO_2e$) |
| Total | 12,240 |
| Co-Generation | 5,880 |
| Electricity Generation | 5,080 |
| Electricity Imports | 1,280 |
| **National Electricity Emissions** | (MMT $CO_2e$) |
| Total | 1,937.5 |
| Industry | 519.2 |
| Transportation | 3.8 |
| Commercial | 676.0 |
| Residential | 697.5 |
| Agriculture | 41.0 |

From the 2015 BAAQMD Emissions Inventory and the 2016 U.S. EPA Emissions Inventory

[37] "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016." U.S. EPA. 2018. epa.gov/sites/production/files/2018-01/documents/2018_complete_report.pdf

[38] "Final 2017 Clean Air Plan. Spare the Air, Cool the Climate: A blueprint for clean air and climate protection in the Bay Area." Bay Area Air Quality Management District. Adopted April 19, 2017. baaqmd.gov/~/media/files/planning-and-research/plans/2017-clean-air-plan/attachment-a_-proposed-final-cap-vol-1-pdf.pdf

for emissions reductions. The top recommended measures include second life batteries, hydrogen fuel cells and electrolyzers, and Allam Cycle Turbine power plants. These measures could complement renewables and other forms of low carbon power generation and storage.

## Details on Top Recommended Measures

### Second-life batteries

Second-life batteries (i.e., those previously used for another purpose such as electric vehicles EVs) can be repurposed to diesel generators. They can support a variety of uses such as off-grid events, construction sites, and EV charging.[39]

*Emissions:* Second-life batteries produce zero emissions and can displace significant particulate matter when compared to diesel generators.

*Economics:* Second-life battery systems come at a cost premium (~$35,000) compared to a similar sized diesel generator (~$28,000). However, lower operating costs for the second-life battery systems provide an expected payback between 2-3 years.

*Barriers:* The most significant barrier to success is cost followed by regulatory issues. The technology and vendors are still very young and higher production levels are needed to lower costs and achieve economies of scale. Consumers are hesitant to switch from their current systems and may need to be educated regarding their available options. Additionally, second-life batteries are not considered in many energy policies and are ineligible for most incentives.

### Hydrogen Fuel Cells and Electrolyzers

Renewable hydrogen generation and fuel cell vehicles can significantly displace vehicle emissions. Hydrogen fuel cells also can provide a long-term energy storage option.[40]

*Emissions:* Electrolyzers can use excess renewable electricity generation to produce hydrogen with zero fossil-fuel emissions. Fuel cell vehicles and storage systems only produce water vapor.

*Economics:* There is a significant premium for using hydrogen as fuel vs stationary electricity generation. At current prices stationary fuel cells are more expensive than battery systems. However, fuel cells are better suited longer-term energy storage (i.e., more than a few hours) than batteries.

*Barriers:* Fuels cells have very high barriers to widespread deployment. Although several commercial deployments have proven the efficacy of the technology in both storage and vehicle fuel applications, markets are either very small in the case of demand for fuel cell vehicles or very restrictive in the case of energy storage applications.

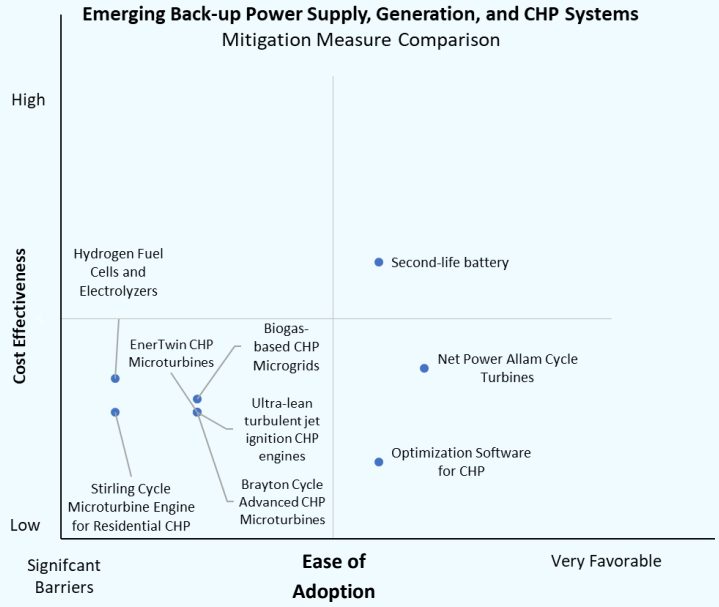



Figure 2-8. Power Generation—Mitigation Measure Comparison

1 measure not shown. See Appendix C.

### Allam Cycle Turbines

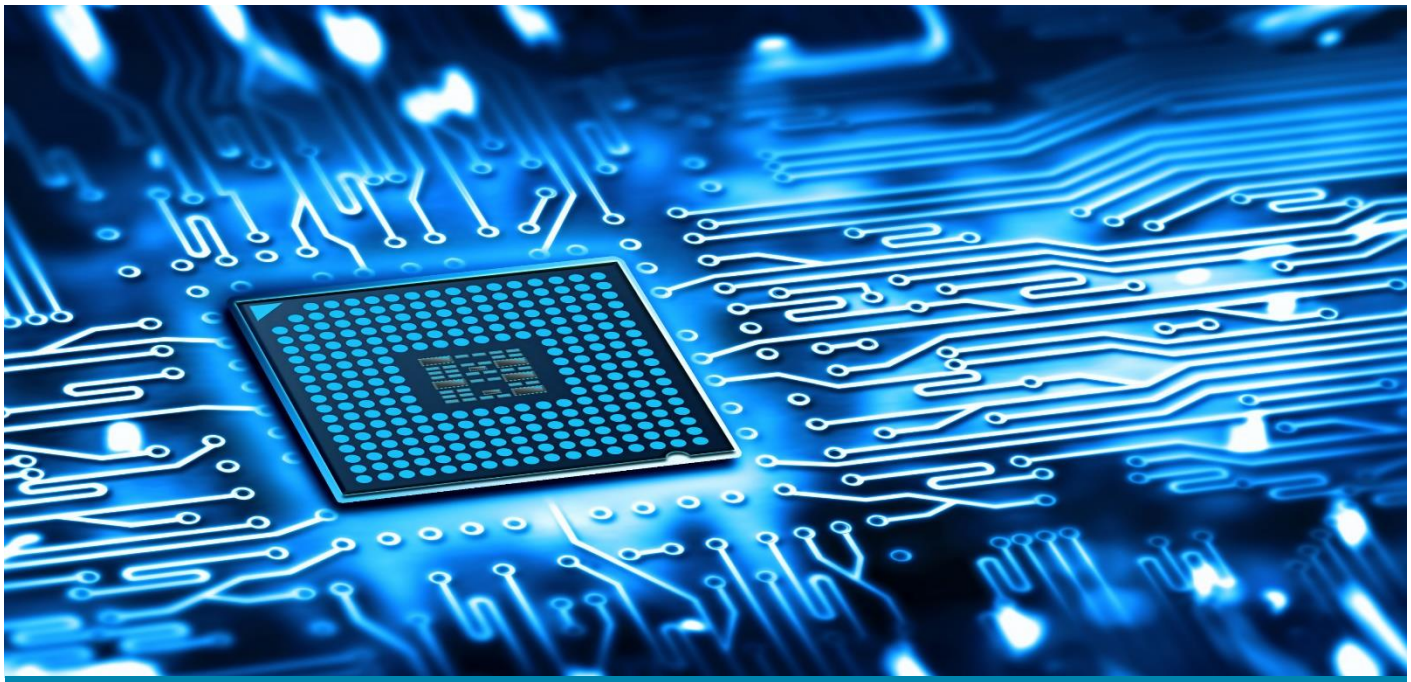
The Allam Cycle uses a high-pressure, recuperative, oxyfuel, supercritical $CO_2$ cycle that makes carbon capture part of the core power generation process.[41]

*Emissions:* $CO_2$ produced by combustion in the Allam Cycle is recycled back to the combustor multiple times producing a working fluid that is mostly pure, high-pressure $CO_2$. The Allam Cycle also uses an oxy-combustion process to virtually eliminate $NO_x$ production. The technology claims a superior efficiency and heat rate to traditional natural gas fired power generation. As a semi-closed loop, has control over the emissions streams from the plant.

*Economics:* Allam Cycle power plants have a high cost of deployment on par with traditional natural gas fired power plants but have compelling project economics. Industrial gases captured in the process are sold to generate revenue in addition to that from electricity sales. Additionally, updates to the 45Q Tax Credit provide $35 a ton by 2026 for $CO_2$ for enhanced oil recovery and $50 per ton by 2026 for direct injection projects.[42]

*Barriers:* There are moderate barriers anticipated with Allam Cycle power generation. The first demonstration plant is under construction currently and is being supported by several highly robust and experienced engineering and power generation firms.

[39] Freewire Technologies. freewiretech.com/ev-charging/
[40] ITM Power. itm-power.com/about/technology
[41] Net Power. netpower.com/technology/
[42] Merchant, E. "Can Updated Tax Credits Bring Carbon Capture Into the Mainstream?" GreenTech Media. (2018). greentechmedia.com/articles/read/can-updated-tax-credits-make-carbon-capture-mainstream



## 2.5 | Electronics—Semiconductor Manufacturing

The semiconductor industry uses multiple GHGs in its manufacturing processes. These include long-lived fluorinated GHGs used for plasma etching and chamber cleaning, fluorinated heat transfer fluids used for temperature control and other applications, and nitrous oxide ($N_2O$) used to produce thin films through chemical vapor deposition. The gases most commonly employed in plasma etching and chamber cleaning are trifluoromethane (HFC-23 or $CHF_3$), perfluoromethane ($CF_4$), perfluoroethane ($C_2F_6$), nitrogen trifluoride ($NF_3$), and sulfur hexafluoride ($SF_6$), although other fluorinated compounds are also used.

For 2016, total GWP-weighted emissions of all fluorinated GHGs and $N_2O$ from deposition, etching, and chamber cleaning processes in the U.S. semiconductor industry were estimated to be 5.0 MMT $CO_2$-e.[43] PFCs from semiconductor manufacturing accounted for less than 1% of Air District emissions in 2015.[44]

**Semiconductor Manufacturing**

| Prominent GHG Type(s) | PFCs, $SF_6$, $NF_3$ |
|---|---|
| **Annual Emissions** | **2015** |
| **Bay Area Emissions** | (Thousand MT $CO_2$e) |
| Semi-conductor factories | 90 |
| **National Process Emissions** | (MMT $CO_2$e) |
| Semiconductor manufacture | 5.0 |
| PFCs | 3.1 |
| $SF_6$ | 0.7 |
| $NF_3$ | 0.6 |
| $N_2O$ | 0.3 |
| HFCs | 0.3 |

From the 2015 BAAQMD Emissions Inventory and the 2016 U.S. EPA Emissions Inventory

### Mitigation Measure Comparison

This assessment identified 10 mitigation measures related to semiconductor manufacturing. Figure 2-9 compares the cost effectiveness and overall ease of adoption of the identified measures. The top measures described in this section are emerging technologies that have high potential for implementation and emissions reductions. A complete list of the identified measures and their weighted rankings across the key comparison variables is shown in Appendix C.

The top recommended measures for semiconductor manufacturing include leak detection and elimination, process optimization, and remote plasma cleanout of CVD chamber using $NF_3$. These measures could help mitigate high-GWP GHG emissions, albeit from a small overall source of Bay Area emissions.

[43] "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016." U.S. EPA. 2018. epa.gov/sites/production/files/2018-01/documents/2018_complete_report.pdf

[44] "Final 2017 Clean Air Plan. Spare the Air, Cool the Climate: A blueprint for clean air and climate protection in the Bay Area." Bay Area Air Quality Management District. Adopted April 19, 2017. baaqmd.gov/~/media/files/planning-and-research/plans/2017-clean-air-plan/attachment-a_-proposed-final-cap-vol-1-pdf.pdf

## Details on Top Recommended Measures

### Leak detection and elimination

Fluorocarbons (FCs) are widely used in the semiconductor industry in dry processing applications such as film etching, chemical vapor deposition (CVD), chamber cleaning, and as coolants for semiconductor manufacturing tools. Detection and measurement of FCs is key to process control, safety, emissions reductions.[45]

*Emissions:* Eliminating fugitive emissions not only helps to mitigate the release of high-GWP GHG emissions into the atmosphere but can improve semiconductor production processes. Commercially available leak detectors are highly sensitive and can help manufactures to nearly eliminate leaks from their processes.[46]

*Economics:* Reduction costs are estimated around $1 per ton of $CO_2e$ reduced. Equipment installation can increase the cost per emissions reduction.[47]

*Barriers:* Leak detectors are a mature technology with a market penetration as high as 93% in the U.S. Barriers to firms not already using leak detectors should be low, as there are widely available and can improve production processes. Fluorinated gas emission reduction policies may determine whether firms will take on additional costs for more sophisticated leak detection and elimination technologies.[47]

### Process optimization

Measures that include installing sensors and control systems and adjusting process parameters—such as chamber pressure, temperature, plasma power, cleaning gas flow rates, gas flow time, and gas ratios— for the etching and CVD processes. These measures can help to minimize waste gas volumes, high-GWP waste gas concentrations, and/or maximize high-GWP gas decomposition.

*Emissions:* Process optimization, sensors, and control systems allow semiconductor producers to improve efficiencies and address issues where detected. Emissions could be reduced by 1-5%.

*Economics:* Process optimization is specific to each plant and process and the amount of equipment and overall cost is dependent on size of the plant.

*Barriers:* Process optimization faces low barriers to deployment. The effectiveness will be unique to each plant and vary on a case-by-case basis. The plants stand to gain from operational efficiencies and a reduction in high-GWP GHG emissions serves as a bonus.

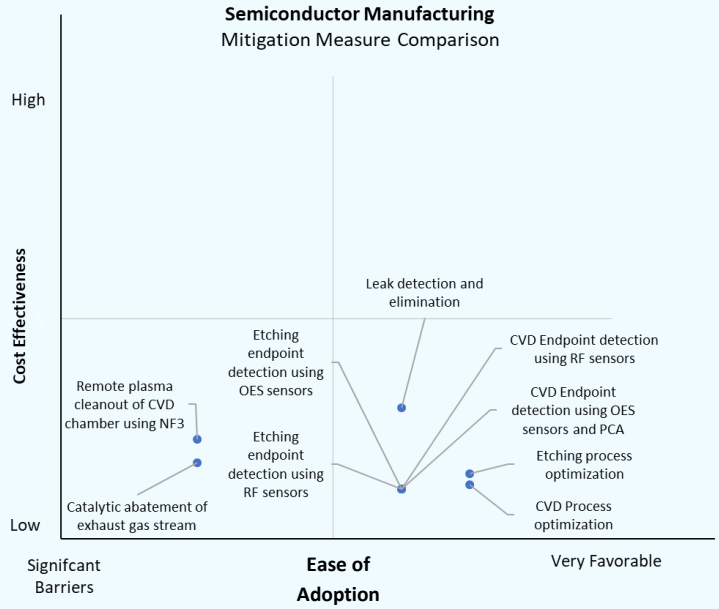



Figure 2-9. Semiconductor Manufacturing—Mitigation Measure Comparison

1 measure not shown. See Appendix C.

### Remote plasma cleanout of CVD chamber using $NF_3$

Remote plasma cleanouts are a modification to CVD chamber that allows post-fab cleanout using an $NF_3$ plasma. The fluorine radicals and ions generated in the remote plasma unit are routed to the processing chamber where they chemically react with deposits and increase the F-gas disassociation rate (reducing PFC emissions).[48]

*Emissions:* Remote plasma cleanouts can reduce the amount of gases used and significantly reduce PFC emissions when compared to other PFC gases used in CVD.

*Economics:* $NF_3$ can cost about the same or slightly more than fluorocarbons used in semiconductor manufacturing. However, projections indicate that $NF_3$ costs may decline. $NF_3$ offers several advantages to fluorocarbons that may help to lower costs. These advantages include lower equipment costs due to longer tool lifetimes and lower costs associated with emissions abatement/compliance.[49]

*Barriers:* Remote plasma cleanout is recommended as a best practice, but semiconductor producers may be unwilling to risk any changes to their processes.

[45] Anderson, S. "Detecting fluorocarbons with infrared." Sensor Electronics Corp. Electroiq.com. (2016) electroiq.com/2016/12/detecting-fluorocarbons-with-infrared/

[46] "Leak check semiconductor process chambers quickly and reliably." Electroiq.com. (2018) electroiq.com/2018/02/leak-check-semiconductor-process-chambers-quickly-and-reliably/

[47] Schaefer, D. "Global Emissions of SF6 and the Costs of Reducing Them." U.S. EPA. (2016) epa.gov/sites/production/files/2016-02/documents/conf06_ottinger_schaefer.pdf

[48] "Best Practice Guidance for Semiconductor PFC Emission Reduction." World Semiconductor Council. (2017). semiconductorcouncil.org/wp-content/uploads/2017/07/Best-Practice-Guidance-of-PFC-Emission-Reduction.pdf

[49] Iskenderova, Kamilla. Cleaning process in high density plasma chemical vapor deposition reactor. Drexel University, 2003. idea.library.drexel.edu/islandora/object/idea%3A344/datastream/OBJ/download/Cleaning_process_in_high_density_plasma_chemical_vapor_deposition.pdf

## 2.6 | Metals Production

Iron and steel production is a multi-step process that generates process-related emissions of $CO_2$ and $CH_4$ as raw materials are refined into iron and then transformed into crude steel. Iron and steel production includes six distinct production processes: coke production, sinter production, direct reduced iron production, pig iron production, electric arc furnace steel production, and basic oxygen furnace steel production. The number of production processes at a plant is dependent upon the specific plant configuration. Most process $CO_2$ generated from the iron and steel industry is a result of the production of crude iron. The production of primary aluminum—in addition to consuming large quantities of electricity—results in process-related emissions of $CO_2$ and two PFCs: perfluoromethane ($CF_4$) and perfluoroethane ($C_2F_6$).[50]

More than 90% of emissions associated with primary metal industries and fabricated metal products in the Air District are attributed to combustion.[51]

### Metals Production

| Prominent GHG Type(s) | $CO_2$ |
|---|---|
| **Annual Emissions** | **2015** |
| **Bay Area Emissions** | (Thousand MT $CO_2e$) |
| Total | 280 |
| Fabricated Metal Products | 158 |
| *Plumbing and Heating* | *127* |
| *Metal Cans and Shipping Containers* | *21* |
| *Other* | *10* |
| Primary Metal Industries | 122 |
| *Iron and Steel Foundries* | *64* |
| *Nonferrous Rolling and Drawing* | *28* |
| *Blast Furnace and Basic Steel* | *26* |
| *Other* | *3* |
| **National Process Emissions** | (MMT $CO_2e$) |
| Total | 53.7 |
| Iron and Steel Production & Metallurgical Coke Production | 48.9 |
| Aluminum Production | 4.8 |

From the 2015 BAAQMD Emissions Inventory and the 2016 U.S. EPA Emissions Inventory

### Mitigation Measure Comparison

This assessment identified 6 mitigation measures related to iron and steel production. Figure 2-10 compares the cost effectiveness and overall ease of adoption of the identified measures. The top measures described in this section are emerging technologies that have high potential for implementation and emissions reductions. A complete list of the identified measures and their weighted rankings across the key comparison variables is shown in Appendix C.

[50] "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016." U.S. EPA. 2018. epa.gov/sites/production/files/2018-01/documents/2018_complete_report.pdf

[51] "Final 2017 Clean Air Plan. Spare the Air, Cool the Climate: A blueprint for clean air and climate protection in the Bay Area." Bay Area Air Quality Management District. Adopted April 19, 2017. baaqmd.gov/~/media/files/planning-and-research/plans/2017-clean-air-plan/attachment-a_-proposed-final-cap-vol-1-pdf.pdf

## Details on Top Recommended Measures

### Inter-electrode insulation in electrolytic pickling lines

Pickling lines are surface treatments that remove oxides or scale that forms on hot strips of metal. The existing industrial electrolytic steel pickling process is inefficient. Insulation which covers less than 66 percent of the electrolyte cross section area between the anode and cathode electrode groups results in a significant improvement in the process efficiency while maintaining good circulation and homogeneity of the electrolyte solution. [52, 53]

*Emissions:* Experiments have shown process efficiency improvements from 20 percent without insulation to up to 100 percent with it. Insulation can cut electricity related emissions from electrolytic pickling by up to 80 percent.[52]

*Economics:* No specific cost was found for inter-electrode insulation in electrolytic pickling lines. However, the measure is described as relatively low cost and can be installed as a retrofit.

*Barriers:* Inter-electrode insulation is an early stage technology with some technical risk. Complete insulation leads to sludge accumulation in the compartments where the steel band is anodic which results in an inhomogeneous electrolyte and higher maintenance requirements. Additionally, there are other emissions from the pickling process which this measure does not mitigate.

### Walking beam furnace

Walking beam furnaces are a type of efficient reheating furnace. They can be used to produce alloy, carbon, and stainless steels and can process up to 65 metric tons of material per hour. They are suited for handling heavy loads at high production rates and reach temperatures over 3,200°F.[54]

*Emissions:* Walking beam furnaces can reduce electricity and fuel consumption by 25% and 37.5%, respectively, compared to pusher-type furnaces. Fuel reductions lower NOx and $CO_2$ emissions and energy efficiency improvements can lower associated emissions from power production. [52]

*Economics:* Walking beam furnaces are a replacement technology for existing furnace systems. This translates to high upfront implementation costs. However, lower operational costs can lead to a rapid return on investment for steel producers.[55]

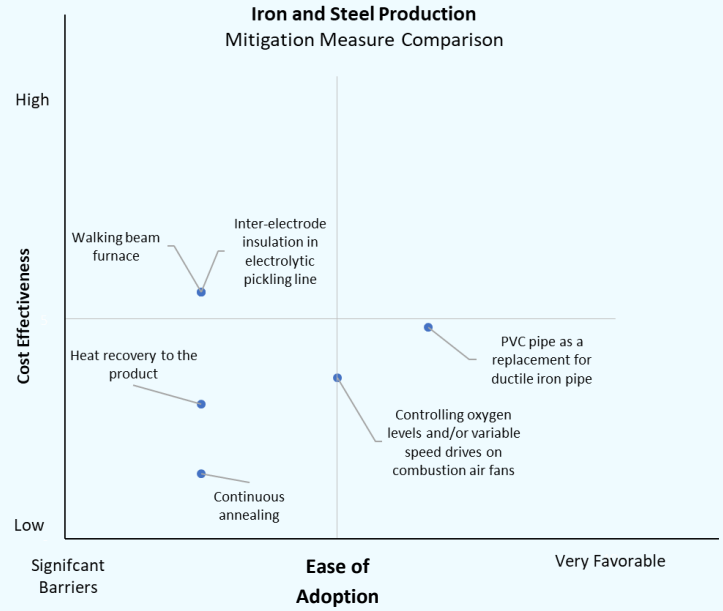



Figure 2-10. Metals Production—Mitigation Measure Comparison

See Appendix C for more details on identified measures.

*Barriers:* Walking beam furnaces are commercially available from several large industrial manufacturers. While they can achieve significant energy and cost savings, the need to replace equipment and higher up-front costs for these systems may act as a deterrent.

### Controlling oxygen levels and/or variable speed drives on combustion air fans

Excess air can substantially decrease combustion efficiency and produce excessive waste gases. Controlling oxygen levels and/or implementing VSD on combustion air fans can help to optimize combustion in the furnace.[52]

*Emissions:* Oxygen level control and VSD on combustion fans can reduce emissions by 16.6 kg $CO_2$/t-rolled steel. Energy savings can vary depending on the specific installation, but estimates range from approximately 10% to 48%. [56]

*Economics:* Estimated investment costs for implementing VSD on a combustion fan are approximately $0.72/ton of product. This can achieve a return on investment of 10-16 months. Savings depend on the furnace's load factor and will vary by installation.[52]

*Barriers:* Oxygen control and VSD for combustion fans can be installed as a retrofit and has wide applicability. System changes may be considered a risk by operators which could prevent adoption.

[52] "Available and Emerging Technologies for Reducing Greenhouse Gas Emissions form the Iron and Steel Industry." U.S. EPA. (2012). epa.gov/sites/production/files/2015-12/documents/ironsteel.pdf

[53] "Pickling metal surfaces". G.W.P. AG. (2018). gwp-ag.com/services/series-production/surface-treatments/pickling/index.html

[54] "Lindber Walking Beam Furnace." Lindberg/MPH. (2018). lindbergmph.com/heat-treat-furnaces/lindberg-walking-beam-furnace

[55] Heinlein, Jens et al. "Energy saving in walking beam furnaces by a new concept for skip pipe insulation." Heat Processing. (2016). heat-processing.com/fileadmin/HPO/Dateien_Redaktion/Selected_Reports/FB_Springer_hp_022016.pdf

[56] "Oxygen Level Control and VSDs on Combustion Fans." Industrial Efficiency Technology Database. ietd.iipnetwork.org/content/oxgen-level-control-and-vsds-combustion-fans

## 2.7 | Petroleum Systems

Methane emissions from petroleum systems are primarily associated with onshore and offshore crude oil production, transportation, and refining operations. During these activities, $CH_4$ is released to the atmosphere as leaked emissions, vented emissions (including emissions from operational upsets), and emissions from fuel combustion. Crude oil refining processes and systems account for approximately 16 percent of total $CO_2$ emissions from the oil industry. Almost all (97 percent) of the $CO_2$ from refining is from flaring.[57]

The San Francisco Bay Area has five major oil refineries that produce air pollution and GHGs. Oil refineries are subject to more than 20 specific Air District regulations and programs. Oil refineries currently account for 70 percent of the GHG emissions from stationary sources in the Bay Area.[58]

### Mitigation Measure Comparison

This assessment identified 26 mitigation measures related to petroleum systems. Figure 2-11 compares the cost effectiveness and overall ease of adoption of the identified measures. The top measures described in this section are emerging technologies that have high potential for implementation and emissions reductions. A complete list of the identified measures and their weighted rankings across the key comparison variables is shown in Appendix C.

**Petroleum Refining**

| Prominent GHG Type(s) | $CO_2$, $CH_4$ |
|---|---|
| **Annual Emissions** | **2015** |
| **Bay Area Emissions** | (Thousand MT $CO_2e$) |
| Total | 21,120 |
| Refineries | 15,680 |
| Natural Gas Combustion | 4,980 |
| Natural Gas Distribution | 460 |
| **National Process Emissions** | (MMT $CO_2e$) |
| Total | 199.0 |
| Petroleum Refining | 176.6 |
| *Stationary Combustion* | *120.1* |
| *Catalytic Cracking/Reforming* | *46.9* |
| *Flares* | *5.7* |
| *Other* | *3.9* |
| Natural Gas Transmission/Compression | 22.4 |

From the 2015 BAAQMD Emissions Inventory and the 2016 U.S. EPA Emissions Inventory

The top recommended measures for petroleum systems include boiler maintenance, steam trap and distribution system maintenance, and optimization of pumps and motors. These mitigation measures do not involve installation or replacement of large refinery components but

[57] "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016." U.S. EPA. 2018. epa.gov/sites/production/files/2018-01/documents/2018_complete_report.pdf

[58] "Final 2017 Clean Air Plan. Spare the Air, Cool the Climate: A blueprint for clean air and climate protection in the Bay Area." Bay Area Air Quality Management District. Adopted April 19, 2017. baaqmd.gov/~/media/files/planning-and-research/plans/2017-clean-air-plan/attachment-a_-proposed-final-cap-vol-1-pdf.pdf

rather are commercially available process improvements. Boiler and steam trap maintenance are similar in their low-cost approach with the potential for major reductions in fuel use for steam production. Pumps and motor optimization focuses on reducing electricity use and is more expensive than the other two measures.

## Details on Top Recommended Measures

### Boiler - Maintenance

Boilers are an essential and fundamental part of petroleum systems and are ubiquitous throughout refinery processes. Emissions come from both fuel use and the boiled substances themselves. The majority of boiler fuel can be saved by reducing total fuel input by increasing the heating efficiency. Boiler operation and maintenance (O&M) measures are therefore directed at reducing leaks and buildups of deposits in boilers and on burners, thereby increasing efficiency.[59]

*Emissions:* Reducing leaks and buildup on burners can achieve about 10% average fuel savings for boiler operations. These savings can be significant in the Bay Area and globally. Boiler maintenance may also reduce emissions of criteria air pollutants.

*Economics:* Boiler maintenance requires no new installation or equipment and can be a low-cost measure. Maintenance is a recurring cost and operational change but can be a positive return on investment due to performance improvements and energy savings.

*Barriers:* There are few barriers to implementation and low risks associated with boiler maintenance. Improper maintenance can cause the burners and condensate return systems to wear or shift out of adjustment. This risk is easily avoidable if following best practices and losses in efficiency should be readily detectable. If conducted properly, boiler maintenance has an immediate payback.

### Steam trap & distribution system maintenance

Steam traps are valves that allow condensation and unneeded gases to exit steam piping. Both distribution systems and steam traps can develop leaks allowing steam to escape. Leaks require the production of more steam to heat refinery operations. This decreases overall system efficiency, increasing fuel use and related emissions.[59]

*Emissions:* It is common to find between 15% and 30% of installed steam traps malfunctioning in the absence of a steam trap maintenance program after 3 to 5 years of operations. Conservative estimates suggest 10% energy savings by implementing regular steam trap checks and follow-up maintenance.

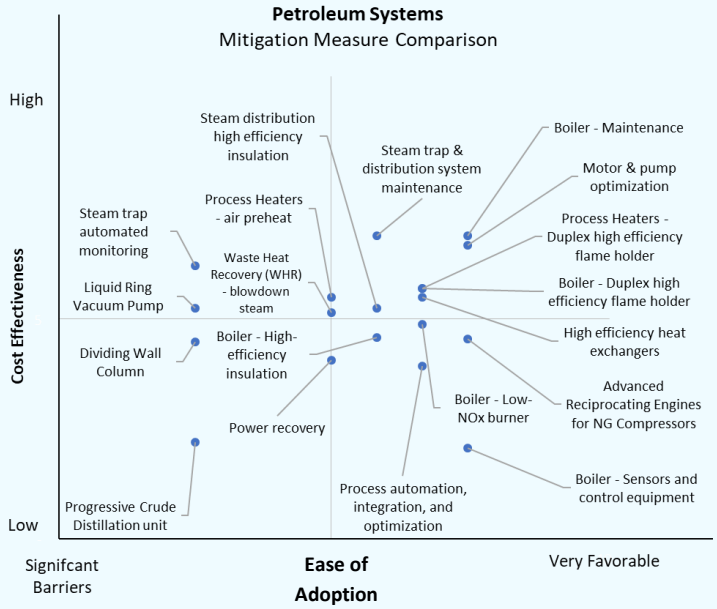



Figure 2-11. Petroleum Systems—Mitigation Measure Comparison

6 measures not shown. See Appendix C.

*Economics:* Annual savings depend on the refinery capacity and process steam requirements. Replacement equipment and repairs can be achieved at a very low cost, resulting in fast payback periods.

*Barriers:* Steam trap & distribution system maintenance is a low-cost measure with low barriers to implementation.

### Motor & pump optimization

Ensuring motors and pumps are optimally sized and utilized efficiently across refinery processes can achieve significant energy savings. Optimization may equipment replacements or simply a reconfiguration of process settings to reduce energy use.

*Emissions:* Motors and pumps are indirect contributors to emissions by utilizing large amounts of electricity. Equipment and/or control system improvements for motors and pumps can lead to electricity savings of 30% to 50%.

*Economics:* New motors and pumps cost on the order of tens of thousands of dollars. However, energy costs may comprise roughly 95% of the lifetime equipment costs. Optimized equipment and the resulting energy savings can more than make up for the initial capital investment.

*Barriers:* Higher upfront costs of energy efficient motors and pumps may be a deterrent for new installations. However, energy considerations and lifetime equipment costs should be emphasized. Additionally, motors and pumps affect multiple parts of petroleum systems and therefore a more holistic "systems approach" for these devices is required for optimal lifecycle performance.

[59] "Energy STAR Guide to Petroleum Refineries." Energy STAR. (2015). energystar.gov/sites/default/files/tools/ENERGY_STAR_Guide_Petroleum_Refineries_20150330.pdf

## 2.8 | Waste

The waste management sector includes GHG emissions from landfills and composting activities. A variety of air pollutants are produced as waste decomposes in landfills and composting operations. Landfills are the largest source of GHGs from the waste management sector in the Bay Area, due to methane from the uncontrolled decomposition of organic materials, as well as the fact that landfills are much larger in scale than composting facilities. Composting is also a source of methane and $CO_2$, as well as ROG, particulate matter and ammonia. The water sector accounts for approximately 1 percent of Bay Area GHG emissions. Sixty percent of GHGs in this sector (primarily methane) are directly emitted from the treatment of water and wastewater at publicly owned treatment works (POTWs). Forty percent of the GHG emissions associated with water use (primarily carbon dioxide) are generated indirectly, because of the energy used to pump, convey, recycle, and treat water and wastewater throughout the Bay Area. [60]

Landfills accounted for approximately 16.4 percent of total U.S. anthropogenic methane ($CH_4$) emissions in 2016, the third largest contribution of any $CH_4$ source in the United States. Additionally, wastewater treatment and composting of organic waste accounted for approximately 2.3 percent and 0.3 percent of U.S. $CH_4$ emissions, respectively. $N_2O$ emissions from the discharge of wastewater treatment effluents into aquatic environments, from the treatment process, and from composting account for 1.9 percent of total U.S. $N_2O$ emissions.[61]

### Waste

| Prominent GHG Type(s) | $CH_4$, $CO_2$ |
|---|---|
| **Annual Emissions** | **2015** |
| **Bay Area Emissions** | (Thousand MT $CO_2e$) |
| Total | 2,300 |
| Landfills | 1,850 |
| Composting/POTWs | 450 |
| **National Emissions** | (MMT $CO_2e$) |
| Total | 150.4 |
| Incineration of Waste | 11.0 |
| Landfills | 115.7 |
| Wastewater Treatment | 19.7 |
| Composting | 4.0 |

From the 2015 BAAQMD Emissions Inventory and the 2016 U.S. EPA Emissions Inventory

### Mitigation Measure Comparison

This assessment identified 35 mitigation measures related to waste. Figure 2-12 and Figure 2-13 compare the cost effectiveness and overall ease of adoption of the identified measures, organized by municipal landfills/other and

[60] "Final 2017 Clean Air Plan. Spare the Air, Cool the Climate: A blueprint for clean air and climate protection in the Bay Area." Bay Area Air Quality Management District. Adopted April 19, 2017. baaqmd.gov/~/media/files/planning-and-research/plans/2017-clean-air-plan/attachment-a_-proposed-final-cap-vol-1-pdf.pdf

[61] "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016." U.S. EPA. 2018. epa.gov/sites/production/files/2018-01/documents/2018_complete_report.pdf

composting/POTWs. The top measures described in this section are emerging technologies that have high potential for implementation and emissions reductions. A complete list of the identified measures and their weighted rankings across the key comparison variables is shown in Appendix C.

The waste measures are divided into landfill/other and composting/publicly owned treatment works (POTW). The top recommended landfill/other measures include landfill gas (LFG) waste-to-energy, active LFG recovery systems, and biochar production form agricultural and forest waste. Top composting/POTW measures include nitrification tank gas capture and co-firing, adjusting operating parameters to reduce GHG formation in sludge paths, and aerated static piles (ASP).

Landfills and wastewater treatment are two significant sources of emissions in the Air District and across the United States. Solutions at the root of the problem, such as waste diversion from landfills, should be a priority. However, steps should be taken to mitigate emissions and make use of the available resources where landfills already exist.

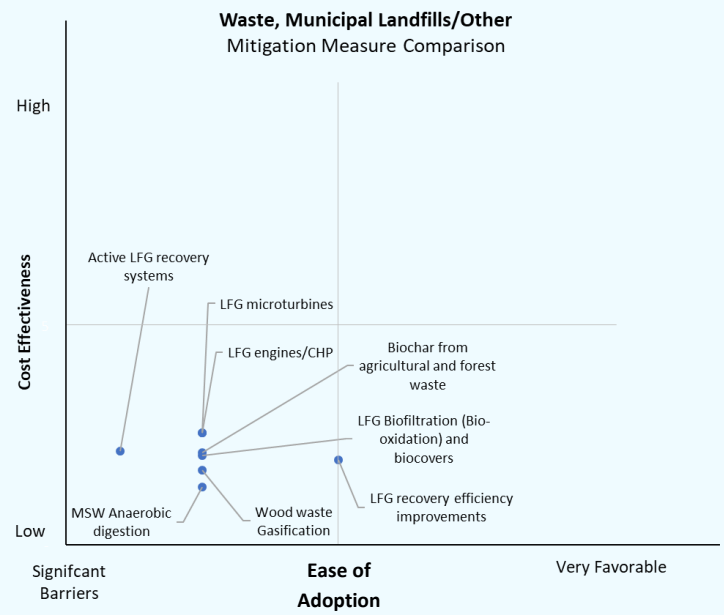



Figure 2-12. Municipal Landfills/Other—Mitigation Measure Comparison

7 measures not shown. See Appendix C.

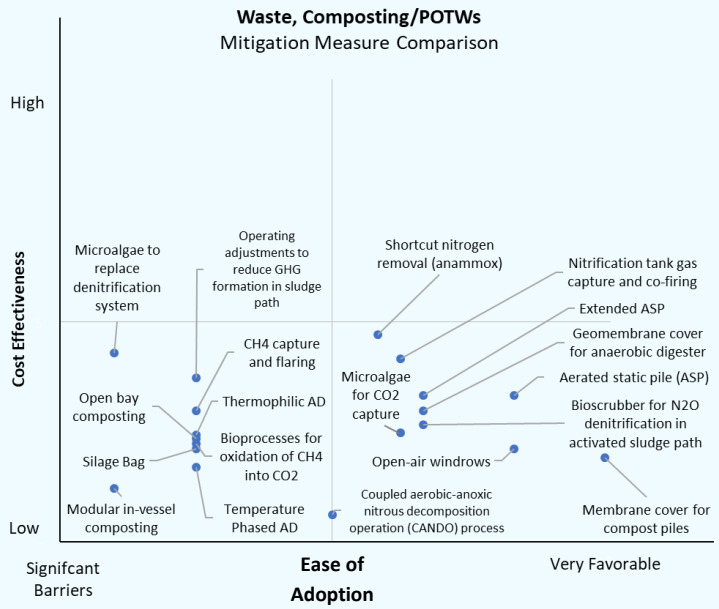



Figure 2-13. Composting/POTWs—Mitigation Measure Comparison

1 measure not shown. See Appendix C.

## Details on Top Recommended Municipal Landfills/Other Measures

### Landfill Gas Waste-to-Energy

LFG is produced as organic material decomposes in a landfill. LFG has a high methane content that several technologies can convert it into energy. CHP systems such as microturbines and reciprocating engines can be used to generate steam and power from LFG.

*Emissions:* The methane reductions from microturbines and engines are assumed to be identical to flaring.[62] However, LFG-fired generators also displace grid electricity (529 lb $CO_2e$/MWh).[63] Assuming 385 GWh of generation among the district's landfill generators (55 MW capacity x 0.8PF), [63] emissions reduction due to power replacement can be estimated at 4.6%.

*Economics:* Cost estimates for CHP microturbines and reciprocating engines vary widely between $2 and $57 per metric ton of $CO_2e$ reduced (inclusive of $CH_4$ reductions). These systems can achieve an eventual return on investment from energy sales.

*Barriers:* LFG waste-to-energy systems are well-established technologies in California and across the United States. Microturbines are a newer technology with fewer deployments than traditional LFG generators which can result in some hesitation to adoption. However, microturbines may increase efficiency and improve overall project economics. The economic viability and payback period of these systems depend on energy costs and the landfills proximity to users for produced steam. Generators may also require air permitting, depending on the size.

[62] "Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from Municipal Solid Waste Landfills." U.S. EPA. (2011). epa.gov/sites/production/files/2015-12/documents/landfills.pdf

[63] "eGRID Summary Tables 2016." U.S. EPA. (2016). epa.gov/sites/production/files/2018-02/documents/egrid2016_summarytables.pdf

### Active LFG recovery systems

Active LFG recovery systems are likely installed at most, if not all, Air District landfills. LFG recovery systems use wells, gathering pipes buried in the landfill material, and pumps to ensure negative pressure within the collection system. The systems prevent LFG, which is predominantly $CH_4$, from escaping into the atmosphere.

*Emissions:* Active LFG collection captures 75% of $CH_4$ on average compared to landfills with no collection system.[64] The collected LFG must be flared or used productively as fuel or to generate energy to provide emissions reductions.

*Economics:* Active LFG collection systems add costs relative to passive systems for pumps and compressors. Active LFG recovery systems can cost approximately $25,000 per acre for a large (>100 acre) landfill site.[65]

*Barriers:* Active LFG recovery systems may already be deployed at all suitable sites in the Air District. Those without active collection systems will need to be evaluated on a case-by-case basis to determine their economic viability.

### Biochar from agricultural and forest waste

Biochar can be created with portable, modular kilns that can be brought to agricultural and forest locations with biomass waste. This produces a salable product, helps to lower the risk of wildfires, and avoids emissions from rotting biomass from what would be an otherwise wasted resource.

*Emissions:* $CO_2$ emissions from the kilns have a lower GWP than if the biomass was left to decay and produce $CH_4$. The kilns sequester some of the carbon into biochar, which has a value-added use as a soil amendment.

*Economics:* Biochar can be produced from several underutilized or wasted sources of biomass. The kilns have capital costs, O&M costs, and variable transportation costs. There may be a return on investment if there is a sufficient market for biochar to be sold as an agricultural amendment.

*Barriers:* Making productive use of agricultural and other biomass waste presents an important challenge for California and the United States. However, portable kilns for biomass waste utilization and biochar production are a very early stage technology with limited real-world demonstration. They will likely face deployment challenges, especially considering the economic uncertainties.

## Details on Top Recommended Municipal Composting/POTWs Measures

### Shortcut nitrogen removal (anammox)

Anammox bacteria (ANaerobic AMMonia OXidation) convert wastewater ammonia ($NH_3$) into inert nitrogen gas ($N_2$) much more efficiently than traditional nitrogen removal processes. The anammox process eliminates the need for aeration (one of the most energy-intensive processes in a POTW) and reduces sludge volumes.[66]

*Emissions:* Traditional wastewater denitrification processes require large amounts of dissolved oxygen and are one of the most energy-intensive processes in a POTW. The anammox process reduces carbon requirements and can even result in a net consumption of $CO_2$—in contrast to conventional treatment processes that release $CO_2$.[66] In Alexandria's demonstration unit, anammox saved energy by using 60% less oxygen than conventional methods and reduced supplemental carbon use by more than 40%.[67]

*Economics:* An anammox system may have high up-front implementation costs. However, anammox provides a rapid return on investment due to lower energy and sludge disposal costs. The single most energy-intensive operation at an average POTW is aeration, which consumes about 57% of total energy. Anammox eliminates the need to aerate sludge during the denitrification process. Additionally, sludge transport and disposal accounts for nearly 25% of POTW operating costs. The anammox process lowers sludge volumes, reducing costs there as well.

*Barriers:* The anammox process is still relatively new and has limited deployment. However, it has been demonstrated to be highly effective in those deployments. Mainstream deammonification at AlexRenew is a milestone in the development of the technology that provides a blueprint for other facilities to follow. Anammox has an added benefit in that the process can help to reduce the total nitrogen discharged into local waterways and landfills.[67]

### Adjust operating parameters to reduce formation of GHGs in sludge path

Optimization of POTW processes to minimize formation of $N_2O$, $CH_4$, and $CO_2$ during the activated sludge processes and other biological waste treatment steps. This includes adjustments such as increasing solids retention time (SRT) and concentration of dissolved oxygen, ammonia, and other compounds that can reduce the formation of $N_2O$.

*Emissions:* SRT changes can drastically change the $CO_2$ production. For example, increasing SRT from 10 to 30 days

[64] "Municipal Solid Waste Landfills." U.S. EPA. epa.gov/ttnchie1/ap42/ch02/final/c02s04.pdf

[65] "LFGcost-Web." Landfill Methane Outreach Program. U.S. EPA. (2017) epa.gov/lmop/download-lfgcost-web

[66] "Energy-Positive Water Resource Recovery Workshop Report." U.S. Department of Energy. (2015). energy.gov/sites/prod/files/2015/10/f27/epwrr_workshop_report.pdf

[67] "Meet Anammox." Alexandria Renew Enterpises. (2015). alexrenew.com/anammox

increases $CO_2$ production by around 7.6%.[68] Process changes will change the emissions profile in a way specific to each POTW. Process optimization may increase one GHG (i.e., $CO_2$) to lower overall emissions from higher GWP GHGs (i.e., $N_2O$).

*Economics:* Process economics will change depending on the selected parameters and the associated outputs (i.e., quantities of methane and sludge production). Processes should be optimized to minimize GHG production and maximize the economic viability of operations.

*Barriers:* This measure has fairly-high barriers to implementation. Process changes will be unique to each plant and emissions reductions can only be confirmed through testing. Additionally, POTW operators are highly risk averse and may avoid making process changes without a strong incentive or mandate and extensive demonstration.

### Aerated static pile (ASP)

An aerated static pile (ASP) is a bulk composting method that uses forced air (usually via PVC ducts or dedicated trenches) to aerate a static pile or row of compost without mechanical turning. The waste material, such as sewage sludge, is usually mixed with a bulking agent to increase porosity. ASP is typically used for a curing phase after primary composting.

*Emissions:* ASPs have lower methane leakage than landfills and the potential for greater emissions reductions by avoiding organics decomposition not captured by LFG collection systems (i.e., fugitive emissions from partially-covered landfills). Composting can achieve between up to a 45% reduction in $CO_2e$ compared to landfills.[69]

*Economics:* Over a 10-year lifespan ASP has an estimated annual cost of $45 per ton of composted organics. These estimates are based on fixed capital costs estimated at $5.4 million for 40,000 ton per year facility plus labor costs of $32 per ton per year.[70] While costs of ASP are comparable to landfilling, MSW organics separation and collection can add costs not accounted for above.

*Barriers:* ASP is an established and widespread technology that can be expanded to divert organic waste from landfills. Composting should be expanded considering its emissions reduction potential and cost parity compared to landfilling.

[68] Campos, J.L. et al. "Greenhouse Gases Emissions from Wastewater Treatment Plants: Minimization, Treatment and Prevention." Journal of Chemistry. (2016). dx.doi.org/10.1155/2016/3796352.

[69] Lou, X.F. and Nair, J. "The impact of landfilling and composting on greenhouse gas emissions – a review." Bioresource Technology. (2009). doi.org/10.1016/j.biortech.2008.12.006.

[70] Pisarek, Natalia. "Large-Scale compositing Options for YVR." University of British Columbia. (2012). open.library.ubc.ca/media/download/pdf/52966/1.0103540/1

# 3 | Methodology

The technology assessment and matrix tool used to produce this report followed a three-phase approach. These phases included identification of the emissions-intensive industries to prioritize and relevant mitigation measures; data collection to evaluate the mitigation measures across key comparison variables; and technology evaluation (ranking, comparing, and prioritizing the mitigation measures based on emissions abatement potential, cost, and other factors).

- **Emissions Mitigation**
  - Industry Subpart-Process emissions impact
  - District emissions impact
  - National emissions impact
- **Economics**
  - Investment Scale (per individual deployment)
  - Cost Relative to Baseline
  - Return on Investment
- **Maturity**
  - Technology Readiness Level
  - Measure Provider Maturity
- **Barriers**
  - Technical Barriers
  - Economic/Market Barriers
  - Policy Barriers

This approach was successfully executed by drawing on subject matter expertise, conducting literature reviews and research, and interviewing technology vendors.

**Industry sectors used to categorize mitigation measures**

| | |
|---|---|
| Agriculture | Petroleum Product Suppliers |
| Buildings | Mining |
| Chemicals | Nat. Gas and NGL Suppliers |
| $CO_2$ Supply and Injection | Minerals |
| Data Centers | Misc. Combustion Sources |
| Distributed Generation | Petroleum and Nat. Gas Sys. |
| Electrical Equipment | Petroleum Refining |
| Electronics Manufacturing | Power Plants |
| Fluorinated Chemicals | Pulp and Paper |
| Industrial Gas Suppliers | Transportation |
| Metals | Waste |

## 3.1 | Identification

Phase I required building an inventory of mitigation measures suitable to reduce GHG emissions in sectors that impact the Air District. First, we identified industry sectors, shown in the adjacent textbox, based on the sectoral categories used by the U.S. Environmental Protection Agency's (EPA) Greenhouse Gas Reporting Program (GHGRP) and narrowed them down to relevant sectors using Air District's emissions data.[71,72]

For each sector, a literature review identified resources that document GHG emissions mitigation technologies and measures. These resources include technology roadmaps, regulatory agency reports, academic survey literature, industry association best practice guides, and technology training materials and primers. Some of the most prominent sources are listed in Appendix B.

The literature review provided an initial set of mitigation measures and technologies that are either currently available and encouraged for use (e.g., EPA studies), or are expected to become available in the future (e.g., DOE technology roadmaps). Although these literature sources do not serve as a comprehensive inventory, they typically provide a complete overview of the various types of emissions activities within a sector (i.e., operation type and process unit), and the different methods used for mitigating emissions from that activity (i.e., mitigation measure category and type). For example, in the Buildings sector, most emissions activities are "indirect emissions" (i.e., electricity produced elsewhere, but consumed on site), and therefore most mitigation measures fall into the category of "energy efficiency" with many different mitigation measure types, including HVAC, lighting, and building envelope efficiency. Under-utilized mitigation measures are given priority in the assessment matrix, given the uncertainty around their performance, and greater potential for deployment under various policies.

Assumptions about baseline technologies in each sector are necessary and documented in the matrix. In general, the baseline technology is assumed to be widely deployed if it is considered the industry standard in the assessment literature, or if a review of the major sources in the Air District reveals that most sources have already deployed the technology. For each sector, the baseline technology is indicated in the Matrix notes, typically in the "Emissions reductions potential" column.

The database includes vendors for some of the mitigation measures. Where vendors are identified only major vendors are considered with proximity to California markets also given consideration (i.e., minor vendors with California presence may be included where minor vendors located elsewhere may not). The database includes primarily domestic vendors, and only

[71] "Final 2017 Clean Air Plan. Spare the Air, Cool the Climate: A blueprint for clean air and climate protection in the Bay Area." Bay Area Air Quality Management District. Adopted April 19, 2017. baaqmd.gov/~/media/files/planning-and-research/plans/2017-clean-air-plan/attachment-a_-proposed-final-cap-vol-1-pdf.pdf
[72] "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016." U.S. EPA. 2018. epa.gov/sites/production/files/2018-01/documents/2018_complete_report.pdf

international vendors when sufficient domestic vendors are not available. For pre-commercial technologies without established vendors, a laboratory, research groups, university, or funding agencies may also be included in the vendor database.

## 3.2 | Data Collection

The mitigation measures in the matrix are fully characterized by cost, performance, and barriers to deployment as well as other factors to allow the Air District to make the most informed decisions and best use possible of the tool. Emissions and cost performance measures are quantified using a variety of methods and assumptions that are detailed in the matrix.

In many sectors, secondary source literature provides a useful set of parameters for performance and cost, oftentimes normalized to a common set of baseline assumptions. These sources are especially valuable when provided by regulatory agencies or in technology roadmaps, where the assumptions about process use and technology implementation may dominate the performance metrics of an individual measure or technology. For example, refinery mitigation measures are well-characterized by the EPA report, "Energy Efficiency Improvement and Cost Saving Opportunities for Petroleum Refineries."[73] However, these types of reports are not available for every sector and measure type and use of such resources is limited to situations relevant to the Air District.

Primary source literature is the largest source of performance and cost data for mitigation measures in the matrix. Primary source literature includes technical and sales documentation from vendors, case studies, and performance reports from purchasers of a measure or technology in another jurisdiction. For most emissions and cost performance estimates, primary source documentation provides an estimate of the emissions mitigation potential or cost expressed as a percentage improvement as compared to a baseline technology.

## 3.3 | Measure Evaluation

The mitigation measures are evaluated across an array of criteria including emission reduction potential, economics, maturity, and barriers. These key comparison variables are grouped into categories and assigned scores so that the measures can be more easily compared. These categories and the associated scores are explained in detail in section 2.3 and Appendix C.

Emissions mitigation potential and cost reflect a wide range of uncertainty stemming from the applicability of the mitigation measure to general emissions sources in the Air District. While limited process specific emissions information was available at a facility level, it was outside the scope of this effort to evaluate the emissions abatement potential of mitigation measures at individual locations and the results are higher-level estimations.

Estimates of emissions mitigation potential are based either on a direct literature source indicating a percentage improvement over baseline (e.g., 10% lower GHG emissions, compared to assumed baseline technology), or are based on a percentage reduction in energy consumption for an identical activity. The specific method used for each measure is described in detail in the matrix notes ("Emissions reductions potential"). Where direct combustion fuel savings are used, emissions mitigation potential is estimated from the carbon content associated with the fuel, based on EPA fuel-specific emission factors.[74] Where indirect energy is used (i.e., electricity), emissions are based on California-specific carbon intensity of electricity, using EPA eGRID data.[75] In some cases, assumptions need to be made to establish the baseline technology energy use because data involving the baseline technology's energy use is incomplete or unavailable. All assumptions and the resulting estimates are recorded in the matrix notes.

Cost estimates are based on published estimates in either primary or secondary literature sources or vendor interviews. Most cost estimates are based on explicit dollar amounts; however, some are based on percentage difference vs. a baseline technology. In either case, cost estimates for baseline technologies are also necessary to characterize the "cost relative to baseline," so additional research is conducted to identify baseline cost assumptions. These assumptions are included in the matrix "cost notes".

**Mitigation Measure Evaluation Criteria**

| | |
|---|---|
| **Emissions Mitigation** | **Economics** |
| Industry Subpart-Process emissions impact | Investment Scale (per individual deployment) |
| District emissions impact | Cost Relative to Baseline |
| National emissions impact | Return on Investment of Mitigation Measure |
| **Maturity** | **Barriers** |
| TRL Level | Technical Barriers |
| Measure Provider Maturity | Economic/ Market Barriers |
| | Policy Barriers |

[73] EPA. 2015. *Energy Efficiency Improvement and Cost Saving Opportunities for Petroleum Refineries*. Washington, DC: U.S. Environmental Protection Agency. February 2015. Energy Efficiency Improvement and Cost Saving Opportunities for Petroleum Refineries.
[74] EPA. 2014. *Emission Factors for Greenhouse Gas Inventories.* Washington, DC: U.S. Environmental Protection Agency. April 2014. epa.gov/sites/production/files/2015-07/documents/emission-factors_2014.pdf
[75] EPA. 2018. eGRID Summary Tables. Washington, DC: U.S. Environmental Protection Agency. February 2018. epa.gov/sites/production/files/2018-02/documents/egrid2016_summarytables.pdf

Additional key comparison rankings are selected based on subjective research from the primary and secondary sources. Technical barriers are rated higher at earlier TRL levels, or for process that require significant changes to industry processes. Economic barriers are rated higher for measures that require large investments or for industries with little economic incentive to change. Policy barriers are rated as high when legislation exists that inhibits adoption or deployment of the measure.

# 4 | Matrix Organization and Use

As part of this project, the Air District required the development of a mitigation measure assessment matrix to allow it to compare emissions reduction technologies across industries. This tool was developed in a Microsoft Excel format and this section describes the information in the workbook tool, as it is laid out in each Excel tab.

## 4.1 | Data Dictionary and Validation Tabs

The Data Dictionary refers to each column in the Matrix and describes the information therein. It indicates whether the column is completed via manual entry, a drop-down menu, or is auto-filled. Key comparison variables are indicated with a blue highlight. The data dictionary shows the comparison variable selections and their associated weighted values used in the analysis tabs. The complete data dictionary is provided in Appendix A.

The Category Validation tab provide the inputs for the matrix drop-down options and key comparison variables. Each named range is indicated with a blue header. Changes to the Category Validation tab will affect the matrix and analysis tabs.

The Sectors Validation tab uses Industry Sector and Subsector definitions from the EPA Greenhouse Gas Reporting Program (GHGRP). The District Sectors tab uses industry sector, subpart, and district source definitions from the 2015 BAAQMD Emissions Inventory. The sectors are nested so that the matrix will only provide subsector options for a relevant industry selection.

## 4.2 | Emissions Estimates and Sources

Emissions information included in the matrix is intended for consideration at a high-level for order of magnitude estimates only.

Air District emissions estimates are based on the 2015 Air District Emissions Inventory.[76] The information provided in the matrix is aggregate only and does not identify any individual facilities. The matrix autopopulates emissions estimates based on selections for Air District Sector, the Air District Subsector, and Air District Source.

National emissions estimates are based on a combined data set from the GHGRP and the 2015 EPA Inventory of U.S. Greenhouse Gas Emissions and Sinks.[77,78] The matrix autopopulates emissions estimates based on selections for the GHGRP Industry and the GHGRP Industry Subpart.

Unless otherwise indicated, the national emissions data represent process emissions (i.e., emissions associated with a reaction, process, or feedstock, not fuel combustion). This corresponds to emissions categorized as “Process Type”, “General” in the 2015 Air District emissions inventory data. Emissions from the Buildings sector is not quantified other than at the National level due to insufficient data availability.

The matrix provides additional context into the sources, thinking, and calculations used for the emissions key comparison variable rankings attributed to each mitigation measure.

## 4.3 | Key Comparison Variables and Weighting

The matrix uses a series of key comparison variables, with weighted scoring, to rank and compare the mitigation measures. The key comparison variables are considered from the perspective of the emissions source. Additional context is available in the matrix to help define the baseline for the technology or sector and to state all relevant assumptions and sources. The comparison values and their descriptions are as follows:

**Emissions Mitigation Potential**

*Industry Subpart-Process emissions impact ranking*

(1.0) Negligible emissions reduction vs baseline
(2.5) 1-5% emissions reduction vs baseline
(5.0) 5-15% emissions reduction vs baseline
(7.5) 15-50% emissions reduction vs baseline
(10.0) 50-100% emissions reduction vs baseline

*District emissions impact ranking*

(0) Negligible avoided emissions
(0.1) Hundreds of tons of avoided emissions possible
(1.0) Thousands of tons of avoided emissions possible
(5.0) >10,000 tons of avoided emissions possible

[76] Internal data provided by the Air District. Information on Air District Emissions Inventories available from, baaqmd.gov/research-and-data/emission-inventory
[77] “GHGRP Reported Data.” US EPA. epa.gov/ghgreporting/ghgrp-reported-data
[78] “Inventory of U.S. Greenhouse Gas Emissions and Sinks.” US EPA. April 2018. epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2016

(10.0) >100,000 tons of avoided emissions possible

*National emissions impact ranking*

(0) Negligible avoided emissions
(0.1) Thousands of tons of avoided emissions possible
(1.0) >10,000 tons of avoided emissions possible
(5.0) >100,000 tons of avoided emissions possible
(10.0) >1 MMT of avoided emissions possible

### Measure Maturity

*TRL Level*[79]

(0) Pre-TRL 7 (e.g., Technology development or demonstration phase (pilot-scale, lab-scale, and earlier))
(2.5) TRL 7 (e.g., Full-scale, similar (prototypical) system demonstrated in relevant environment)
(5.0) TRL 8 (e.g., Actual system completed and qualified through test and demonstration.)
(7.5) TRL 9 (e.g., Actual system operated over the full range of expected mission conditions.)
(10) Early commercial (e.g., system commercially available)
(10) TPC-CAT (Theoretical Process Change using Commercially Available Technology)

*Measure Provider Maturity*

(1) Emerging (e.g., single vendor and/or technology developer may be young and fragile)
(5) Established (e.g., company or technology developer has some experience or history)
(10) Robust (e.g., multiple vendors and/or company or technology developer has significant resources and history)

### Economics

*Investment Scale*
*(per individual deployment)*

(1.5) Mega-Project ($$$ millions)
(3) Very Large Investment ($ millions)
(4.5) Large Investment ($ hundreds of thousands)
(6) Mid-Size Investment ($ tens of thousands)
(7.5) Small Investment ($ thousands)
(9) Very Small Investment ($ hundreds)
(10) No cost measure

*Cost Relative to Baseline*

(1) Higher cost than baseline
(5) Comparable cost to baseline
(10) Lower life-time cost than baseline

*Return on Investment of mitigation measure*

(1) Low-viability (high added-cost per emissions reduction)
(2.5) OK-viability (low added-cost per emissions reduction)
(5) Good-viability (costs about the same as baseline, but with emissions reduction)
(7.5) Eventual return on investment (>2yrs)
(10) Rapid return on investment (<2yrs)

### Barriers

*Technical Barrier Ranking*

(1) Very High - Measure has not been demonstrated in an operational environment and/or requires significant material process changes
(2.5) High - Measure has limited operational demonstration and/or requires material process changes
(5) Mid - Measure qualified through testing in operational environments
(7.5) Low - Measure operated over full range of operational conditions and/or requires minimal process changes
(10) Very Low - Measure is commercially widespread and/or requires minimal process changes

*Economic/ Market Barrier Ranking*

(1) Very High - Emissions source is highly risk averse or has little market incentive to change and/or the mitigation measure has low economic viability

[79] U.S. Department of Energy G 413.3-4A, Technology Readiness Assessment Guide, p. 9, directives.doe.gov/directives-documents/400-series/0413.3-EGuide-04a

(2.5) High - Emissions source has little incentive to change, there is low demand, and/or the mitigation measure adds costs

(5) Mid - Mitigation measure has minimal economic implications for the emissions source and/or measure will face opposition from incumbents despite positive economics

(7.5) Low - Emissions source has some economic incentive to adopt the mitigation measure

(10) Very Low - Emissions source has economic incentive to adopt the mitigation measure and is likely to do so

*Policy Barrier Ranking*

(1) Very High - Existing policy actively inhibits the mitigation measure and/or permitting is an issue

(2.5) High - Existing policy favors other mitigation measures and/or permitting may be an issue

(5) No policy or permitting issues anticipated

(7.5) Low - Existing policy creates a favorable environment for the mitigation measure (general)

(10) Very Low - Existing policy actively encourages the mitigation measure (specific)

**Aggregated Scoring**

*Cost Effectiveness*

Emissions Reduction Potential * Economic Viability / 10

*Emissions Reduction Potential*

Average of "Industry-subpart process emissions ranking", "District emissions impact ranking", and "National emissions impact ranking"

*Economic Viability*

Average of "Investment scale", "Cost relative to baseline", and "Return on investment". Note: Investment scale weighted double

*Overall Barriers*

If any of "Tech Barrier", "Economic/Market Barrier", or "Policy Barrier" =1 or 2.5, then the Overall Barriers score = 1 or 2.5 respectively. Otherwise, returns the average of the three Barrier scores.

## 4.4 | Analysis and Visualization

As discussed in the previous section, the key comparison variable rankings have associated weightings. Two visualization tabs are available in the matrix, Summary Charts and Filter Chart, which can be used to compare the mitigation measures.

Summary Charts pulls information directly from the matrix and uses various drop-down options to visualize the mitigation measure data in different ways. This tab helps to inform and visualize the contents of the matrix. The user can see cross-sections of the number of measures by sector, and how measures are distributed across comparison variable categories such as TRL Level or Investment Scale. Summary Charts also presents scatter-plot analysis of mitigation measure categories and specific measures on user selected X and Y axes. Lastly, the tab includes area charts that assess mitigation measures across five variables simultaneously.

Filter Chart is a dedicated scatter plot that pulls information directly from the matrix. However, if a new mitigation measure is added to the matrix it also needs to be manually added to the Filter Chart tab. The Filter Chart allows for the user to define the desired comparison variables for the X and Y axes. It then allows the user to filter the analysis table on the sheet by any of the other comparison variables to continue to downselect and compare measures based on multiple attributes.

# Appendix A – Assessment Matrix Data Dictionary

## Emissions Mitigation Measure Matrix Data Dictionary

Rows identified in blue indicate key comparison variables

| ID | Description | |
|---|---|---|
| 1 | Tech ID | Dynamic ID based on the GHGRP Industry Sector and Mitigation Measure Category |
| 2 | Emissions Mitigation Measure | Specific name of an identified mitigation measure<br>(lowest level of granularity) |
| 3 | Description | Additional notes and high-level description of the mitigation measure |
| 4 | Vendor(s) | Vendor(s) identified in relation to the mitigation measure |
| 5 | POC | Mitigation measure point of contact (those that have been contacted only) |
| 6 | Mitigation Measure Category | Pre-defined list of 15 mitigation measure categories<br>(highest level categorization of the mitigation measures) |
| 7 | Mitigation Measure Type | Manual entry to further define the mitigation measure<br>(mid-level categorization) |
| 8 | Control technology change type vs major unit operation effected | Drop-down menu to select<br>**Modify** (i.e., alters equipment or process at the emissions source)<br>**Replace** (i.e., replaces a process or equipment at the emissions source)<br>**Displace** (i.e., measure displaces the emissions but is not implemented at the emissions source) |
| 9 | Operation Type | Drop-down menu to select<br>**Process emissions** (i.e., emissions associated with a reaction, process, or feedstock, not fuel combustion)<br>**Stationary Combustion** (i.e., boilers, heaters, furnaces, kilns, ovens, flares, thermal oxidizers, dryers, and any other equipment or machinery that combusts carbon bearing fuels or waste stream materials)<br>**Electricity Generation**<br>**Fugitive Emissions** (i.e., emissions of gases or vapors from pressurized equipment due to leaks and other unintended or irregular releases of gases)<br>**Bld-Direct Emissions** (i.e., buildings measure the displaces on-site emissions)<br>**Bld-Indirect Emissions** (i.e., buildings measure that displaces off-site emissions)<br>**Bld-Combined Systems** (i.e., buildings measure that displaces both on-site and off-site emissions) |
| 10 | Process/Unit Operation Effected (Description) | Manual input. What unit process does the mitigation measure specifically address? |
| 11 | Cross-cutting applicability | Manual input. Is the mitigation measure applicable to other industry sectors, subparts, or unit operations? |
| | **Emissions Source Information** | |
| 12 | GHGRP Sector | Drop-down menu. Revised list based on the EPA GHG Reporting Program Sectors |
| 13 | GHGRP Subpart | Drop-down menu. Revised list based on the EPA GHG Reporting Program Industry Subparts |
| 14 | District Sector | Drop-down menu. Based on the 2015 district emissions inventory database (Industry_Title) |
| 15 | District Subsector | Drop-down menu. Based on the 2015 district emissions inventory database (Industry_Subcategory) |
| 16 | District Source | Drop-down menu. Based on the 2015 district emissions inventory database (Src_Desc_New) |
| | **Emissions Source Information** | Note, these are rough estimates at based. Only used to scale the order of magnitude of emissions for a given sector |
| 17 | District 2015 (Source Emissions) | Calculated based on the District Source selected in column 15. Short tons per year. |
| 18 | District 2015 (Subsector Emissions) | Calculated based on the District Subsector selected in column 14. Short tons per year. |
| 19 | District 2015 (Industry Emissions) | Calculated based on the District Sector selected in column 13. Short tons per year. |
| 20 | National 2015 (Subpart Emissions) | Calculated based on the GHGRP Industry subsector selected in column 12. Million metric tons per year. |
| 21 | National 2015 (Sector Emissions) | Calculated based on the GHGRP Industry sector selected in column 11. Million metric tons per year. |
| | **Emissions Reductions Possible** | |
| 22 | Reductions potential | Manual notes. Discusses the emissions reductions possible per source based on lit review and interviews. |
| 23 | Industry Subpart-Process emissions impact ranking | **Comparison Variable selections and weighted values include:**<br>(1.0) Negligible emissions reduction vs baseline<br>(2.5) 1-5% emissions reduction vs baseline |

| | | |
|---|---|---|
| | | (5.0) 5-15% emissions reduction vs baseline<br>(7.5) 15-50% emissions reduction vs baseline<br>(10.0) 50-100% emissions reduction vs baseline |
| 24 | District emissions impact ranking | **Comparison Variable selections and weighted values include:**<br>(0) Negligible avoided emissions<br>(0.1) Hundreds of tons of avoided emissions possible<br>(1.0) Thousands of tons of avoided emissions possible<br>(5.0) >10,000 tons of avoided emissions possible<br>(10.0) >100,000 tons of avoided emissions possible |
| 25 | National emissions impact ranking | **Comparison Variable selections and weighted values include:**<br>(0) Negligible avoided emissions<br>(0.1) Thousands of tons of avoided emissions possible<br>(1.0) >10,000 tons of avoided emissions possible<br>(5.0) >100,000 tons of avoided emissions possible<br>(10.0) >1 MMT of avoided emissions possible |
| | *Emissions types impacted* | |
| 26 | BC | Check with an x if this emissions source is affected. Quantify in column 21 |
| 27 | $CO_2$ | Check with an x if this emissions source is affected. Quantify in column 21 |
| 28 | HFC | Check with an x if this emissions source is affected. Quantify in column 21 |
| 29 | PFC | Check with an x if this emissions source is affected. Quantify in column 21 |
| 30 | $CH_4$ | Check with an x if this emissions source is affected. Quantify in column 21 |
| 31 | $N_2O$ | Check with an x if this emissions source is affected. Quantify in column 21 |
| 32 | $SF_6$ | Check with an x if this emissions source is affected. Quantify in column 21 |
| | **Technology Readiness** | |
| 33 | TRL Level | **Comparison Variable selections and weighted values include:**<br>(0) Pre-TRL 7 (e.g., Technology development or demonstration phase (pilot-scale, lab-scale, and earlier))<br>(2.5) TRL 7 (e.g., Full-scale, similar (prototypical) system demonstrated in relevant environment)<br>(5.0) TRL 8 (e.g., Actual system completed and qualified through test and demonstration.)<br>(7.5) TRL 9 (e.g., Actual system operated over the full range of expected mission conditions.)<br>(10) Commercial (e.g., system commercially available)<br>(10) TPC-CAT (Theoretical Process Change using Commercially Available Technology) |
| 34 | Measure Provider Maturity | **Comparison Variable selections and weighted values include:**<br>(1) Emerging (e.g., single vendor and/or technology developer may be young and fragile)<br>(5) Established (e.g., company or technology developer has some experience or history)<br>(10) Robust (e.g., multiple vendors and/or company or technology developer has significant resources and history) |
| 35 | Demonstration/ Deployment Notes | Manual Input. Notes on any deployment or commercialization activities. Is the vendor a multi-national or a startup? How reliable is this? |
| 36 | Expected Date of Commercial Availability | Month/Year |
| 37 | Notes on CA Market Potential | Manual Input. Consider compared to knowledge of the emissions source based on District data |
| 38 | Notes on National Market Potential | Manual Input. Consider compared to national emissions data, market knowledge, policy landscape, etc. |
| | **Economics** | |
| 39 | Cost notes | Discuss capital and operating costs and other general notes on the cost, particularly when compared to the baseline. Quantify in terms of cost per emissions reduction if possible. |
| 40 | Investment Scale (per individual deployment) | **Comparison Variable selections and weighted values include:**<br>(1.5) Mega-Project ($$$ millions)<br>(3) Very Large Investment ($ millions)<br>(4.5) Large Investment ($ hundreds of thousands)<br>(6) Mid-Size Investment ($ tens of thousands)<br>(7.5) Small Investment ($ thousands)<br>(9) Very Small Investment ($ hundreds)<br>(10) No cost measure |
| 41 | Cost Relative to Baseline | **Comparison Variable selections and weighted values include:**<br>(1) Higher cost than baseline<br>(5) Comparable cost to baseline<br>(10) Lower life-time cost than baseline |

| | | |
|---|---|---|
| 42 | Economic viability of mitigation measure | **Comparison Variable selections and weighted values include:**<br>(1) Low-viability (high added-cost per emissions reduction)<br>(2.5) OK-viability (low added-cost per emissions reduction)<br>(5) Good-viability (costs about the same as baseline, but with emissions reduction)<br>(7.5) Eventual return on investment (>2yrs)<br>(10) Rapid return on investment (<2yrs) |
| | **Barriers, Dependencies, and Risks** | |
| 43 | Technological Barriers | Manual input, notes. |
| 44 | TB Score | **Comparison Variable selections and weighted values include:**<br>(1) Very High - Measure has not been demonstrated in an operational environment and/or requires significant material process changes<br>(2.5) High - Measure has limited operational demonstration and/or requires material process changes<br>(5) Mid - Measure qualified through testing in operational environments<br>(7.5) Low - Measure operated over full range of operational conditions and/or requires minimal process changes<br>(10) Very Low - Measure is commercially widespread and/or requires minimal process changes |
| 45 | Economic-Market Barriers | Manual input, notes. |
| 46 | EMB Score | **Comparison Variable selections and weighted values include:**<br>(1) Very High - Emissions source is highly risk averse or has little market incentive to change and/or the mitigation measure has low economic viability<br>(2.5) High - Emissions source has little incentive to change, there is low demand, and/or the mitigation measure adds costs<br>(5) Mid - Mitigation measure has minimal economic implications for the emissions source and/or measure will face opposition from incumbents despite positive economics<br>(7.5) Low - Emissions source has some economic incentive to adopt the mitigation measure<br>(10) Very Low - Emissions source has economic incentive to adopt the mitigation measure and is likely to do so |
| 47 | Policy Barriers | Manual input, notes. |
| 48 | PB Score | **Comparison Variable selections and weighted values include:**<br>(1) Very High - Existing policy actively inhibits the mitigation measure and/or permitting is an issue<br>(2.5) High - Existing policy favors other mitigation measures and/or permitting may be an issue<br>(5) No policy or permitting issues anticipated<br>(7.5) Low - Existing policy creates a favorable environment for the mitigation measure (general)<br>(10) Very Low - Existing policy actively encourages the mitigation measure (specific) |
| 49 | Additional Benefits | Manual input. Comments on any additional Environmental, Social, or Economic Benefits |
| | Additional Notes and Possible District Actions | |
| 50 | Opportunities | Opportunities to catalyze energy systems change or additional GHG emissions beyond the specific technologies and emissions sources |
| 51 | Possible District Action | **Comparison Variable selections include:**<br>Incentivize - Mitigation measure could create a high-impact. Needed to incentive first adopters to demonstrate the measure and/or to support implementation of low/no-cost measures.<br>Regulate - Mitigation measure is well established, could create a high-impact, and imposes minimal burden on the emissions source. Emissions source has little incentive to change without the regulation.<br>Educate - Mitigation measure could make a high-impact may become more widespread with increased awareness.<br>Monitor - Mitigation measure is not yet demonstrated or there is not a clear role for the District at this time. |
| 52 | Notes | Notes on the potential need for District action. |
| | Key Comparison Scores | |
| 53 | Cost Effectiveness | (Emissions Reduction Potential * Economic Viability) / 10 |
| 54 | Emissions Reduction Potential | Average of Process Reduction Score, District Reduction Score, and National Reduction Score |
| 55 | Economic Viability | Average of Investment Score (weighted double), Cost Relative Score, and ROI Score |
| 56 | Overall Barriers | If any of columns 44 (Tech Barrier), 46 (Economic/Market Barrier), or 48 (Policy Barrier) =1 or 2.5, then the Overall Barriers score = 1 or 2.5 respectively. Otherwise, returns the average of the three Barrier scores. |
| | **Data Sources** | |
| 57 | Sources, citations, references and notes | Provide a description and link to the sources used for this mitigation measure. Note any literature, interviews, or other materials. |

# Appendix B – Prominent Resources

A high-level literature review for each sector identified GHG emissions mitigation measures. These sources include technology roadmaps, regulatory agency reports, academic survey literature, industry association best practice guides, and technology training materials and primers. Some of the most prominent resources used are listed below. References specific to only one mitigation measure, such as vendor website or product brochure, were also identified and are included in the MS Excel matrix or in the industry specific sections of this report.


**Emissions Inventories**

"Final 2017 Clean Air Plan. Spare the Air, Cool the Climate: A blueprint for clean air and climate protection in the Bay Area." Bay Area Air Quality Management District. Adopted April 19, 2017. baaqmd.gov/~/media/files/planning-and-research/plans/2017-clean-air-plan/attachment-a_-proposed-final-cap-vol-1-pdf.pdf

"Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016." U.S. EPA. 2018. epa.gov/sites/production/files/2018-01/documents/2018_complete_report.pdf

**Agriculture**

ICF Consulting. "Abatement of Emissions of Other Greenhouse Gases – Nitrous Oxide." IEAGHG, CRE Group Ltd, 9 June 2000, ieaghg.org/docs/General_Docs/Reports/PH3-29 nitrous oxide.pdf

Sudmeyer, Rob. "Reducing Nitrous Oxide Emissions from Agricultural Soils." Department of Primary Industries and Regional Development: Agriculture and Food, Government of Western Australia, 21 Aug. 2017, www.agric.wa.gov.au/climate-change/reducing-nitrous-oxide-emissions-agricultural-soils

**Buildings**

"Commercial Buildings Energy Consumption Survey (CBECS). U.S. Energy Information Administration. (2012). eia.gov/consumption/commercial/data/2012/

Lee, Dasheng, and Chin-Chi Cheng. "Energy savings by energy management systems: A review." Renewable and Sustainable Energy Reviews 56 (2016): 760-777.

UMich Industrial Assessment Center. "Technology and Equipment Resources." (2018). iac.engin.umich.edu/technologies/

"Quadrennial Technology Review Chapter 5: Increasing Efficiency of Building Systems and Technologies" U.S. Department of Energy. (2017). energy.gov/sites/prod/files/2017/03/f34/qtr-2015-chapter5.pdf

**Cement**

Cembureau. "Innovation in the Cement Industry." Cembureau, Cembureau, 1 Feb. 2017, cembureau.eu/media/1225/10819_cembureau_innovationbooklet_eu-ets_2017-02-01.pdf

Hills, Thomas, et al. "Carbon Capture in the Cement Industry: Technologies, Progress, and Retrofitting." Environmental Science & Technology, vol. 2016, no. 50, ser. 1, 2 Dec. 2015, pp. 366–377. 1, doi:10.1021/acs.est.5b03508.

International Finance Corporation. "Increasing the Use of Alternative Fuels at Cement Plants: International Best Practice." IFC, World Bank Group, 2017, ifc.org/wps/wcm/connect/cb361035-1872-4566-a7e7-d3d1441ad3ac/Alternative_Fuels_08%2004.pdf?MOD=AJPERES

**CHP**

ARPA-E. "Projects." ARPA-E, ARPA-E, arpa-e.energy.gov/?q=arpa-e-site-page/projects

"Catalog of CHP Technologies." U.S. Environmental Protection Agency. epa.gov/chp/catalog-chp-technologies

**Electronics Manufacturing**

CARB. "Initial statement of reasons for proposed regulation to reduce greenhouse gas emissions from semiconductor operations." (2009). arb.ca.gov/regact/2009/semi2009/semiisor.pdf

EPA. "Global mitigation of Non-CO2 GHGs abatement measures." (2013). epa.gov/sites/production/files/2016-06/documents/mac_report_2013.pdf

World Semiconductor Council. "Best Practice Guidance for Semiconductor PFC Emission Reduction." (2017). semiconductorcouncil.org/wp-content/uploads/2017/07/Best-Practice-Guidance-of-PFC-Emission-Reduction.pdf

**Metals**

"Industrial Efficiency Technology Database (IETD)." Industrial Efficiency Technology Database, Institute for Industrial Productivity, ietd.iipnetwork.org/

Sector Policies and Programs Division: Office of Air Quality Planning and Standards. "Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from the Iron and Steel Industry." EPA, U.S. Environmental Protection Agency, Sept. 2012, epa.gov/sites/production/files/2015-12/documents/ironsteel.pdf

**Petroleum Systems and Refineries**

Chemical Engineers' Resource Page. "Pinch Technology: Basics for Beginners." (2018 (undated)). pages.mtu.edu/~jwsuther/erdm/pinchtech.pdf

DOE. "Preheated Combustion Air, Process Heat Tip Sheet #1, Office of Industrial Technologies." (2002). nrel.gov/docs/fy02osti/31756.pdf

EPA. "Energy Efficiency Improvement and Cost Saving Opportunities for Petroleum Refineries." (2015). energystar.gov/buildings/tools-and-resources/energy-efficiency-improvement-and-cost-saving-opportunities-petroleum-refineries

IEA. "Technology Roadmap Energy and GHG Reductions in the Chemical Industry via Catalytic Processes." (2013). iea.org/publications/freepublications/publication/Chemical_Roadmap_2013_Final_WEB.pdf

Morrow, WR III, J Marano, J Sathaye, A Hasanbeigi, T Xu. "Assessment of Energy Efficiency Improvement in the United States Petroleum Refining Industry." (2013). osti.gov/servlets/purl/1171121

Wang, Y, R Smith, and J Kim. "Heat exchanger network retrofit optimization involving heat transfer enhancement." (2012). sciencedirect.com/science/article/pii/S1359431112001147

**Waste**

Campos, JL, D Valenzuela-Heredia, A Pedrouso, A Val del Rio, M Belmonte, and A Mosquera-Corral. "Greenhouse Gases Emissions from Wastewater Treatment Plants: Minimization, Treatment, and Prevention." (2016). hindawi.com/journals/jchem/2016/3796352/

Composting Council of Canada. "Compost Processing Technologies." compost.org/pdf/compost_proc_tech_eng.pdf

EPA. "Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from Municipal Solid Waste Landfills." (2011). epa.gov/sites/production/files/2015-12/documents/landfills.pdf

EPA. "Types of Composting and Understanding the Process." (2016). epa.gov/sustainable-management-food/types-composting-and-understanding-process

Frutos, OD, IA Arvelo, R Perez, G Quijano, and R Munoz. "Continuous nitrous oxide abatement in a novel denitrifying off-gas bioscrubber." (2014). link.springer.com/article/10.1007%2Fs00253-014-6329-8

Gabbar, HA, M Aboughaly, N Ayoub. "Comparative study of MSW heat treatment processes and electricity generation." (2018). sciencedirect.com/science/article/pii/S1743967117300120

Ge, H, PD Jensen, and DJ Batstone. "Temperature phased anaerobic digestion increases apparent hydrolysis rate for waste activated sludge." (2011). ncbi.nlm.nih.gov/pubmed/21185054

GMI. "Municipal Wastewater Methane: Reducing Emissions, Advancing Recovery and Use Opportunities." (2013). globalmethane.org/documents/ww_fs_eng.pdf

Levis, J, K Hodge, and M Barlaz. "Compost Process Modeling." (2015). ncsu.edu/~jwlevis/Presentations/Composting.pdf

Zhang, S. "What is the Highest and Best Use of Organic Solid Waste: Production of Compost or Production of Energy." (2012). sustain.ubc.ca/sites/sustain.ubc.ca/files/Zero%20Waste%20%20-%20Siduo%20Zhang%20-%20Compost%20vs%20%20Energy%20Production.pdf

Zhu, J, Q Wang, M Yuan, GYA Tan, F Sun, C Wang, W Wu, and PH Lee. "Microbiology and potential applications of aerobic methane oxidation coupled to denitrification (AME-D) process: A review." (2015). sciencedirect.com/science/article/pii/S0043135415304176?via%3Dihub

Zhu-Barker, X, SK Bailey, U KT Paw, M Burger, and WR Horwath. "Greenhouse gas emissions from green waste composting windrow." (2017). ncbi.nlm.nih.gov/pubmed/27751682

**Other**

Advanced Manufacturing Office. "Bandwidth Study on Energy Use and Potential Energy Savings Opportunities in U.S. Food and Beverage Manufacturing." Energy.gov, U.S. Department of Energy: Advanced Manufacturing Office, Sept. 2017, energy.gov/sites/prod/files/2017/12/f46/Food_and_beverage_bandwidth_study_2017.pdf

Advanced Manufacturing Office. "Bandwidth Study on Energy Use and Potential Energy Savings Opportunities in U.S. Glass Manufacturing ." Energy.gov, U.S. Department of Energy: Advanced Manufacturing Office, Sept. 2017, energy.gov/sites/prod/files/2017/12/f46/Glass_bandwidth_study_2017.pdf

Murtagh, Connie, and Jim Vallette. "Optimizing Recycling: Reclaimed Asphalt Pavement (RAP) in Building & Construction." Healthy Building Network, San Francisco Department of the Environment, 2017, s3.amazonaws.com/hbnweb.dev/uploads/files/stopwaste-asphalt-report.pdf

Sagar, V. R., and P. Suresh Kumar. "Recent Advances in Drying and Dehydration of Fruits and Vegetables: a Review." Journal of Food Science and Technology, vol. 47, no. 1, 2010, pp. 15–26., doi:10.1007/s13197-010-0010-8.

Scalet, Bianca Maria, et al. "Best Available Techniques (BAT) Reference Document for the Manufacture of Glass." European Commission, Joint Research Centre, 2013, eippcb.jrc.ec.europa.eu/reference/BREF/GLS_Adopted_03_2012.pdf

Springer, Cecilia, and Ali Hasanbeigi. "Emerging Energy Efficiency and Carbon Dioxide Emissions reduction Technologies for the Glass Industry." Lawrence Berkeley National Laboratory, China Energy Group, July 2017, china.lbl.gov/sites/default/files/lbl_glass_final.pdf

Worrell, Ernst, et al. "Energy Efficiency Improvement and Cost Saving Opportunities for the Glass Industry." Energy Star, U.S. Environmental Protection Agency, Mar. 2008, energystar.gov/ia/business/industry/Glass-Guide.pdf

# Appendix C – Comparison Variable Score Summary

Appendix C lists the identified mitigation measures by industry sector along with their associated comparison variable scores. The following reference table describes the weighting of each comparison variable and how scores are calculated. The technology evaluation strove to be as complete as possible. However, sufficient data is not available for all the mitigation measures.

Table 5. Comparison Variable Score Reference Table

| **Cost Effectiveness** | (Emissions Reduction Potential * Economic Viability) / 10 | |
|---|---|---|
| **Ease of Adoption (Overall Barriers)** | Overall Barriers defaults to Very High or High if any of Technical, Economic and Market, or Policy Barriers is Very High or High. Otherwise, is the average of the three Barrier scores. | |
| **Technical Barriers**<br>(1) Very High - Measure has not been demonstrated in an operational environment and/or requires significant material process changes<br>(2.5) High - Measure has limited operational demonstration and/or requires material process changes<br>(5) Mid - Measure qualified through testing in operational environments<br>(7.5) Low - Measure operated over full range of operational conditions and/or requires minimal process changes<br>(10) Very Low - Measure is commercially widespread and/or requires minimal process changes | **Economic and Market Barriers**<br>(1) Very High - Emissions source is highly risk averse or has little market incentive to change and/or the mitigation measure has low economic viability<br>(2.5) High - Emissions source has little incentive to change, there is low demand, and/or the mitigation measure adds costs<br>(5) Mid - Mitigation measure has minimal economic implications for the emissions source and/or measure will face opposition from incumbents despite positive economics<br>(7.5) Low - Emissions source has some economic incentive to adopt the mitigation measure<br>(10) Very Low - Emissions source has economic incentive to adopt the mitigation measure and is likely to do so | **Policy Barriers**<br>(1) Very High - Existing policy actively inhibits the mitigation measure and/or permitting is an issue<br>(2.5) High - Existing policy favors other mitigation measures and/or permitting may be an issue<br>(5) No policy or permitting issues anticipated<br>(7.5) Low - Existing policy creates a favorable environment for the mitigation measure (general)<br>(10) Very Low - Existing policy actively encourages the mitigation measure (specific) |
| **Emissions Reduction Potential** | Average of Process Reduction Score, District Reduction Score, and National Reduction Score | |
| **Process Emissions Impact Ranking**<br>(1.0) Negligible emissions reduction vs baseline<br>(2.5) 1-5% emissions reduction vs baseline<br>(5.0) 5-15% emissions reduction vs baseline<br>(7.5) 15-50% emissions reduction vs baseline<br>(10.0) 50-100% emissions reduction vs baseline | **District Emissions Impact Ranking**<br>(0) Negligible avoided emissions<br>(0.1) Hundreds of tons of avoided emissions possible<br>(1.0) Thousands of tons of avoided emissions possible<br>(5.0) >10,000 tons of avoided emissions possible<br>(10.0) >100,000 tons of avoided emissions possible | **National Emissions Impact Ranking**<br>(0) Negligible avoided emissions<br>(0.1) Thousands of tons of avoided emissions possible<br>(1.0) >10,000 tons of avoided emissions possible<br>(5.0) >100,000 tons of avoided emissions possible<br>(10.0) >1 MMT of avoided emissions possible |
| **Economic Viability** | Average of Investment Scale (weighted double), Cost Relative Score, and ROI Score | |
| **Investment Scale**<br>(per individual deployment)<br>(1.5) Mega-Project ($$$ millions)<br>(3) Very Large Investment ($ millions)<br>(4.5) Large Investment ($ hundreds of thousands)<br>(6) Mid-Size Investment ($ tens of thousands)<br>(7.5) Small Investment ($ thousands)<br>(9) Very Small Investment ($ hundreds)<br>(10) No cost measure | **Cost Relative to Baseline**<br>(1) Higher cost than baseline<br>(5) Comparable cost to baseline<br>(10) Lower life-time cost than baseline | **ROI of Mitigation Measure**<br>(1) Low-viability (high added-cost per emissions reduction)<br>(2.5) OK-viability (low added-cost per emissions reduction)<br>(5) Good-viability (costs about the same as baseline, but with emissions reduction)<br>(7.5) Eventual return on investment (>2yrs)<br>(10) Rapid return on investment (<2yrs) |
| **TRL & Company Maturity** | Average of TRL Score and Measure Provider Maturity | |
| **TRL Level**<br>(0) Pre-TRL 7 (e.g., Technology development or demonstration phase (pilot-scale, lab-scale, and earlier))<br>(2.5) TRL 7 (e.g., Full-scale, similar (prototypical) system demonstrated in relevant environment)<br>(5.0) TRL 8 (e.g., Actual system completed and qualified through test and demonstration.)<br>(7.5) TRL 9 (e.g., Actual system operated over the full range of expected mission conditions.)<br>(10) Commercial (e.g., system commercially available)<br>(10) TPC-CAT (Theoretical Process Change using Commercially Available Technology) | **Measure Provider Maturity**<br>(1) Emerging (e.g., single vendor and/or technology developer may be young and fragile)<br>(5) Established (e.g., company or technology developer has some experience or history)<br>(10) Robust (e.g., multiple vendors and/or company or technology developer has significant resources and history) | |

Table 6. Agriculture Mitigation Measures, Comparison Variable Score Summary

| Measure Name | Subsector | Cost Effectiveness | Barriers (Favorability) | Emissions Reduction Potential | Economic Viability | Investment Scale (Affordability) | TRL & Company Maturity |
|---|---|---|---|---|---|---|---|
| **Agriculture** | | | | | | | |
| Soil Testing | Agricultural Soil Management | 7.6 | 6.7 | 9.2 | 8.3 | 7.5 | 7.5 |
| Biochar Use | Agricultural Soil Management | 7.3 | 2.5 | 9.2 | 7.9 | 7.5 | 7.5 |
| Dietary Design | Enteric Fermentation | 6.4 | 7.5 | 7.5 | 8.5 | 9.0 | 7.5 |
| Pyrolysis of Manure | Manure Management | 6.1 | 2.5 | 9.2 | 6.7 | 7.5 | 6.3 |
| Compost Use | Agricultural Soil Management | 5.1 | 6.7 | 9.2 | 5.6 | 7.5 | 7.5 |
| Methane Capture | Manure Management | 4.5 | 2.5 | 8.3 | 5.4 | 6.0 | 7.5 |
| Nitrification Inhibitor | Agricultural Soil Management | 4.0 | 7.5 | 9.2 | 4.3 | 6.0 | 10.0 |
| Legume Crops | Agricultural Soil Management | 3.7 | 2.5 | 6.7 | 5.6 | 7.5 | 5.5 |
| Hydrothermal Liquefaction | Manure Management | 2.4 | 1.0 | 10.0 | 2.4 | 1.5 | 0.5 |
| Hydrothermal Carbonization | Manure Management | - | 2.5 | - | 3.4 | 3.0 | 6.3 |
| Chemical Treatments for Dry Manure | Manure Management | - | - | - | - | - | 5.0 |

Table 7. Commercial Building (non-HVAC) Mitigation Measures, Comparison Variable Score Summary

| Measure Name | Subsector | Cost Effectiveness | Barriers (Favorability) | Emissions Reduction Potential | Economic Viability | Investment Scale (Affordability) | TRL & Company Maturity |
|---|---|---|---|---|---|---|---|
| **Buildings (Commercial non-HVAC)** | | | | | | | |
| Building Energy Management Systems (EMS) | Commercial - non-HVAC | 5.5 | 7.5 | 7.5 | 7.3 | 6.0 | 10.0 |
| Dynamic windows | Commercial - non-HVAC | 3.0 | 5.8 | 5.0 | 6.1 | 6.0 | 7.5 |
| Solar water heater | Commercial - non-HVAC | 3.0 | 5.8 | 5.0 | 6.0 | 7.5 | 10.0 |
| Low-emissivity window coatings/tints | Commercial - non-HVAC | 2.7 | 8.3 | 5.0 | 5.4 | 6.0 | 10.0 |
| Low-emissivity/tinted window films | Commercial - non-HVAC | 2.7 | 8.3 | 5.0 | 5.4 | 6.0 | 10.0 |
| LED lighting - new | Commercial - non-HVAC | 2.0 | 7.5 | 2.5 | 7.9 | 7.5 | 10.0 |
| LED lighting - retrofit | Commercial - non-HVAC | 2.0 | 7.5 | 2.5 | 7.9 | 7.5 | 10.0 |
| Condensing hot water heater | Commercial - non-HVAC | 1.9 | 8.3 | 2.5 | 7.7 | 9.0 | 10.0 |
| Tankless water heater | Commercial - non-HVAC | 1.9 | 7.5 | 2.5 | 7.4 | 9.0 | 10.0 |
| Commercial $CO_2$ electric heat pump water heater | Commercial - non-HVAC | 1.8 | 1.0 | 2.5 | 7.0 | 9.0 | 0.5 |
| Automated window shades | Commercial - non-HVAC | 1.4 | 6.7 | 2.5 | 5.4 | 6.0 | 5.0 |
| Integrated lighting control system | Commercial - non-HVAC | 1.4 | 6.7 | 2.5 | 5.4 | 6.0 | 7.5 |
| Hybrid/heat-pump water heater | Commercial - non-HVAC | 0.7 | 2.5 | 1.0 | 6.6 | 9.0 | 10.0 |
| Direct Current (DC) buildings | Commercial - non-HVAC | - | 2.5 | - | - | - | 8.8 |
| Absorption heat pump water heater | Commercial - non-HVAC | - | 1.0 | 2.5 | - | - | 6.3 |
| Automated demand response | Commercial - non-HVAC | - | - | - | - | 7.5 | 6.3 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Built-in photovoltaics (BIPV) windows | Commercial - non-HVAC | - | - | - | - | - | 6.3 |
| Circuit-level hardware sensors | Commercial - non-HVAC | - | - | - | 5.3 | 7.5 | 4.3 |
| Commercial building battery storage system | Commercial - non-HVAC | - | - | - | - | - | 10.0 |
| Fluid cooling for cooling systems | Commercial - non-HVAC | - | - | - | - | - | 1.8 |
| Integrated PV | Commercial - non-HVAC | - | - | - | - | - | 5.0 |
| Laser-based emissions sensors | Commercial - non-HVAC | - | - | - | 4.3 | 6.0 | 1.8 |
| Near real-time environmental data sensory package | Commercial - non-HVAC | - | - | - | 3.3 | 4.5 | 0.5 |
| Web and mobile platform streamlining commercial lighting compliance | Commercial - non-HVAC | - | - | - | 9.3 | 9.0 | 1.8 |

Table 8. Commercial Building (HVAC) Mitigation Measures, Comparison Variable Score Summary

| Measure Name | Subsector | Cost Effectiveness | Emissions Reduction Potential | Economic Viability | Barriers (Favorability) | Investment Scale (Affordability) | TRL & Company Maturity |
|---|---|---|---|---|---|---|---|
| **Buildings (Commercial HVAC)** | | | | | | | |
| Heat recovery ventilation (HRV) system | Commercial - HVAC | 2.7 | 6.7 | 5.0 | 5.4 | 6.0 | 10.0 |
| Variable frequency drive (VFD) for chillers | Commercial - HVAC | 2.1 | 8.3 | 2.5 | 8.3 | 7.5 | 10.0 |
| High-volume, low-speed (HVLS) ceiling fans | Commercial - HVAC | 2.0 | 5.8 | 2.5 | 7.9 | 7.5 | 7.5 |
| Variable refrigerant flow (VRF) ASHP | Commercial - HVAC | 1.4 | 7.5 | 2.5 | 5.4 | 6.0 | 10.0 |
| Magnetic-bearing chiller compressors | Commercial - HVAC | 1.4 | 5.8 | 2.5 | 5.4 | 6.0 | 10.0 |
| Air-source heat pumps (ASHP), air-cooled chiller (ACCH), and water-cooled chillers for HVAC | Commercial - HVAC | - | 8.3 | - | - | - | 10.0 |
| Radiant cooling (hydronic) | Commercial - HVAC | - | 6.7 | 5.0 | - | - | 7.5 |
| Radiant heating (hydronic) | Commercial - HVAC | - | 6.7 | 5.0 | - | - | 7.5 |
| Active air quality monitoring for HVAC load reduction | Commercial - HVAC | - | 5.8 | 5.0 | - | - | 7.5 |
| Radiant heating (electric) | Commercial - HVAC | - | 5.8 | 5.0 | - | - | 5.5 |
| DC-powered HVAC systems | Commercial - HVAC | - | 2.5 | 2.5 | - | - | 4.3 |

Table 9. Residential Building Mitigation Measures, Comparison Variable Score Summary

| Measure Name | Subsector | Cost Effectiveness | Barriers (Favorability) | Emissions Reduction Potential | Economic Viability | Investment Scale (Affordability) | TRL & Company Maturity |
|---|---|---|---|---|---|---|---|
| **Buildings (Residential)** | | | | | | | |
| Mini-split Air-source heat pumps (ASHP) | Residential | 4.0 | 7.5 | 5.0 | 7.9 | 7.5 | 5.0 |
| Air-source heat pumps (ASHP) for HVAC | Residential | 3.5 | 8.3 | 5.0 | 7.1 | 7.5 | 5.0 |
| Tankless water heater | Residential | 3.0 | 7.5 | 5.0 | 6.0 | 7.5 | 5.0 |
| Insulating concrete forms | Residential | 3.0 | 5.8 | 5.0 | 6.0 | 7.5 | 5.0 |
| Solar water heater | Residential | 2.7 | 5.8 | 5.0 | 5.3 | 7.5 | 5.0 |
| Smart thermostats | Residential | 2.3 | 8.3 | 2.5 | 9.3 | 9.0 | 10.0 |
| LED lighting - new | Residential | 2.2 | 10.0 | 2.5 | 8.9 | 9.0 | 5.0 |
| LED lighting - retrofit | Residential | 2.2 | 9.2 | 2.5 | 8.9 | 9.0 | 5.0 |
| Automated window shades | Residential | 2.1 | 6.7 | 2.5 | 8.5 | 9.0 | 5.0 |
| Low-emissivity windows | Residential | 2.1 | 6.7 | 2.5 | 8.5 | 9.0 | 5.0 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Hybrid/heat-pump water heater | Residential | 1.6 | 5.8 | 2.5 | 6.6 | 9.0 | 10.0 |
| High-volume, low-speed (HVLS) ceiling fans | Residential | 1.6 | 5.0 | 2.5 | 6.4 | 7.5 | 5.5 |
| Residential heat recovery ventilator | Residential | 1.5 | 5.0 | 2.5 | 6.0 | 7.5 | 10.0 |
| HVAC dampers for zone control | Residential | 0.6 | 5.8 | 1.0 | 6.4 | 7.5 | 10.0 |
| High-R value windows | Residential | - | 5.8 | 1.0 | - | - | 7.5 |
| Continuous insulation systems | Residential | - | - | - | - | - | 5.0 |
| Integrated PV | Residential | - | - | - | - | - | 5.0 |
| Residential battery storage system | Residential | - | - | - | - | - | 5.0 |
| Thermal demand response | Residential | - | - | - | - | 9.0 | 4.3 |

Table 10. Cement Production Mitigation Measures, Comparison Variable Score Summary

| Measure Name | Subsector | Cost Effectiveness | Barriers (Favorability) | Emissions Reduction Potential | Economic Viability | Investment Scale (Affordability) | TRL & Company Maturity |
|---|---|---|---|---|---|---|---|
| **Cement Production** | | | | | | | |
| Fly Ash SCM | Cement Production | 7.6 | 6.7 | 9.2 | 8.3 | 7.5 | 7.5 |
| Slag SCM | Cement Production | 7.6 | 6.7 | 9.2 | 8.3 | 7.5 | 7.5 |
| Belite-Rich Cement | Cement Production | 5.1 | 2.5 | 9.2 | 5.6 | 7.5 | 5.5 |
| Fuel Switching | Cement Production | 3.5 | 5.8 | 6.7 | 5.3 | 6.0 | 10.0 |
| Calcium Sulfoaluminate (CSA) Cement | Cement Production | 3.3 | 2.5 | 5.8 | 5.6 | 7.5 | 7.5 |
| Torrefaction and Pyrolysis to produce Biocoal | Cement Production | 3.3 | 2.5 | 7.5 | 4.3 | 6.0 | 5.5 |
| Electricity demand side management (DSM) | Cement Production | 3.1 | 2.5 | 4.2 | 7.5 | 7.5 | 5.0 |
| Cement $CO_2$ Direct Capture Units (DCU) | Cement Production | 2.3 | 2.5 | 10.0 | 2.3 | 3.0 | 5.0 |
| $CO_2$ Derived Calcium Carbonate and SCM | Cement Production | 1.5 | - | 8.3 | 1.8 | - | 4.3 |
| Amine scrubbing | Cement Production | 1.3 | 1.0 | 10.0 | 1.3 | 1.5 | 2.5 |
| Calcium Looping | Cement Production | 1.3 | 1.0 | 10.0 | 1.3 | 1.5 | 2.5 |
| Partial and Full Oxy Fuel Combustion | Cement Production | 1.3 | 1.0 | 10.0 | 1.3 | 1.5 | 5.0 |
| $CO_2$ Derived Limestone Replacement | Cement Production | - | - | 10.0 | - | - | 4.3 |
| Emission Capture to grow Algae | Cement Production | - | - | - | - | - | 1.8 |

Note: Supplemental Cementitious Materials (SCM)

Table 11. CHP and Power Generation Mitigation Measures, Comparison Variable Score Summary

| Measure Name | Subsector | Cost Effectiveness | Barriers (Favorability) | Emissions Reduction Potential | Economic Viability | Investment Scale (Affordability) | TRL & Company Maturity |
|---|---|---|---|---|---|---|---|
| **CHP and Power Generation** | | | | | | | |
| Second-life battery | Electricity Generation | 6.3 | 5.8 | 9.2 | 6.9 | 6.0 | 5.5 |
| Net Power Allam Cycle Turbines | Electricity Generation - Power Plants | 3.9 | 6.7 | 10.0 | 3.9 | 1.5 | 5.5 |
| Hydrogen Fuel Cells and Electrolyzers | Hydrogen Fuel Cells/ Electrolyzers | 3.7 | 1.0 | 10.0 | 3.7 | 3.0 | 5.5 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Arsensis, biogas-based CHP Microgrid System | CHP | 3.2 | 2.5 | 5.8 | 5.5 | 4.5 | 4.3 |
| Brayton Cycle Advanced Microturbine Engine for Residential CHP | CHP | 2.9 | 2.5 | 3.7 | 7.9 | 7.5 | 0.5 |
| EnerTwin CHP Microturbines for Residential and Small Commercial Use | CHP | 2.9 | 2.5 | 3.7 | 7.9 | 7.5 | 4.3 |
| Ultra-lean, turbulent jet ignition (TJI), CHP | CHP | 2.9 | 2.5 | 3.7 | 7.9 | 7.5 | 0.5 |
| Stirling Cycle Microturbine Engine for Residential CHP | CHP | 2.9 | 1.0 | 3.7 | 7.9 | 7.5 | 0.5 |
| Optimization Software for CHP | CHP | 1.8 | 5.8 | 2.5 | 7.1 | 7.5 | 10.0 |
| Nickel-zinc battery power solutions | Electricity Generation | - | - | - | 5.3 | 7.5 | 6.3 |

Table 12. Semiconductor Manufacturing Mitigation Measures, Comparison Variable Score Summary

| Measure Name | Subsector | Cost Effectiveness | Barriers (Favorability) | Emissions Reduction Potential | Economic Viability | Investment Scale (Affordability) | TRL & Company Maturity |
|---|---|---|---|---|---|---|---|
| **Electronics Manufacturing** | | | | | | | |
| Leak detection and elimination | Semiconductors | 3.0 | 6.3 | 5.0 | 6.0 | 7.5 | 10.0 |
| Remote plasma cleanout of CVD chamber using NF3 | Semiconductors | 2.3 | 2.5 | 5.0 | 4.6 | 6.0 | 5.0 |
| Catalytic abatement of exhaust gas stream | Semiconductors | 1.8 | 2.5 | 10.0 | 1.8 | - | 5.5 |
| Etching process optimization | Semiconductors | 1.5 | 7.5 | 2.5 | 6.0 | 7.5 | 10.0 |
| CVD Process optimization | Semiconductors | 1.3 | 7.5 | 2.5 | 5.0 | 6.0 | 10.0 |
| CVD Endpoint detection using OES sensors and PCA | Semiconductors | 1.1 | 6.3 | 2.5 | 4.6 | 6.0 | 10.0 |
| CVD Endpoint detection using RF sensors | Semiconductors | 1.1 | 6.3 | 2.5 | 4.6 | 6.0 | 10.0 |
| Etching endpoint detection using OES sensors | Semiconductors | 1.1 | 6.3 | 2.5 | 4.6 | 6.0 | 7.5 |
| Etching endpoint detection using RF sensors | Semiconductors | 1.1 | 6.3 | 2.5 | 4.6 | 6.0 | 10.0 |
| Replace process gases with low-GWP or GWP-free gases | Semiconductors | - | 2.5 | 10.0 | - | 7.5 | 5.0 |

Table 13. Metals Production Mitigation Measures, Comparison Variable Score Summary

| Measure Name | Subsector | Cost Effectiveness | Barriers (Favorability) | Emissions Reduction Potential | Economic Viability | Investment Scale (Affordability) | TRL & Company Maturity |
|---|---|---|---|---|---|---|---|
| **Metals Production** | | | | | | | |
| Walking beam furnace | Iron and Steel Production | 5.7 | 2.5 | 6.2 | 9.2 | 10.0 | 6.3 |
| PVC pipe as a replacement for ductile iron pipe | Iron and Steel Production | 4.8 | 6.7 | 7.0 | 6.9 | 6.0 | 7.5 |
| Inter-electrode insulation in electrolytic pickling line | Iron and Steel Production | 3.9 | 2.5 | 4.3 | 9.2 | 10.0 | 2.5 |
| Controlling oxygen levels and/or variable speed drives on combustion air fans | Iron and Steel Production | 3.7 | 5.0 | 5.0 | 7.3 | 6.0 | 0.0 |
| Heat recovery to the product | Iron and Steel Production | 3.1 | 2.5 | 7.0 | 4.4 | 4.5 | 6.3 |
| Continuous annealing | Iron and Steel Production | 1.5 | 2.5 | 6.2 | 2.4 | 1.5 | 7.5 |

Note: PVC piping is an alternative to ductile iron pipes for water and other infrastructure. PVC pipe can be up to 70% less expensive than iron pipe, and last longer with greater pumping efficiency. This measure is included as a higher-level consideration, but it would reduce demand for iron piping and would be opposed by U.S. metal produces because it displaces the need for their product.

Table 14. Petroleum Systems Mitigation Measures, Comparison Variable Score Summary

| Measure Name | Subsector | Cost Effectiveness | Barriers (Favorability) | Emissions Reduction Potential | Economic Viability | Investment Scale (Affordability) | TRL & Company Maturity |
|---|---|---|---|---|---|---|---|
| **Petroleum Systems** | | | | | | | |
| Boiler - Maintenance | Combustion | 6.9 | 7.5 | 8.3 | 8.3 | 7.5 | 5.0 |
| Steam trap & distribution system maintenance | Refining - Other | 6.9 | 5.8 | 8.3 | 8.3 | 7.5 | 5.0 |
| Motor & pump optimization | Refining - Other | 6.7 | 7.5 | 9.2 | 7.3 | 6.0 | 5.0 |
| Steam trap automated monitoring | Refining - Other | 6.3 | 2.5 | 7.5 | 8.3 | 7.5 | 5.0 |
| Boiler - Duplex high efficiency flame holder | Combustion | 5.7 | 6.7 | 6.3 | 9.2 | 10.0 | 3.8 |
| Process Heaters - Duplex high efficiency flame holder | Combustion | 5.7 | 6.7 | 6.3 | 9.2 | 10.0 | 5.0 |
| High efficiency heat exchangers | Refining - Other | 5.5 | 6.7 | 8.8 | 6.3 | 4.5 | 7.5 |
| Process Heaters - air preheat | Combustion | 5.5 | 5.0 | 8.8 | 6.3 | 4.5 | 5.0 |
| Steam distribution high efficiency insulation | Refining - Other | 5.3 | 5.8 | 8.3 | 6.3 | 4.5 | 5.0 |
| Liquid Ring Vacuum Pump | Refining - Other | 5.3 | 2.5 | 8.3 | 6.3 | 4.5 | 7.5 |
| Waste Heat Recovery (WHR) - blowdown steam | Refining - Other | 5.2 | 5.0 | 7.5 | 6.9 | 6.0 | 7.5 |
| Boiler - Low-NOx burner | Combustion | 4.9 | 6.7 | 10.0 | 4.9 | 3.0 | 7.5 |
| Advanced Reciprocating Engines (Waukesha Series Five rich-burn engines (VHP platform)) | Natural Gas Transmission/ Compression | 4.6 | 7.5 | 5.5 | 8.3 | 7.5 | 8.8 |
| Boiler - High-efficiency insulation | Combustion | 4.6 | 5.8 | 5.0 | 9.2 | 10.0 | 5.0 |
| Dividing Wall Column | Refining - Other | 4.5 | 2.5 | 9.2 | 4.9 | 3.0 | 10.0 |
| Power recovery | Catalytic Cracking/Reforming | 4.1 | 5.0 | 8.3 | 4.9 | 3.0 | 5.0 |
| Distillation - CDU maintenance | Refining - Other | 4.1 | - | 7.5 | 5.5 | 4.5 | 5.0 |
| Process automation, integration, and optimization | Refining - Other | 4.0 | 6.7 | 6.3 | 6.3 | 4.5 | 8.8 |
| Progressive Crude Distillation unit | Refining - Other | 2.2 | 2.5 | 9.2 | 2.4 | 1.5 | 7.5 |
| Boiler - Sensors and control equipment | Combustion | 2.1 | 7.5 | 2.5 | 8.3 | 7.5 | 10.0 |
| Distillation - Chilled water condenser | Refining - Other | 0.2 | - | 0.3 | 5.1 | 4.5 | 5.0 |
| Flare gas recovery | Flares | - | 9.2 | 9.2 | - | - | 10.0 |
| Hydrogen management optimization | Refining - Other | - | 7.5 | - | 6.5 | 6.0 | 5.0 |
| Hydrogen recovery | Refining - Other | - | 7.5 | - | 7.3 | 6.0 | 10.0 |
| Boiler - Water pre-treatment | Combustion | - | 2.5 | - | 6.3 | 4.5 | 10.0 |
| Energy management system | Refining - Other | - | 2.5 | - | 6.3 | 4.5 | 10.0 |
| Distillation - Optimize distillation column operation | Refining - Other | - | - | - | - | - | 7.5 |

Table 15. Waste, Municipal Landfills/Other Mitigation Measures, Comparison Variable Score Summary

| Measure Name | Subsector | Cost Effectiveness | Barriers (Favorability) | Emissions Reduction Potential | Economic Viability | Investment Scale (Affordability) | TRL & Company Maturity |
|---|---|---|---|---|---|---|---|
| **Waste (Municipal Landfills/Other)** | | | | | | | |
| LFG engines/CHP | Municipal Landfills | 2.6 | 2.5 | 7.5 | 3.4 | 3.0 | 10.0 |
| LFG microturbines | Municipal Landfills | 2.6 | 2.5 | 7.5 | 3.4 | 3.0 | 7.5 |
| Active LFG recovery systems | Municipal Landfills | 2.2 | 1.0 | 8.3 | 2.6 | 3.0 | 7.5 |
| LFG Biofiltration (Bio-oxidation) and biocovers | Municipal Landfills | 2.1 | 2.5 | 6.2 | 3.3 | 4.5 | 5.0 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Biochar from agricultural and forest waste | Waste Sources of Indirect GHG | 2.1 | 2.5 | 5.0 | 4.3 | - | 5.5 |
| LFG recovery efficiency improvements | Municipal Landfills | 1.9 | 5.0 | 5.8 | 3.3 | 4.5 | 7.5 |
| Wood waste Gasification | Gasification | 1.7 | 2.5 | 5.0 | 3.4 | 3.0 | 4.3 |
| MSW Anaerobic digestion | Municipal Landfills | 1.3 | 2.5 | 10.0 | 1.3 | 1.5 | 6.3 |
| MSW catalytic gasification | Municipal Landfills | - | 2.5 | - | 3.7 | 3.0 | 4.3 |
| Passive LFG recovery systems | Municipal Landfills | - | 2.5 | 7.5 | - | - | 7.5 |
| MSW pyrolysis | Municipal Landfills | - | 1.0 | - | 2.3 | 3.0 | 0.5 |
| Geomembrane landfill cap/cover | Municipal Landfills | - | - | - | - | - | 7.5 |
| LFG cleanup | Municipal Landfills | - | - | - | - | - | 5.0 |
| Methane sensors for leak detection | Municipal Landfills | - | - | 5.8 | - | - | 7.5 |
| Waste incinerators | Solid Waste Combustion | - | - | - | - | - | 5.0 |

Table 16. Waste, Composting/POTWs Mitigation Measures, Comparison Variable Score Summary

| Measure Name | Subsector | Cost Effectiveness | Barriers (Favorability) | Emissions Reduction Potential | Economic Viability | Investment Scale (Affordability) | TRL & Company Maturity |
|---|---|---|---|---|---|---|---|
| **Waste (Composting/POTWs)** | | | | | | | |
| Shortcut nitrogen removal (anammox) | Municipal Wastewater | 4.8 | 5.8 | 7.5 | 6.3 | 4.5 | 7.5 |
| Microalgae to replace denitrification system | Municipal Wastewater | 4.3 | 1.0 | 10.0 | 4.3 | 6.0 | 1.8 |
| Nitrification tank gas capture and co-firing | Municipal Wastewater | 4.2 | 6.3 | 7.5 | 5.6 | 7.5 | 5.0 |
| Adjust operating parameters to reduce formation of GHGs in sludge path | Municipal Wastewater | 3.8 | 2.5 | 5.0 | 7.5 | - | 5.5 |
| Aerated static pile (ASP) | Composting | 3.4 | 8.3 | 9.2 | 3.7 | 3.0 | 7.5 |
| Extended Aerated Static Pile | Composting | 3.4 | 6.7 | 9.2 | 3.7 | 3.0 | 7.5 |
| Geomembrane cover for anaerobic digester | Municipal Wastewater | 3.0 | 6.7 | 10.0 | 3.0 | - | 7.5 |
| Methane capture and flaring from activated sludge | Municipal Wastewater | 3.0 | 2.5 | 10.0 | 3.0 | - | 10.0 |
| Bioscrubber for $N_2O$ denitrification in activated sludge path | Municipal Wastewater | 2.7 | 6.7 | 7.5 | 3.6 | 4.5 | 7.5 |
| Microalgae cultivation for $CO_2$ capture in sludge stream | Municipal Wastewater | 2.5 | 6.3 | 5.0 | 5.0 | 6.0 | 1.8 |
| Thermophilic AD for high-efficiency biogas production | Municipal Wastewater | 2.5 | 2.5 | 5.0 | 4.9 | 3.0 | 5.5 |
| Open bay composting | Composting | 2.4 | 2.5 | 9.2 | 2.6 | 3.0 | 7.5 |
| Bioprocesses for oxidation of $CH_4$ into $CO_2$ | Municipal Wastewater | 2.3 | 2.5 | 7.5 | 3.0 | - | 0.0 |
| Open-air windrows | Composting | 2.1 | 8.3 | 5.8 | 3.7 | 3.0 | 7.5 |
| Enclosed Aerated Static Pile (Silage Bag) | Composting | 2.1 | 2.5 | 9.2 | 2.3 | 3.0 | 7.5 |
| Membrane cover for compost piles | Composting | 1.9 | 10.0 | 7.5 | 2.6 | 3.0 | 7.5 |
| Temperature-phased AD for biogas production | Municipal Wastewater | 1.7 | 2.5 | 5.0 | 3.4 | 3.0 | 4.3 |
| Modular in-vessel composting | Composting | 1.2 | 1.0 | 9.2 | 1.3 | 1.5 | 5.5 |
| Coupled aerobic-anoxic nitrous decomposition operation (CANDO) process | Municipal Wastewater | 0.6 | 5.0 | 1.0 | 6.3 | - | 4.3 |
| Rotary drums/digesters | Composting | - | - | 9.2 | - | - | 5.5 |

Table 17. Other Mitigation Measures, Comparison Variable Score Summary

| Measure Name | Subsector | Cost Effectiveness | Barriers (Favorability) | Emissions Reduction Potential | Economic Viability | Investment Scale (Affordability) | TRL & Company Maturity |
|---|---|---|---|---|---|---|---|
| **Other** | | | | | | | |
| Mobile recycling systems (Cold-in-place recycling) | Asphalt production | 7.5 | 7.5 | 10.0 | 7.5 | - | 10.0 |
| Oscillating combustion | Glass Production | 6.9 | 6.3 | 7.5 | 9.2 | 10.0 | 3.8 |
| Increased recycled asphalt percentages | Asphalt production | 5.6 | 6.3 | 7.5 | 7.5 | - | 10.0 |
| Carbon capture and conversion to sodium bicarbonate system | Carbon Dioxide Supply and Injection | 5.6 | 1.0 | 10.0 | 5.6 | 7.5 | 0.5 |
| Heat pump dehumidifier assisted drying | Food Processing | 5.2 | 5.8 | 7.5 | 6.9 | 6.0 | 5.0 |
| Oxy-fuel fired forehearths | Glass Production | 4.9 | 6.7 | 8.3 | 5.9 | 4.5 | 5.0 |
| Advanced ohmic heating | Food Processing | 4.4 | 5.8 | 7.5 | 5.9 | 4.5 | 5.5 |
| Microwave drying | Food Processing | 4.4 | 5.0 | 7.5 | 5.9 | 4.5 | 7.5 |
| Superheated steam (SS) fluidized drying | Food Processing | 3.5 | 2.5 | 7.5 | 4.7 | 4.5 | 7.5 |
| Plasma Melter | Glass Production | 2.8 | 1.0 | 8.3 | 3.3 | 4.5 | 0.5 |
| Motor re-sizing or Variable speed drives | Glass Production | 2.4 | 7.5 | 2.8 | 8.3 | 7.5 | 7.5 |
| Increased cullet rate | Glass Production | 1.7 | 2.5 | 2.8 | 5.9 | 4.5 | 7.5 |
| Image-based control of glass melting furnaces | Glass Production | 1.1 | 2.5 | 1.2 | 9.2 | 10.0 | 6.3 |
| Optimized distribution of rock during veiling (V-flight) | Asphalt production | - | 6.3 | - | 4.3 | - | 7.5 |
| Infrared heating for corn drying | Food Processing | - | 5.0 | 6.7 | - | - | 2.5 |
| Mechanical dewatering | Food Processing | - | 5.0 | 7.0 | - | - | 7.5 |
| Centrifugal ball mills with vertical axis and continuous operation | Glass Production | - | 2.5 | 3.3 | - | - | 7.5 |
| Flameless Burner | Glass Production | - | 2.5 | 7.5 | - | - | 1.8 |
| No heat spray drying technology | Food Processing | - | 2.5 | 7.5 | - | - | 0.5 |
| Osmotic Dehydration | Food Processing | - | 2.5 | 7.5 | - | - | 0.0 |
| Green parabolic trough collector (Solar thermal collector for industrial steam generation) | Industrial Gas Suppliers | - | - | - | 10.0 | - | 3.8 |

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