

Appendices



Appendix A: EPA Grant Compliance

Summary of CCAP Elements and Location within Report

AIR Quality Plan Element	Document Location
GHG Inventory and Projections	Regional Emissions Inventory and Appendix B
GHG Reduction Targets	GHG Reduction Results and Appendix B
Review of Authority to Implement for Each Measure	Authority to Implement
Plan to Leverage Other Federal Funding for Each Measure	Funding Sources
Quantified GHG Reduction Measures	GHG Reduction Results and Appendix B
Benefit Analysis	Co-Benefits and Appendix B
Workforce Planning Analysis	Workforce Analysis and Appendix C

Information on public engagement can be found in the [2024 Community Report](#) and in the Engagement Activity Summary of this report.

Appendix B: Technical Methodology

This Technical Appendix covers the main quantification elements of the *Pathways to the Future: Air Quality Plan*, including methodologies for the GHG inventory, Business-As-Usual (BAU) projections, measure GHG reductions and costs, and co-pollutant impacts.

GHG Inventory

The GHG inventory provides a comprehensive account of emissions within the metropolitan statistical area (MSA) for calendar year 2022. It includes emissions from stationary energy, transportation, waste and wastewater, industrial processes and use, and agriculture, as well as carbon fluxes from natural and working lands, including carbon sequestration from forests and other land-based sinks. Emissions are expressed in metric tons of CO₂-equivalent (MTCO₂e) using 100-year Global Warming Potentials (GWPs) from the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5). The methodologies and data sources used to quantify emissions from each subsector are described below.

Stationary Energy (Buildings)

Residential Buildings

Emissions from residential buildings result from the combustion of fossil fuels for space heating, water heating, and cooking, and from electricity use in appliances. Stationary energy emissions for residential buildings were calculated using Virginia's natural gas and other fuel consumption data acquired from Environmental Protection Agency's (EPA) State Inventory Tool (SIT) Stationary Combustion and CO₂ from Combustion of Fossil Fuel modules. The state-level data were then scaled to the counties within the MSA based on a population scaling factor.

Residential electricity emissions were calculated using U.S. Energy Information Administration's (EIA) State Energy Data System (SEDS) residential sector energy consumption estimates for total electricity use for Virginia. The consumption data were multiplied by the 2022 grid emission factor for the SERC Virginia/Carolina region (SRVC) eGRID region. The state electricity emissions data were then scaled to each county using population.

Data sources include:

- [EPA State Inventory Tool \(SIT\)](#)
- [EIA State Energy Data System \(SEDS\)](#)
- [EIA Annual Energy Outlook \(AEO\) 2023](#)
- [U.S. Census Bureau](#)
- [U.S. Bureau of Economic Analysis](#)

- [EPA eGRID](#)
- PlanRVA population and employment data
- [U.S. Bureau of Labor Statistics](#)
- [EPA Greenhouse Gas Reporting Program \(GHGRP\) Facility-Level Information on Greenhouse Gas Tool \(FLIGHT\)](#)
- Fugitive data from EIA Form 176

Commercial and Institutional Buildings and Facilities

Commercial and institutional building emissions result from the combustion of fossil fuels for space heating, water heating, and cooking as well as electricity used in commercial, government, industrial, data centers, and other non-residential buildings and facilities. Stationary energy emissions for commercial buildings were calculated using natural gas and other fuel consumption data acquired from EPA's SIT Stationary Combustion and CO₂ from Combustion of Fossil Fuel modules. The state-level data were then scaled to the counties within the MSA based on an employment scaling factor.

Commercial electricity emissions were calculated by scaling SEDS commercial electricity consumption data for Virginia using the employment scaling factor. The consumption data were then multiplied by the electric grid emissions factor for the SRVC eGRID region for 2022.

Data sources include:

- [EPA State Inventory Tool \(SIT\)](#)
- [EIA State Energy Data System \(SEDS\)](#)
- [EIA Annual Energy Outlook \(AEO\) 2023](#)
- [U.S. Census Bureau](#)
- [U.S. Bureau of Economic Analysis](#)
- [EPA eGRID](#)
- PlanRVA population and employment data
- [U.S. Bureau of Labor Statistics](#)
- [EPA Greenhouse Gas Reporting Program \(GHGRP\) Facility-Level Information on Greenhouse Gas Tool \(FLIGHT\)](#)
- Fugitive data from EIA Form 176

Manufacturing Industries and Construction

GHG emissions result from the combustion of fossil fuels for energy use in industrial buildings and processes, as well as from electricity consumption and power equipment. Emissions for stationary industrial buildings were calculated using two data sources: SIT and facility-specific data obtained from EPA's Greenhouse Gas Reporting Program (GHGRP). SIT data downscales national data to the state level whereas GHGRP requires annual reporting of greenhouse gas emissions from large industrial greenhouse gas emitters.

The emissions data from SIT were scaled down to the county level using employment data population and then compared with GHGRP emission data for each county. If GHGRP emissions were larger than SIT

emissions for a county, the GHGRP value was used. If scaled SIT emissions were larger, the difference between the SIT and GHGRP emissions were noted, and the SIT value was used as a conservative approach.

Electricity consumption for Virginia was calculated using industrial megawatt hours values from SEDS. To calculate emissions for the state, the consumption data were multiplied by the electric grid emissions factor for the SRVC eGRID region for 2022. The emissions were then downscaled from the state to county level using employment data.

Data sources include:

- [EPA State Inventory Tool \(SIT\)](#)
- [EPA GHGRP FLIGHT](#)
- [EIA State Energy Data System \(SEDS\)](#)
- [EIA Annual Energy Outlook \(AEO\) 2023](#)
- Employment data
- PlanRVA employment data

Energy Industries

Emissions from energy industries include all emissions from energy production and energy use in energy industries, such as emissions from generation of energy for grid-distributed electricity, steam, heat, and cooling. Calculation of these emissions depends on whether the GHG inventory is a consumption-based or generation-based inventory.

Consumption-based: For a consumption-based GHG inventory, the only emissions calculated for this subsector were emissions from any energy consumed directly by an energy production facility. For example, electricity consumed at an electricity generation facility. To estimate these emissions, the consumption data were multiplied by the following emission factors:

- Region-specific CO₂, CH₄, and N₂O emission factors from utilities or obtained from EPA's eGRID.
- Fuel-specific CO₂, CH₄, and N₂O emission factors from EPA's GHG Emission Factor Hub.

Otherwise, emissions from energy production (e.g., electricity generation) were allocated to the end-use sector where that energy is ultimately used (e.g., residential buildings, commercial buildings, transportation, etc.) as Scope 2 emissions.

Generation-based: For a generation-based GHG inventory, Scope 1 emissions from individual energy production facilities within the MSA were calculated based on the type of fuel consumed, amount of fuel consumed, and/or amount of energy generated. These emissions were not allocated to their end-use sectors due to lack of available data. As a result, Scope 2 emissions within the MSA were not calculated for any sector to avoid double-counting. To estimate these emissions, these data were acquired from EPA's eGRID 2022 dataset, which contains 2022 CO₂, CH₄, and N₂O emissions data for all power plants in the MSA. Emissions for each gas were multiplied by the IPCC AR5 GWP and summed as carbon dioxide equivalent emissions.

It was assumed that eGRID's adjusted CO₂ emissions represent fossil emissions, and that the difference between eGRID's unadjusted and adjusted CO₂ emissions represents biogenic CO₂ emissions. eGRID's unadjusted CH₄ and N₂O emissions were used in the inventory to ensure non-CO₂ emissions from biogenic sources were accounted for. Note, generation-based emissions were only used for informational purposes.

Data sources include:

- [EPA eGRID](#) for GHG emissions from power plants
- [EPA eGRID](#) average annual grid GHG emission factor data for electricity consumption
- [EPA GHG Emission Factor Hub](#)

Fugitive Emissions from Oil and Natural Gas Systems

Fugitive methane emissions from oil and natural gas systems come from leakage of methane from these systems, such as from natural gas distribution pipes. These emissions were calculated by multiplying the natural gas energy consumption from each county by an energy density of 41.7 MJ/kg and a leakage rate of 0.88% derived from EPA.

Data sources include:

- [Estimate of Methane Emissions from the US Natural Gas Industry](#)

Industrial Processes & Product Use (IPPU)

Industrial Processes

Emissions from industrial processes result from chemical and physical transformations during manufacturing activities, such as cement production, metal processing and chemical use. Emissions were calculated using a combination of emissions data from EPA's SIT and EPA's GHGRP FLIGHT. Industrial process emissions were calculated using a combination of emissions data from EPA's SIT and EPA's GHGRP FLIGHT. GHGRP FLIGHT has emissions data directly from facilities while SIT estimates emissions for the entire state from national data. GHGRP only requires large facilities to report, whereas SIT would estimate emissions for the entire industrial processes sector, including from non-reporter facilities that are not required to submit data under GHGRP.

First, the industrial process (IP) Module from SIT was used to calculate emissions from the entire state for limestone and dolomite usage, soda ash, iron and steel production, and urea consumption. These state-level emissions were downscaled to each county using employment data from Bureau of Labor Statistics (BLS). Secondly, Virginia's GHGRP FLIGHT data were compiled for the following sectors: chemicals, other, minerals, metals, and pulp and paper. Reporting facilities within the MSA were identified in the GHGRP dataset. For those facilities, the reported GHGRP subpart was used to assign emissions to the appropriate industrial subsector. Emissions from facilities that only reported to Subpart C, General Stationary Fuel Combustion, were excluded as this is not relevant to the sector.

The FLIGHT data from reporting facilities were then combined with the SIT data to account for non-reporters for sectors that have data in both datasets. If the FLIGHT emissions value was greater than SIT's emissions value, the SIT data were not used. If scaled SIT emissions were larger, the difference between the SIT and GHGRP emissions were noted and the SIT value was used. Cement manufacturing and lime manufacturing are "all-in" sectors in GHGRP, meaning that there is no minimum threshold for reporting and all facilities must report emissions. Therefore, GHGRP data from these sectors were not combined with SIT data.

Data sources include:

- [EPA SIT](#) IP Module
- [EPA GHGRP FLIGHT](#)
- PlanRVA employment data

Product Use

Emissions from product use come from industrial products such as refrigerants in cooling systems. Product use emissions were calculated using EPA's SIT IP module. The IP Module from SIT was used to calculate emissions from the entire state for ozone depleting substitutes (ODS) substitutes and electric power transmission and distribution systems. These state-level emissions were then downscaled to each county using population data.

Data sources include:

- [EPA SIT](#) IP Module
- PlanRVA population data

Natural and Working Lands

Forest Carbon Flux

Forests sequester CO₂ during photosynthesis and act as a carbon sink. If trees are removed and used elsewhere, they can be a source of emissions. The EPA SIT Land Use, Land Change and Forestry module was used to estimate carbon sequestration in forested lands in Virginia using the default SIT inputs for forest carbon flux. The output data from SIT were downscaled to the county level by multiplying by the ratio of forested area in the county and state.

Data sources include:

- [EPA SIT](#) Land Use Module
- [National Land Cover Dataset](#)

Urban Trees

Urban trees act as a carbon sink by sequestering carbon through photosynthesis. Carbon sequestration from urban tree canopies was estimated using tree cover percentages and urban area estimates. The tree canopy percentage for each county was sourced from the 2021 NLCD tree canopy percentage. Urban area in square kilometers for 2018 were acquired from the Chesapeake Bay Program's 1 meter resolution land cover data settlement pixels. The urban area was then multiplied by the percentage of total tree cover for each county. Emissions were calculated by multiplying the urban tree canopy area by the average net carbon emissions per area of tree cover from the U.S. Inventory.

Data sources include:

- [Urban Tree Canopy Assessment](#)
- [U.S Inventory of GHG Emissions and Sinks](#)
- [2018 Chesapeake Bay Program](#)
- [Urban and Rural](#)
- [National Land Cover Dataset](#)

Landfilled Yard Trimmings and Food Scraps

GHG removals from landfilled yard trimmings and food scraps result from the long-term storage of carbon in organic materials that remain sequestered in landfill environments. SIT was used to calculate sequestration from the landfilled yard trimmings and food scraps subsector. SIT default values were used for the composition of yard trimmings, annual quantity of landfilled yard trimmings and food scraps, carbon content, dry weight to wet weight ratio, proportion of carbon from each material stored indefinitely in landfills, and the half-life of degradable carbon in each material. The output from SIT was downscaled to the county level using population.

Data sources include:

- [EPA SIT](#) Land Use Module
- [Urban and Rural](#)

Forest Fires

Emissions from forest fires result from the combustion of carbon stored in plant and tree organic material. SIT was used to estimate emissions from forest fires, which produce CO₂, N₂O, and CH₄ emissions. SIT's default emission factors and combustion efficiencies were used. The non-CO₂ emissions from Forest Fires worksheet uses the area burned per year. The forest fire emissions were downscaled using forest fire extents from Monitoring Trends in Burn Severity (MTBS) for 2022 for each county.

Data sources include:

- [EPA SIT](#) Land Use Module
- [Measuring Trends in Burn Severity dataset](#)

Soils

Soils result in both emissions and removals from the application of synthetic fertilizers, land management practices, and changes in soil carbon stocks. SIT's land use, land use change, and forestry (LULUCF) module was used to estimate N₂O emissions resulting from fertilizer application to settlement soils. To calculate N₂O emissions from settlement soils, the amount of synthetic fertilizer applied was multiplied by the emission factor for direct N₂O emissions. The module also estimates agricultural soil carbon flux and includes carbon flux from aboveground biomass, belowground biomass, deadwood, and litter in cropland and grassland ecosystems. The net change in agricultural soil carbon is the change in the amount of carbon stored primarily in mineral and organic soils over time. The SIT output was downscaled to the county level using the National Land Cover Dataset. To calculate the N₂O emissions from settlement soils and agricultural soil carbon flux, the ratio of county to state developed areas were multiplied by the Virginia data derived from SIT. To calculate the

N₂O emissions from agricultural soil carbon flux, the ratio of county to state cropland areas were multiplied by the Virginia data derived from SIT.

Data sources include:

- [EPA SIT](#) Land Use Module
- [National Land Cover Dataset](#)

Agriculture

N₂O from Soils

Nitrous oxide emissions from soils result from microbial processes like nitrification and denitrification. Data from SIT was used to estimate nitrous oxide emissions from fertilizer use. Nitrous oxide emissions from soils were separated into direct and indirect emissions from synthetic fertilizer and organic fertilizer (i.e., manure, activated sewage sludge, and other organic materials).

Data from SIT was scaled using the method described in EPA's Guidance for County and Regional Inventories for Agriculture and Land Management with slight variations. SIT data were pulled for the state of Virginia for all historic years. SIT had proxied fertilizer use from 2016 for years 2017-2024; instead, this inventory used linear interpolation to generate fertilizer use estimates from 2017-2022. Then, EPA guidance was followed to convert fertilizer years to annual years.

Fertilizer activity data were not available at the county level, and so total fertilizer application data for Virginia was scaled for Richmond counties using United States Department of Agriculture (USDA) National Agricultural Statistical Service (NASS) data on county crop acres as a proportion of total Virginia crop acres.

Data from SIT was scaled using the method described in EPA's Guidance for County and Regional Inventories for Agriculture and Land Management with slight variations. SIT data were pulled for the state of Virginia for all historic years. SIT had proxied fertilizer use from 2016 for years 2017-2024; instead, this inventory used linear interpolation to generate fertilizer use estimates from 2017-2022. Then, EPA guidance was followed to convert fertilizer years to annual years. Estimates of calendar year fertilizer consumption were generated based on EPA assumptions of percent application of various fertilizer for synthetic nitrogen, manure, activated sewage sludge, and other organic materials for Virginia.

Direct emissions were calculated by multiplying the consumption of fertilizer by the IPCC direct emission factor for kg N₂O/kg N. Indirect emissions were calculated by multiplying the consumption of fertilizer by the percent of total nitrogen volatilized from organic matter, the total nitrogen leached from organic matter and IPCC emission factors for volatilization of nitrous oxide and leaching of nitrous oxide.

Data sources include:

- [EPA SIT](#) Agriculture Module
- [USDA NASS data](#)
- [EPA's Guidance for County and Regional Inventories for Agriculture and Land Management](#)
- [IPCC emission factors](#)

Livestock

Emissions from livestock come from two processes: enteric fermentation, which produces CH₄, and manure management, which produces both CH₄ and N₂O. The amount of CH₄ emitted by enteric fermentation depends on the number of livestock, type of livestock (i.e., type of digestive system), and amount of feed consumed.

Manure releases CH₄ as it decomposes under anaerobic conditions and emits N₂O through nitrification and denitrification. The amount of N₂O released by manure management practices depends on the total amount of nitrogen excretion for the management system. This requires calculating the average nitrogen excretion rate per head for each livestock category as well as the fraction of annual excretion that is managed within the system.

Livestock data for cattle (dairy and beef), chickens (broilers, and layers), horses, mules, goats, swine and sheep was acquired from USDA Quick Stats. Dairy and beef cattle were separated by multiplying cattle population totals by the average percent proportion of dairy to beef cattle in the state of Virginia. The chicken population was adjusted to an average annual population (as broilers for example typically live for 45-60 days in the U.S.) according to the IPCC population adjustment method.

Because detailed data on subspecies populations, excretion rates, average weights, etc., were not available at the state or county level, implied emission factors were used for enteric fermentation and manure management per head. EPA's State Level Disaggregates of the U.S. Greenhouse Gas Inventory were used for emission totals, dividing by the population of each animal to find overall emission factors per emission source. The livestock populations by county were multiplied by these emission factors to find total emissions for each type of livestock.

Data sources include:

- [USDA Quick Stats](#) NASS data
- [U.S. Inventory of GHG Emissions and Sinks](#)
- [USDA NASS data](#)
- [IPCC emission factors](#)
- [U.S. GHG Emissions and Sinks](#)

Liming

Liming emissions were calculated using the EPA's State Level Disaggregates inventory data for 2021 as a proxy for 2022. Total emissions from limestone and dolomite consumption in Virginia were divided by the IPCC emissions factor to find tons of limestone and dolomite consumed in the state. These data were then scaled to the county level using percent of state cropland as described under agricultural soils. This county-level tonnage data were then multiplied by the IPCC emissions factor to find emission totals by county.

Data sources include:

- [EPA State Level Disaggregates inventory data](#)
- [IPCC emission factors](#)

Urea

Urea emissions were calculated using the state total of urea consumption from SIT. Virginia annual consumption of urea in 2022 was scaled to the county level using percent of state cropland per county. The estimated state consumption was then multiplied by the IPCC emission factor for urea fertilization to find total emissions by county.

Data sources include:

- [EPA SIT](#) Agriculture Module
- [USDA Quick Stats](#) NASS data
- [IPCC emission factors](#)

Field Burning of Agricultural Residues

The number of acres planted with crops with high rates of field burning of agricultural residues: corn, soybeans, cotton, lentils, rice, sugarcane, and wheat were acquired from USDA. This acreage data were multiplied by the residue to crop ratio, fraction residue burned, dry matter fraction, burning efficiency, combustion efficiency, and carbon content for each crop using assumptions from SIT .

Data sources include:

- [EPA SIT](#) Agriculture Module
- [USDA Quick Stats](#) NASS data

Transportation

On-Road

GHG emissions from on-road transportation are due to the combustion of fossil fuels, such as gasoline and diesel, in vehicle engines and are found in vehicle exhaust. These emissions were calculated using a bottom-up approach using EPA's Motor Vehicle Emissions Simulator (MOVES5). MOVES5 accounts for on-road vehicles through categorization of fuel type, vehicle class, and model year. For each category of vehicle, MOVES provides a quantification of the population of vehicles, vehicle miles traveled, and emissions allocated by county. To calculate emissions from electric vehicles, the energy consumption for each vehicle class from MOVES was multiplied by emission factors from the SRVC eGRID region.

To separate biogenic CO₂ emissions from fossil CO₂ emissions, it was assumed that gasoline contains 10% ethanol by volume and that E-85 contains 85% ethanol by volume. The volume of fuel consumed by on-road vehicles was found by dividing the gasoline and E-85 energy consumption by their energy densities, and each component fuel was multiplied by the applicable emission factor to obtain CO₂ emissions.

Data sources include:

- [EPA Motor Vehicle Emissions Simulator \(MOVES5\)](#)
- [eGRID](#)

Railways

Railways emit pollutants from diesel combustion in freight and passenger trains. To calculate emissions from railways, freight rail activity data from the Bureau of Transportation Statistics (BTS) Freight Analysis Framework (FAF). FAF provides the number of ton-miles originating in and bound for a given destination. These data were allocated by county and by freight rail provider using GIS data from the BTS National Transportation Atlas Database. Railway track miles were tabulated by county and freight provider to allocate ton-miles bound for and originating in the MSA. Half of the total ton-miles from the FAF are included in the Richmond MSA inventory per guidance in GPC protocols to avoid double counting with other jurisdictions.

Fuel usage data in ton-miles per gallon were then multiplied by the activity data to acquire fuel quantities. Fuel usage for the two freight providers in the Richmond MSA, CSX and Norfolk Southern, was provided in company sustainability reports. The fuel quantities were then multiplied by emission factors from EPA's GHG Emission Factor Hub to determine GHG emissions.

For passenger rail provided by Amtrak, the number of track miles within each county by Amtrak route was calculated from GIS data from the BTS National Transportation Atlas Database. The total annual miles were calculated using the number of trips per year based on the schedule of each route. From total miles, fuel use was determined with an Amtrak-specific fuel economy factor for diesel gallon equivalent. From fuel use emissions were generated using EPA EPA's GHG Emission Factor Hub to determine GHG emissions

Railroad support emissions generated within the Motor Vehicle Emissions Simulator (MOVES) nonroad model has been included as a part of the railways sector and is included in the railways total emissions (see nonroad MOVES methodology in the off-road section below).

Data sources include:

- [U.S. DOT Freight Analysis Framework](#)
- [Bureau of Transportation Statistics \(BTS\) National Transportation Atlas Database \(NTAB\)](#)
- [CSX](#) and [Norfolk Southern](#) corporate reports
- [Amtrak route information](#)
- [Association of American Railroads Freight Rail and Climate Change](#)
- [EPA GHG Emission Factor Hub](#)

Waterborne Navigation

GHG emissions from waterborne navigation come from the combustion of fossil fuels such as diesel in recreational and commercial boats, or other waterborne vessels. Emissions from tugs, pushing barges, excursion boats, commercial fishing boats and work boats were calculated using California Air Resources Board (CARB) harbor craft emissions inventory methodology (California Air Resource Board, 2021). The emissions for Richmond port craft were scaled based on a scaling factor between the port of Los Angeles and Richmond using short tons of cargo found in waterborne cargo and trips data from the U.S. Army Corps of Engineers Institute of Water Resources.

Emissions associated with pleasure craft were calculated using EPA's MOVES5 tool's NONROAD module. This tool provides an estimate for population, source hours, sector, fuel type, and emissions for nonroad equipment. Emissions associated with pleasure craft were attributed to the waterborne navigation category in this inventory.

Data sources include:

- [California Air Resources Board \(CARB\) Port Analysis](#)
- [U.S. Army Corps of Engineers Waterborne Cargo and Trips](#)
- [EPA MOVES5](#)

Aviation

Emissions from aviation result from the combustion of jet fuel in aircraft engines and from airport support equipment. To calculate aviation emissions, activity data were acquired from the Federal Aviation Administration (FAA) through The Operations Network (OPSNET). OPSNET provides the number of landings and takeoffs (LTO) from local and itinerant flights from Richmond International Airport (code RIC). OPSNET does not provide data for small private airports, and thus LTO data for the Richmond MSA are only available for RIC. Emissions from aircraft were calculated using IPCC GHG inventory guidelines for aircraft.

Airport support equipment emissions generated within the MOVES nonroad model have been included as a part of the aviation sector and are included in aviation total emissions (see nonroad MOVES methodology in the off-road section below).

Data sources include:

- [Federal Aviation Administration's Operations Network \(FAA OPSNET\)](#)
- [IPCC Emission factor for Average Fleet LTO operations](#)
- [EPA MOVES5](#)

Off-Road

GHG emissions from off-road sources result from the combustion of fossil fuels in vehicles and equipment used in subsectors such as lawn and garden, construction, agriculture and industrial operations. GHG emissions from off-road vehicles were calculated using EPA MOVES's NONROAD module. This module accounts for vehicles based on the fuel type and sector to generate populations, source hours, energy consumption, and total annual CO₂ and CH₄. The MOVES nonroad module does not currently calculate N₂O emissions and was estimated using the ratio of the CH₄ and N₂O emission factors for specific vehicle type and fuel type combinations.

Emissions from aircraft support equipment, pleasure craft, and railroad support sectors were calculated in MOVES but included in the totals of the aviation, waterborne navigation, and railways sectors rather than the off-road sector total.

Data sources include:

- [EPA MOVES5](#)
- [EPA GHG Emission Factor Hub](#)

Waste

Disposal of Solid Waste Generated in the MSA

Emissions from solid waste are from the generation of methane as waste breaks down without the presence of oxygen in landfills. These emissions from waste generated in the MSA were calculated using the methane commitment method from the Global Protocol for Community-Scale GHG Inventories. This method calculates downstream emissions associated with solid waste sent to landfills during each inventory year. The methane commitment method takes a lifecycle approach, calculating landfill emissions based on the amount of waste disposed in a given year and assigning emissions to the year of waste generation under the assumption that the emissions will actually occur in future years as waste decays and produces methane.

The methane commitment estimate for solid waste sent to landfill was calculated based on the mass of solid waste sent to landfill during the inventory year, the methane generation potential of waste based on the waste composition, the fraction of methane recovered at the landfill, and the oxidation factor for the landfill. Activity data on the amount of waste disposed of in landfills in 2022 was obtained from EPA's Landfill Methane Outreach Program (LMOP). The methane generation potential of waste was calculated using default multiplication factors from GPC and a waste characterization study from CVWMA and VPPSA. The fraction of methane recovered and the oxidation factors were acquired from GHGRP FLIGHT for eight landfills in the MSA. For landfills without GHGRP FLIGHT data, the average fraction of methane recovered from the eight landfills and the default oxidation factor from GPC were used. The methane commitment equation from GPC was used to calculate emissions from each landfill within the MSA and these values were summed to obtain the emissions for the entire MSA.

Data sources include:

- [Global Protocol for Community-Scale Greenhouse Gas Emission Inventories | World Resources Institute](#)
- [Central Virginia Waste Management Authority \(CVWMA\)](#) and [Virginia Peninsulas Public Service Authority \(VPPSA\)](#) Solid Waste Management Plans
- [Greenhouse Gas Reporting Program \(GHGRP\) Facility-Level Information on Greenhouse Gas Tool \(FLIGHT\)](#)
- [EPA Landfill Methane Outreach Program \(LMOP\)](#)
- Population data provided by PlanRVA
- Municipal solid waste disposal data

Biological Treatment of Waste Generated in the MSA

Emissions from the biological treatment of waste generated in the MSA were assumed to be zero.

Incineration and Open Burning of Waste Generated in the MSA

GHG emissions from incineration and burning of waste result from the combustion of solid waste which releases carbon dioxide and other GHGs. Richmond does not have any incineration sites according to GHGRP FLIGHT data. Therefore, emissions from the incineration and open burning of waste generated in the MSA are assumed to be zero.

Wastewater Generated in the MSA

Septic system emissions account for fugitive emissions resulting from the physical setting and biologic activity during the treatment process. Wastewater emissions were calculated using the GPC equations for methane and nitrous oxide from wastewater treatment plants (WWTPs). The quantity of wastewater flowing through each WWTP and the biological oxygen demand (BOD) from each WWTP was obtained from the U.S. EPA's Enforcement and Compliance History Online database. Data on organic component removed as sludge, nitrogen removed with sludge, and methane recovery were not available and therefore assumed to be zero. Total population served by the WWTPs was estimated using the county population and the WWTP's average flow rate.

Data sources include:

- [Integrated Compliance Information System - National Pollutant Discharge Elimination System \(ICIS-NPDES\)](#)
- [Global Protocol for Community-Scale Greenhouse Gas Emission Inventories | World Resources Institute](#)
- Population data provided by PlanRVA
- [EPA Enforcement and Compliance History Online](#)

GHG BAU Projections

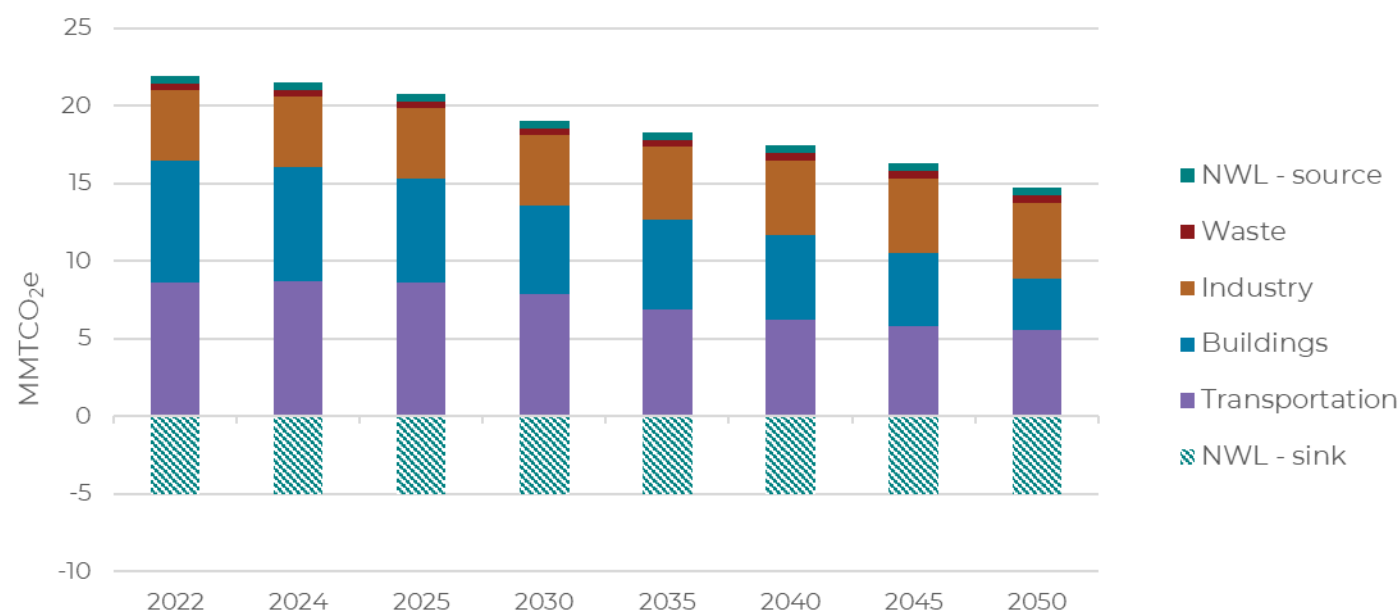
The 2022 GHG inventory and BAU projections establish a quantitative foundation for regional climate-action planning. The inventory defines baseline emissions, and the BAU scenario illustrates how those emissions could evolve through 2050 without additional mitigation. Together, they highlight key emission sources and growth patterns and set the basis for evaluating reduction pathways and co-benefits associated with measure implementation.

The BAU scenario projected future GHG emissions through 2050, assuming no additional mitigation actions beyond those already in place as of 2022. Each sector's emissions were modeled based on historical activity data and growth drivers such as population, employment, energy demand, and industrial output. The projections reflected expected trends under a continuation of current policies and practices. The assumptions and methodologies used to develop BAU projections for each sector are described below.

The BAU grid emissions factor used to estimate emissions associated with electricity consumed in the BAU comes from the Virginia State Climate Pollution Reduction Grant (CPRG) analysis, which modeled the Virginia Clean Economy Act in the BAU. This leads to a significant decline in the grid emissions factor by 2050, driving emission reductions under the BAU scenario. See the State's CPRG report for more information on this assumption.

Compared to the 2022 inventory base year, the BAU forecasts that net GHG emissions will decline 22% by 2035, and 43% by 2050. The transformative impact of the Virginia Clean Economy Act (VCEA) is a primary driver of the emissions reductions in this scenario. The VCEA shifts the source of electricity on the grid away from fossil fuels which means that increased electrification in the transportation and buildings sectors reduces overall emissions, instead of just shifting emissions to the power generation sector¹.

Table B1: GHG BAU Emission Projections



Stationary Energy (Buildings)

Residential Buildings

Year-over-year growth rates from AEO 2023 Table 2 for the South Atlantic region were applied to residential electricity, natural gas, fuel oil, propane, and other stationary fuel consumption from the 2022 inventory. The electricity consumption projections were multiplied by the BAU grid emission factor.

Data sources include:

- [AEO 2023 Table 2](#)

Commercial and Institutional Buildings and Facilities

Year-over-year growth rates from AEO 2023 Table 2 for the South Atlantic region were applied to residential electricity, natural gas, fuel oil, propane, and other stationary fuel consumption from the 2022 inventory. The electricity consumption projections were multiplied by the BAU grid emission factor.

Data sources include:

- [AEO 2023 Table 2](#)

¹ The [Dominion Energy 2025 Update to the 2024 Integrated Resource Plan \(2025 IRP update\)](#) evaluated multiple portfolios that incorporate VCEA requirements. Dominion highlights the challenges of complying with VCEA's net zero GHG target (§10.1-1308 E) while incorporating assumptions related to reasonable capacity deployment levels, affordability concerns, and reliability concerns.

Manufacturing Industries and Construction

For each county in the MSA, emissions from GHGRP-reporting facilities were held flat through 2050. Any remaining energy consumption and emissions data from SIT was projected using the year-over-year growth rates from AEO 2023 Table 2 or the SIT projection tool if the fuel was not present in AEO's projections. The electricity consumption projections were multiplied by the BAU grid emission factor.

Data sources include:

- [AEO 2023 Table 2](#)
- [SIT Projection Tool](#)

Energy Industries

Emissions from energy industries were only projected from a consumption-based perspective as described in other sections of this methodology. Generation-based emissions were not projected.

Fugitive Emissions from Oil and Natural Gas Systems

Fugitive methane emissions projections from oil and natural gas systems were calculated by multiplying the projected natural gas energy consumption from each county each year by an energy density of 41.7 MJ/kg and a leakage rate of 0.88% derived from EPA.

Data sources include:

- [Estimate of Methane Emissions from the U.S. Natural Gas Industry](#)

Industrial Process and Product Use

Industrial Process

BAU emissions from industrial processes were projected using EPA's SIT and facility-level data from EPA's GHGRP FLIGHT. The SIT IP module was used to estimate statewide emissions from limestone and dolomite usage, soda ash consumption, iron and steel production, and urea application. These state-level totals were downscaled to counties in the Richmond MSA using BLS employment data for relevant manufacturing subsectors, consistent with the baseline inventory approach.

For sectors represented in both GHGRP and SIT, facility-level GHGRP emissions were used where available to represent large emitters, while SIT-based estimates were retained to capture emissions from smaller, non-reporting facilities. Cement and lime manufacturing are fully covered under GHGRP (Subpart H and Subpart S), and their reported emissions were used directly without adjustment. In all cases, the BAU scenario assumes industrial process emissions remain constant over time (2022–2050).

Data sources include:

- [EPA SIT IP Module](#)
- [EPA Greenhouse Gas Reporting Program \(GHGRP\)](#)

Product Use

Product use emissions were estimated using EPA's SIT IP module, which includes emissions from ODS substitutes and electric power transmission and distribution systems. Statewide totals were downscaled to the county level using population data from the U.S. Census Bureau (2025).

Consistent with other sectors lacking significant expected change in baseline activity, BAU product use emissions are held constant through 2050. This approach assumes that current refrigerant use, equipment turnover rates, and grid infrastructure practices remain stable over time in the absence of additional policy or technological interventions.

Data sources include:

- [EPA SIT](#) IP Module
- [U.S. Census Bureau](#)

Natural and Working Lands

Forest Carbon Flux

Forest carbon flux in the Richmond MSA is held flat in the BAU scenario. Historical land cover trends indicated that rapid development between 2001 and 2021 was driving losses in forest area and associated carbon sequestration potential. Holding flux constant avoids overestimating sequestration and stabilizes the trajectory to reflect a steady-state stock under continued urban expansion pressure.

Urban Trees

Urban tree carbon flux is likewise held constant in the BAU scenario. Model diagnostics showed that rapid development in high-growth counties was skewing projections and producing unrealistically low sequestration rates. Fixing urban tree growth and mortality rates at baseline conditions provides a conservative estimate aligned with observed canopy stability in recent NLCD and urban forest inventory data.

Landfilled Yard Trimmings and Food Scraps

Emissions and carbon sequestration associated with landfilled organic materials were modeled using SIT methodologies and scaled according to population projections for the Richmond MSA. Population growth increases the total quantity of organics generated and subsequently landfilled, resulting in a modeled increase in total biogenic carbon sequestration within waste burial processes over time.

Data sources include:

- [EPA SIT](#) Land Use Module

Soils

Modeled soil emissions reflect a gradual decline over the BAU period due to continued changes in land cover. NLCD-based transition analysis indicates conversion of agricultural and forested areas to developed land with lower soil carbon flux.

Agriculture

BAU emissions from the Agriculture sector are projected to increase over time, attributable to continued increase in livestock and crop production. Total agriculture emissions are projected to increase by 36.2% from 2022 to 2050, driven by increasing beef production and subsequent enteric fermentation emissions, and a high initial increase in fertilizer application (based on historical rates of change) that is projected to stabilize over time. Emissions from N₂O from managed soils – fertilizers had the highest percent change, increasing by 88.7% over the timeseries. The greatest share of agriculture emissions shifts from enteric fermentation at 44% of 2022 agriculture sector emissions to 42% N₂O from managed soils 2050, due to a high increase in N₂O from managed soils and more moderate increase in livestock emissions.

N₂O from Soils

N₂O from soils emissions include direct and indirect N₂O from nitrogen inputs to agricultural soils, including from synthetic and organic fertilizers, crop residues, and manure deposited by grazing animals. For Virginia, activity data is based on 2022 data from the SIT, detailing the total synthetic fertilizer applied. For N₂O from manure deposited by grazing animals, 2022 SIT data provides the kilograms of nitrogen excretion (Nex) deposited annually onto pasture, range, and paddock per animal head.

N₂O from soils emission factors and constants are sourced from the U.S. GHG Inventory and are aligned with international IPCC guidance. For synthetic and organic fertilizers, 2022 emissions are calculated by multiplying the total amount of fertilizer applied by a direct N₂O emission factor. Indirect emissions are calculated by determining the fraction volatilized, leached, or lost via runoff using GHG inventory constants, then multiplying by an indirect emission factor. For manure deposited by grazing animals, Nex is multiplied by a direct N₂O emission factor. Indirect emissions are similarly calculated using the fraction volatilized, leached, or runoff, combined with the appropriate indirect emission factor.

N₂O from soils emissions estimates are calculated as follows: direct N₂O emissions equal the activity data (amount of input or amendment) multiplied by the direct emission factor. Indirect N₂O emissions equal the activity data multiplied by the fraction volatilized, leached, or runoff, and then by the indirect emission factor.

N₂O from soils BAU input amounts were estimated by using SIT fertilizer consumption data as surrogate data to calculate the annual rate of change of fertilizer use. The fertilizer rates of change were calculated by taking the average of Virginia SIT data from the years 2006-2015 and the synthetic fertilizer rate of change was discounted over time as the historical rate of increase was considered unrealistic for future years. Fertilizer amounts for 2023-2050 were estimated using rates of change applied to the 2022 values. Emissions were estimated based on 2022 values as estimated per the methods described above.

Data sources include:

- [EPA SIT](#) Agriculture Module

Livestock

Livestock emissions sources include CH₄ from enteric fermentation and manure management, and N₂O from manure management. Activity data is sourced from Chesapeake Assessment Scenario Tool (CAST) and USDA NASS QuickStats, and emission factors from the US GHG Inventory's state specific, weighted species emission factors. Emissions estimates are calculated by multiplying the emission factor (emissions per livestock head per year, for each given emission source) by the livestock's population.

Population rates of change were based on USDA 2025 Baseline Projections. Livestock populations from 2023-2050 were estimated based on 2022 values, using the USDA's projected rates of change.

Data sources include:

- [USDA Quick Stats](#) NASS data
- [CAST Tool](#)
- [USDA Baseline Projections](#)

Liming and Urea

Liming utilizes data from SIT for 2022 and uses the same surrogate data method as described above for N₂O from soils. Activity data is multiplied by the emission factor per unit of limestone, dolomite or urea applied to derive emissions estimates.

BAU input amounts were estimated by using the average historical rate of change for liming emissions from Virginia, excluding years with rates of change exceeding 1.5 times the lower or upper quartiles of the data range. Amendment amounts for 2023-2050 were estimated using these rates of change from 2022 values developed using the methods described above. Emissions were estimated based on 2022 values as estimated per the methods described above.

Data sources include:

- [EPA SIT](#) Agriculture Module
- [IPCC emission factors](#)

Field Burning of Agricultural Residues (FBAR)

FBAR emissions were estimated based on 2022 corn, soybeans, and wheat yield data (USDA NASS), and burning constants and parameters from SIT. Emissions estimates for crop residue burning are calculated using specific formulas for CH₄ and N₂O. CH₄ emissions are determined by multiplying the crop yield by the residue-to-crop ratio, the fraction of residue burned, the fraction of dry matter, the carbon content, and the conversion factor from carbon to methane. Similarly, N₂O emissions are estimated by multiplying the crop yield by the residue-to-crop ratio, the fraction of residue burned, the fraction of dry matter, nitrogen content, and the conversion factor from nitrogen to nitrous oxide.

For BAU projections, FBAR was estimated by determining a historical rate of change of wheat yield from USDA-NASS QuickStats data. Annual production was estimated from 2023-2050 using this rate of change applied to 2022 values.

Data sources include:

- [USDA-NASS QuickStats Data](#)

Transportation

On-Road

BAU vehicle miles traveled (VMT), vehicle population, energy consumption, and emissions were projected using EPA Motor Vehicle Emissions Simulator (MOVES5) model. Default input values were used. Scope 1 emissions projections for all counties were obtained between 2022 and 2050 at five-year increments. Scope 2 emissions from electricity consumption were found by multiplying the resulting electricity consumption by the BAU grid emission factor. MOVES5 projections include the impacts of EPA's Multi-Pollutant Emissions Standards for Model Years 2027 and Later Light-Duty and Medium-Duty Vehicles and the Greenhouse Gas Emissions Standards for Heavy-Duty Vehicles – Phase 3. All zero-emission vehicles were modeled to be battery electric.

Data sources include:

- [EPA MOVES5](#)

Railways

Year-over-year growth rates from AEO 2023 Table 7 for energy use by passenger and freight rail were applied to passenger and freight rail emissions, respectively. Railroad emissions from MOVES5 were projected using MOVES5 NONROAD results.

Data sources include:

- [AEO 2023 Table 7](#)

Waterborne Navigation

Year-over-year growth rates from AEO 2023 Table 7 for energy use by domestic and international shipping were applied to inventory-year port craft emissions. Pleasure craft emissions from MOVES5 were projected using MOVES5 NONROAD results.

Data sources include:

- [AEO 2023 Table 7](#)

Aviation

Year-over-year growth rates from AEO 2023 Table 7 for energy use by aircraft were applied to inventory-year port craft emissions. Airport support emissions from MOVES5 were projected using MOVES5 NONROAD results.

Data sources include:

- [AEO 2023 Table 7](#)

Off-Road

Off-road emissions were projected using MOVES5 NONROAD results.

Data sources include:

- [EPA MOVES5](#)

Waste

Disposal of Solid Waste Generated in the MSA

The solid waste emissions from 2022 were projected to 2050 using a population growth factor based on U.S. Census population data.

Data sources include:

- [U.S. Census Population Data](#)

Biological Treatment of Waste Generated in the MSA

No BAU was developed due to a lack of biological treatment of waste in the MSA.

Data sources include:

- [U.S. Census Population Data](#)

Incineration and Open Burning of Waste Generated in the MSA

No BAU was developed due to a lack of incineration in the MSA.

Data sources include:

- [U.S. Census Population Data](#)

Wastewater Generated in the MSA

The wastewater emissions from 2022 were projected to 2050 using a population growth factor based on U.S. Census population data.

Data sources include:

- [U.S. Census Population Data](#)

GHG Reduction Measure Quantification

Approach Overview

This section summarizes the methods used for calculating GHG emission reductions and costs from measures included in the *Pathways to the Future: Air Quality Plan*, building from the BAU projections. The methods outline a “what would it take” approach to reach net zero GHG emissions by 2050 and include aggressive, but feasible, strategies and assumptions. In some instances, existing modeling efforts were used. The sections below detail the modeling approaches and assumptions used for each sector and measure to assess the potential GHG reductions and costs for the Net Zero Scenario.

The analysis was guided by several cross-cutting assumptions applied consistently across all measures:

- **Technology and Market Adoption.** Gradual but widespread adoption of mature and emerging technologies was assumed, with linear or logistic adoption curves extending to 2050. Technology penetration rates reflected published projections from Department of Energy (DOE), EPA, and the National Renewable Energy Laboratory (NREL).
- **Policy Continuity and Investment.** The modeling assumed continued policy support at state and federal levels, including implementation of the VCEA and ongoing infrastructure funding through existing climate and energy programs.

The cost assessment is designed to incorporate the following key elements to quantify total implementation costs tied to a measure, with the perspective of a societal impact, and relied on any public resources available.

- **Capital costs** associated with the upfront investment costs to implement a measure, including investments in infrastructure, equipment, or technology.
- **Operational costs** linked to the execution of each measure, including recurring costs required to operate and maintain the measure, as well as any changes in ongoing expenditures or savings resulting from its implementation, such as variations in fuel and electricity use, or incentives deployed to support the measure.

Further details on the methodology and any sector-specific or measure-specific constraints are provided in the sections below. Results are presented to capture the annual incremental costs (or savings) of implementing each measure over the 2025-2050 timeline as compared to a reference case scenario. Note that all estimates are shown in 2025 real dollars.

Table B2 summarizes cumulative emission reductions and costs modeled across each sector, with negative values shown in parentheses. Table B3 lists all GHG reduction measures.

Table B2: Cumulative Emission Reductions and Costs by Sector

Sector	Emission Reductions (MMTCO ₂ e)		Costs (Million \$2025)	
	2025-2030	2025-2050	2025-2030	2025-2050
Buildings	3.17	45.92	¹ \$(60.46)	¹ \$(1,151.33)
Energy Supply	0.44	3.40	\$256.34	\$(515.30)
Industry	0.44	7.26	² –	² –
Natural & Working Lands	0.12	22.02	\$26.70	\$124.85
Transportation	1.40	40.91	\$3,173.79	\$41,671.57
Waste and Wastewater	0.01	1.77	\$0.78	\$199.77

¹ Buildings sector costs include residential, commercial, and industrial buildings. Costs for industrial process decarbonization (Measure I1) are included here as well due to bundled cost quantification for industrial building and process efficiency costs.

² Industrial sector costs from industrial process decarbonization (Measure I2) are reported under the buildings sector totals.

Table B3: List of GHG Reduction Measures

#	Measure Description	Sector
B1	Invest in energy efficiency, electrification, and other improvements to achieve net zero operations for municipal and school buildings.	Buildings
B2	Increase resident education and awareness of utility, state, and federal incentives for energy efficiency home improvements and electric appliances.	Buildings
B3	Increase energy efficiency in existing commercial and industrial buildings through financial incentives and educational outreach programs.	Buildings
B4	Strongly encourage the design, building, and operation of residential, commercial, and industrial buildings above the current required code.	Buildings
E1	Support the adoption of distributed renewable energy resources.	Energy
E2	Support the development of grid-scale clean energy development and utility efforts to enhance grid resiliency.	Energy
I1	Support local production and use of low-embodied carbon materials through clean procurement frameworks.	Industry
I2	Support emissions reductions from IP.	Industry
NWL1	Remove carbon through nature-based solutions, including preserving existing natural working lands and proactively managing land use changes.	Natural & Working Lands
NWL2	Support and incentivize shared land use with renewable energy and agricultural activities.	Natural & Working Lands

#	Measure Description	Sector
NWL3	Expand urban agriculture and develop region-wide and inter-regional food system distribution.	Natural & Working Lands
NWL4	Increase equitable tree canopy coverage and access to public green spaces.	Natural & Working Lands
NWL5	Increase soil conservation and nutrient management practices in agriculture.	Natural & Working Lands
NWL6	Support livestock management strategies that reduce emissions.	Natural & Working Lands
T1	Reduce emissions from port operations through the adoption of low-carbon fuels, electric equipment, and operational changes.	Transportation
T2	Support, incentivize, and provide assistance for the rapid adoption, equitable installation, and use of zero-emission vehicles.	Transportation
T3	Expand equitable transit access.	Transportation
T4	Reduce VMT through micromobility options and micro modal infrastructure.	Transportation
T5	Expand use of low-carbon transportation materials	Transportation
W1	Decrease amount of waste sent to landfills.	Solid Waste and Wastewater
W2	Support a local, circular economy.	Solid Waste and Wastewater
W3	Support efficiency upgrades at wastewater treatment plants.	Solid Waste and Wastewater

GHG Goals

This plan sets near-term and long-term GHG reduction goals:

- 2035: 22% below 2022 levels (net)
- 2050: net zero GHG emissions

The near-term goal is set based on the BAU emission projections, which reflect the continued successful implementation of existing policies and programs as well as a continuation of current market trends. The long-term goal of net zero emissions by 2050 is aspirational and used to provide information on what it would take to transform the region over the next 25 years. The modeled scenario surpasses the near-term goal and shows a path to net zero emissions. The Net Zero Scenario reduces net GHG emissions by 43% from 2022 levels by 2035 and by 96% by 2050.

Results Overview

The modeling integrated all sectoral measures into a single, internally consistent Net Zero Scenario framework. Each measure's quantified reductions were applied relative to the BAU trajectory. The results underscored several important insights for achieving a net zero emissions future:

- **Electrification and renewable energy deployment** are essential near-term drivers of decarbonization, offering both direct emissions reductions and indirect benefits for other sectors.
- **Carbon sequestration and methane management** provide critical balancing measures to address residual emissions and enhance natural climate solutions.
- **Efficiency and conservation** deliver high cost-effectiveness and co-benefits such as lower energy bills and improved air quality.
- **Policy stability, investment coordination, and data transparency** are vital for sustaining progress and tracking results through 2050.

The quantified results provide a robust analytical foundation for regional climate action planning. They demonstrate that the Richmond MSA can achieve deep decarbonization through a diverse portfolio of measures combining technology deployment, behavioral change, and natural systems management. While the modeled Net Zero Pathway represents a technically feasible scenario, achieving it will depend on sustained collaboration across jurisdictions, agencies, utilities, and community partners.

Based on the BAU projections and the identified measures, this plan sets a target of achieving a 22% reduction in GHG emissions by 2035 from 2022 levels, and a long-term goal of being on a path to net zero GHG emissions by 2050. Building from the BAU analysis, the potential for GHG emission reductions from each measure was assessed, creating the Net Zero Scenario. There are multiple ways for each sector to reduce emissions; this scenario provides just one illustrative path to show the opportunities and relative impact in each sector. Figure B1 shows the region's GHG emission projections by sector. Compared to 2022 (the inventory base year), the BAU pathway achieves a 43% reduction in net emissions by 2035 and a 96% reduction in net emissions by 2050, with just 0.75 MMTCO₂e of net GHG emissions remaining in 2050.

Figure B1: Richmond MSA GHG Emissions by Sector: Net Zero Pathway Scenario

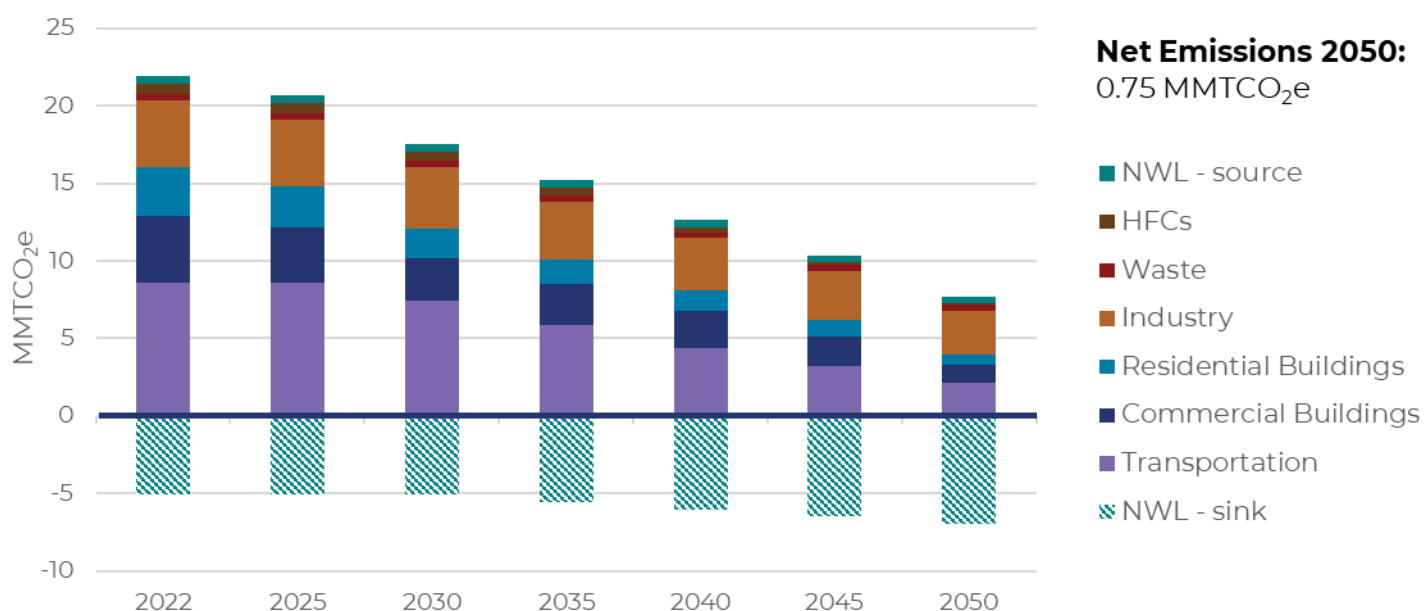


Figure B2 below presents the pathway to net zero scenario via a “wedge chart”, which illustrates the impact on GHG reductions from each measure. The measures driving the largest GHG reductions for this pathway include:

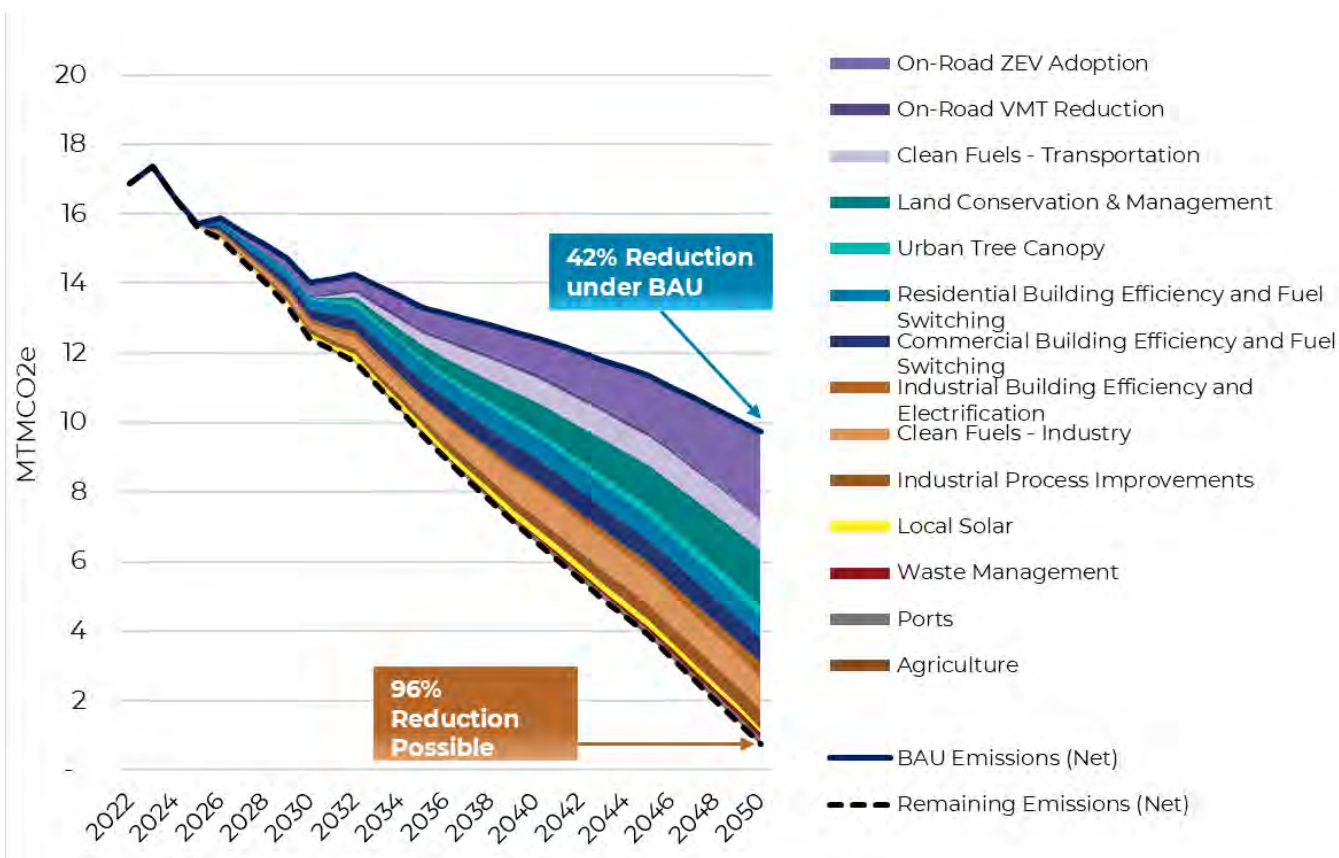
- Adoption of **zero-emission vehicles**. When paired with electricity powered by clean energy (as mandated by the VCEA), this strategy results in the greatest cumulative GHG reductions in the region.

- **Building energy efficiency and electrification** of heating, cooking, and home appliances. The region's expected clean grid is a key enabling factor for the reductions achieved by this measure.
- Increased sequestration protecting and restoring **wetlands** and **forest lands**.
- The use of **low carbon fuels** like hydrogen and renewable natural gas to decarbonize fuel use in industrial facilities.

To present GHG reductions by measure, a “wedge chart” illustrates how different climate mitigation strategies impact GHG emissions over time. Each “wedge” represents a mitigation strategy (e.g., zero-emission vehicles (ZEV) adoption, urban tree canopy expansion, etc.) tied to the GHG measures list in Table B3. Some measures have been aggregated to simplify the chart.

The chart shows the cumulative reductions from the various measures compared to the BAU scenario. The top line of the chart shows the BAU emissions and the bottom line show the emissions under the Net Zero Scenario. The wedges in between represent the various way to close the gap between the BAU and Net Zero Scenarios. The bigger the wedge, the bigger the impact of that measure. Taken together, the wedges are a visual tool to help understand how the multiple measures come together to the plan's goal of net zero GHG emissions by 2050. In order of magnitude, the transportation, buildings, and NWL sectors have the greatest potential for emission reductions, followed by industry and waste. The state target for net zero electric power generation is key to supporting electrification across the transportation, buildings, and industrial sectors without shifting emissions from those sectors to the power sector. As the grid continues to add more clean energy generation and reduce reliance on fossil fuels, emissions in all sectors will improve. But the degree to which these state goals are achieved will impact the potential reductions possible at the local level. State and regional plans are mutually reinforcing.

Figure B2: Net Zero Scenario: GHG Emission Reductions from Each Measure



Buildings

For the building sector measures, GHG reductions were quantified for new and existing residential, commercial, and industrial buildings. Modeled activities include improvements in energy efficiency, increased adoption of electric appliances and equipment, the development of high-performance buildings, and the use of renewable natural gas (RNG). Collectively, these measures are projected to avoid approximately 45.92 MMTCO₂e from 2025 through 2050.

Table B4: Summary of Buildings Sector Measure GHG Reductions MMTCO₂e

Measure	Cumulative 2025-2030 GHG reductions	Cumulative 2025-2050 GHG reductions
Provide technical and financial assistance for energy efficiency, electrification, and other investments to achieve net zero operations for municipal and school buildings.	0.29	2.97
Increase resident education and awareness of utility, state, and federal incentives for energy efficiency home improvements and electric appliances.	1.06	12.62
Strongly encourage the design, building, and operation of residential, commercial, and industrial buildings above current required code.	0.01	0.60
Increase energy efficiency in existing commercial and industrial buildings through financial incentives and educational outreach programs.	1.81	29.73

B1: Provide technical and financial assistance for energy efficiency, electrification, and other investments to achieve net zero operations for municipal and school buildings.

GHG Methodology

GHG emission reductions from municipal and school buildings were estimated using the commercial sector energy savings modeled in measure B3. This analysis draws heavily from NREL's State and Local Planning for Energy (SLOPE) Scenario Planner to estimate potential energy savings from efficiency improvements implemented throughout the region's building stock. More details on this methodology are provided in Measure B4.

Total commercial energy savings from SLOPE's Best Available Energy Efficiency (BAEE) scenario were allocated to the municipal building stock by applying the share of commercial energy use attributable to municipal buildings. This share was derived from the City of Richmond's Citywide and Municipal GHG Inventories.

Key assumptions include:

- Municipal and school buildings were assumed to have similar baseline energy intensity and end-use patterns as the broader commercial building stock.
- Municipal and school building energy consumption as a share of total commercial energy consumption was assumed to follow similar patterns observed in the City of Richmond's GHG Inventories.
- Commercial energy savings from the SLOPE BAEE scenario was assumed to reasonably approximate the scale of achievable energy efficiency improvements in municipal and school buildings within the Richmond MSA.
- Natural gas, fuel oil, and propane use were assumed to decrease proportionally to changes in non-electric fuel use under the BAEE scenario.
- Efficiency improvements were assumed to occur primarily through end-of-life equipment replacements rather than through accelerated retrofits.

Limitations include:

- SLOPE outputs are modeled at the state level and may not capture local variations in building type, age, occupancy, or energy intensity across municipal and school facilities in the MSA.
- Municipal and school buildings represent a small and distinct subset of the commercial sector; their energy use profiles and retrofit potential may differ from private commercial buildings.
- The SLOPE BAEE scenario emphasizes energy efficiency improvements and does not model full building electrification. As a result, estimated emission reductions may understate the potential GHG benefits achievable under a more aggressive electrification pathway supported by continued grid decarbonization.
- The analysis does not account for factors such as limited staff capacity, funding constraints, or procurement challenges that could delay or reduce project implementation in the public sector.

Data sources include:

- [NREL Slope Scenario Planner](#) to estimate state-level change in energy consumption under the Best-Available Energy Efficiency in Buildings scenario.
- [US Census](#) to estimate each county's share of its state population in 2022, used to scale statewide results to the MSA.
- [City of Richmond's Citywide and Municipal GHG Inventories](#) to estimate the share of total commercial energy consumed by municipal buildings.

Cost Approach

Demand-side system costs from NREL's SLOPE tool were used to quantify the costs of implementing energy efficiency upgrades in municipal and school buildings. These include both the upfront investments required to install efficient equipment (capital costs) and the long-term impacts on customer utility bills resulting from changes in electricity and fuel consumption (operational costs).

Table B5 presents the annual and cumulative costs associated with implementing this measure. Relative to the BAU scenario, accelerating the adoption of energy efficiency and electrification retrofits increases near-term capital expenditures. In contrast, operational costs show net savings over time, driven by reduced energy consumption from efficiency improvements that accumulate throughout the study period. In aggregate,

cumulative total costs are negative across the projection horizon, reflecting long-term bill savings that exceed incremental capital investments.

Consistent with the GHG modeling approach, state-level system costs from SLOPE's BAEE scenario were scaled down using each county's share of its state population. Additional details on the cost allocation approach for commercial buildings are discussed under measure B4.

Table B5: Annual Cost of Implementation, in Millions of Real 2025 USD

	2025	2030	2035	2040	2045	2050	2025-2050
Capital Costs	0.0	0.9	0.8	0.2	0.3	0.2	15.2
Operational Costs	0.0	(2.0)	(3.1)	(3.9)	(4.1)	(3.9)	\$(78.9)
Total Costs	0.0	(1.0)	(2.3)	(3.7)	(3.8)	(3.7)	\$(63.8)

Cumulative Cost of Implementation from 2025-2050 (Million 2025 USD): \$(63.8)

Cost data sources include:

- [NREL Slope Scenario Planner](#) to estimate state-level system costs under the Best-Available Energy Efficiency in Buildings scenario.
- US Census to scale statewide results to the Richmond MSA.
- Dominion Energy's Evaluation, Measurement, and Verification Report to estimate costs per MWh saved from Dominion's residential and non-residential energy efficiency programs, used to allocate the share capital costs attributable to commercial buildings.
- City of Richmond's Citywide and Municipal GHG Inventories to estimate the portion of commercial costs attributable to municipal buildings.

B2: Increase resident education and awareness of utility, state, and federal incentives for energy efficiency home improvements and electric appliances.

GHG Methodology

Potential GHG emission reductions from implementing energy efficiency and electrification retrofits in residential buildings were quantified using NREL's SLOPE Scenario Planner. The analysis scaled down state-level energy consumption outputs from SLOPE's BAEE scenario, which uses NREL's Scout Core Measures Scenario Analysis to model adoption of both commercially available and emerging high-efficiency equipment and building envelope technologies across U.S. residential and commercial buildings.

The Scout model quantifies site-level energy savings by comparing efficient technologies to baseline equipment across major end uses, including space heating, cooling, water heating, and lighting. It assumes that building energy efficiency increases over time as consumers adopt aggressive energy conservation measures that reduce direct fuel use in buildings. Relative to the reference scenario, these measures yield a nationwide reduction in energy consumption of approximately 22% by 2050 for residential and commercial

buildings. Additionally, end-use electrification is projected to increase over time due to a combination of technology cost and performance improvements as well as incentives under the Inflation Reduction Act (IRA).

National-level results from Scout were first disaggregated to the state level based on state level projections of energy efficiency potential from Electric Power Research Institute (EPRI). Results for Virginia were then scaled to the Richmond MSA using population shares. Reductions in residential electricity and fuel use were calculated relative to the reference case and scaled to the BAU scenario.

Key assumptions include:

- The SLOPE BAEE scenario was assumed to reasonably approximate the scale of achievable energy efficiency improvements by 2050. This model assumes that energy efficiency of residential and commercial buildings increases over time, consistent with consumers pursuing aggressive energy conservation measures, including equipment, envelope, and other efficiency improvements that reduce direct fuel use in buildings. End-use electrification is also assumed to grow over time due to a combination of technology cost and performance improvements as well as incentives from the IRA.
- Modeled state-level energy efficiency potentials for Virginia were assumed to be representative of trends within the Richmond MSA.
- Natural gas, fuel oil, and propane use were assumed to decrease proportionally to changes in non-electric fuel use under the BAEE scenario.

Limitations include:

- SLOPE outputs are modeled at the state level and may not capture local variations in housing stock characteristics, climate conditions, income levels, or program participation rates across the Richmond MSA.
- The analysis does not account for implementation barriers such as limited consumer awareness, upfront cost constraints, or workforce availability, which may affect the scale and timing of adoption.

Data sources include:

- [NREL Slope Scenario Planner](#) to estimate state-level change in energy consumption under the Best-Available Energy Efficiency in Buildings scenario.
- [US Census](#) to estimate each county's share of its state population in 2022, used to scale statewide results to the Richmond MSA.

Cost Approach

Demand-side system costs from NREL's SLOPE tool were used to quantify the costs of implementing energy efficiency upgrades in existing residential buildings. These include both the upfront investments required to install efficient equipment (capital costs) and the long-term impacts on customer utility bills resulting from changes in electricity and fuel consumption (operational costs). Relative to the BAU scenario, accelerating the adoption of efficiency and electrification retrofits increases near-term capital expenditures. In contrast, operational costs show net savings over time, driven by reduced energy consumption from efficiency improvements that accumulate throughout the study period. As shown in Table B6, cumulative total costs are negative across the projection horizon, reflecting long-term bill savings that exceed incremental capital investments.

Consistent with the GHG modeling approach, state-level system costs from SLOPE's BAEE scenario were scaled down using each county's share of its state population. For the residential sector, capital costs were

allocated based on relative costs per megawatt-hour saved from residential energy efficiency programs reported in Dominion Energy's Evaluation, Measurement, and Verification Report. Fuel consumption costs were allocated according to the residential sector's share of total annual fuel and electricity savings.

Table B6 presents costs for existing and new residential buildings. Operational costs also include RNG fuel costs derived from the American Gas Foundation's Renewable Natural Gas Supply Assessment. These estimates reflect only the commodity purchase cost of RNG and exclude infrastructure, delivery, and administrative costs associated with RNG production, certification, or use.

Table B6: Measure B2 Annual and Cumulative Cost of Implementation (2025\$ Million)

	2025	2030	2035	2040	2045	2050	2025-2050
Capital Costs	-	21.95	27.19	10.72	19.09	15.84	309.20
Operational Costs	13.28	(43.70)	(72.40)	(100.90)	(117.88)	(117.01)	(2,022.83)
Total Costs	13.28	(21.74)	(45.20)	(90.18)	(98.79)	(101.17)	(1,713.63)

Cumulative Cost of Implementation from 2025-2050 (Million 2025 USD): \$(1,713.63)

Cost data sources include:

- [NREL Slope Scenario Planner](#) to estimate state-level system costs under the Best-Available Energy Efficiency in Buildings scenario.
- [US Census](#) to scale statewide results to the Richmond MSA.
- [Dominion Energy's Evaluation, Measurement, and Verification Report](#) to estimate costs per MWh saved from Dominion's residential and non-residential energy efficiency programs, used to allocate the share capital costs attributable to residential building retrofits.
- [American Gas Foundation's Renewable Natural Gas Supply Assessment \(2025\)](#) to estimate RNG prices.

B3: Increase energy efficiency in existing commercial and industrial buildings through financial incentives and educational outreach programs.

This measure quantifies emission reductions from energy efficiency retrofits implemented in both existing commercial and industrial buildings. Including GHG reductions from RNG and hydrogen, 9.63 MMTCO₂e are avoided in commercial buildings and 20.10 MMTCO₂e are avoided in industrial buildings over the 2025–2050 period. Methodologies for each category are discussed below.

GHG Methodology

Commercial Buildings

Potential GHG emission reductions from increasing energy efficiency retrofits in commercial buildings were quantified using NREL's SLOPE Scenario Planner. The analysis scaled down state-level energy consumption outputs from SLOPE's BAEE scenario, which uses NREL's Scout Core Measures Scenario Analysis to model

adoption of both commercially available and emerging high-efficiency equipment and building envelope technologies across U.S. residential and commercial buildings.

The Scout model quantifies site-level energy savings by comparing efficient technologies to baseline equipment across major end uses, including space heating, cooling, water heating, and lighting. It assumes that building energy efficiency increases over time as consumers adopt aggressive energy conservation measures that reduce direct fuel use in buildings. Additionally, end-use electrification is projected to increase over time due to a combination of technology cost and performance improvements as well as incentives under the IRA.

National-level results from Scout were first disaggregated to the state level based on state level projections of energy efficiency potential from EPRI. Results for Virginia were then scaled to the Richmond MSA using population shares. Reductions in commercial electricity and fuel use were calculated relative to the reference case and scaled to the BAU scenario. Energy savings in municipal and school buildings were subtracted from reported totals to avoid double counting with measure B1.

Key assumptions include:

- The SLOPE BAEE scenario was assumed to reasonably approximate the scale of achievable energy efficiency improvements within the MSA by 2050. This model assumes that energy efficiency of commercial buildings increases over time, consistent with consumers pursuing aggressive energy conservation measures, including equipment, envelope, and other efficiency improvements that reduce direct fuel use in buildings. End-use electrification is also assumed to grow over time due to a combination of technology cost and performance improvements as well as incentives from the IRA.
- Modeled state-level energy efficiency potentials for Virginia were assumed to be representative of trends within the MSA.
- Natural gas, fuel oil, and propane use were assumed to decrease proportionally to changes in non-electric fuel use under the BAEE scenario.

Limitations include:

- SLOPE outputs are modeled at the state level and may not capture local variations in housing stock characteristics, climate conditions, income levels, or program participation rates across the MSA.
- The analysis does not account for implementation barriers such as limited consumer awareness, upfront cost constraints, or workforce availability, which may affect the scale and timing of adoption.

Data sources include:

- [NREL Slope Scenario Planner](#) to estimate state-level change in energy consumption under the Best-Available Energy Efficiency in Buildings scenario.
- [US Census](#) to estimate each county's share of its state population in 2022, used to scale statewide results to the Richmond MSA.
- [City of Richmond's Citywide and Municipal GHG Inventories](#) to estimate the share of total commercial energy consumed by municipal buildings.

Industrial Buildings

Potential GHG emission reductions from energy efficiency improvements and electrification of industrial buildings and processes within the Richmond MSA were estimated by integrating facility-level data from

EPA's GHGRP with industry-average energy use and fuel consumption data from EIA's Manufacturing Energy Consumption Survey (MECS). Facility-level stationary combustion emissions were converted into primary energy use by fuel and end use (boilers, process heat, and building systems), then modeled to reflect the impacts of replacing fossil fuels with electricity and improving system efficiency.

Emissions reductions were quantified by applying electrification and efficiency adoption rates consistent with the U.S. DOE's Industrial Decarbonization Roadmap, which outlines sector-specific pathways. These adoption rates represent technology deployment for low-temperature heat, efficient motors and drives, process electrification, and building-related systems such as heating, ventilation, and air conditioning (HVAC) and lighting. Efficiency factors for electrified technologies were drawn from the American Council for an Energy-Efficient Economy (ACEEE), and CO₂ emissions factors for electricity consumption were applied using the BAU grid scenario.

Statewide results were allocated to the MSA using BLS employment data for industrial subsectors as a proxy for local activity. This scaling approach captures the MSA's concentration of energy-intensive facilities associated with shipbuilding, maritime logistics, and advanced manufacturing, as well as smaller-scale fabrication and repair operations.

Key assumptions include:

- The Advanced pathway from DOE's Industrial Decarbonization Roadmap was used as the mitigation scenario, representing incremental adoption of electrification and efficiency measures.
- Grid carbon intensity was assumed to decline in line with the BAU electric power projections for Virginia.
- industrial process emissions (non-combustion) were excluded to avoid double counting with the IP sector.

Limitations include:

- The frameworks used primarily reflect state-level and national data and may not fully capture variation in process energy intensity or technology readiness across individual facilities in the Richmond MSA. Barriers such as upfront capital costs, system downtime during retrofits, and workforce availability were not modeled explicitly but may influence real-world adoption.

Data sources include:

- [EPA GHGRP \(2022\) facility-level emissions](#)
- [EIA Manufacturing Energy Consumption Survey \(MECS\) \(2018\)](#)
- [DOE Industrial Decarbonization Roadmap \(2022\)](#)
- [DOE Industrial Decarbonization Liftoff Report \(2023\)](#)
- [ACEEE Industrial Efficiency Technical Reference \(2023\)](#)
- [BLS County Employment Data \(2024\)](#)

Cost Approach

Commercial Buildings

Demand-side system costs from NREL's SLOPE tool were used to quantify the costs of implementing energy efficiency upgrades in existing commercial buildings. These include both the upfront investments required to install efficient equipment (capital costs) and the long-term impacts on customer utility bills resulting from changes in electricity and fuel consumption (operational costs).

Compared to the BAU scenario, accelerating the adoption of energy efficiency retrofits increases near-term capital expenditures. In contrast, operational costs show net savings over time, driven by reduced energy consumption from efficiency improvements that accumulate throughout the study period. As shown in Table B7, cumulative total costs are negative across the projection horizon, reflecting long-term bill savings that exceed incremental capital investments.

Consistent with the GHG modeling approach, state-level system costs from SLOPE's BAEE scenario were scaled down using each county's share of its state population. For the commercial sector, capital costs were allocated based on relative costs per megawatt-hour saved from non-residential energy efficiency programs reported in Dominion Energy's Evaluation, Measurement, and Verification Report. Fuel consumption costs were allocated according to the commercial sector's share of total annual fuel and electricity savings. Costs for municipal buildings were subtracted from the reported totals to avoid double counting with measure B1.

Table B7 presents costs for existing and new residential buildings. Operational costs also include RNG-related costs, estimated by multiplying annual RNG consumption by the median price reported in the American Gas Foundation's Renewable Natural Gas Supply Assessment. These estimates reflect only the commodity purchase cost of RNG and exclude infrastructure and delivery costs associated with RNG production, certification, or use.

Table B7: Measure B3 Annual and Cumulative Cost of Implementation (2025\$ Million)

	2025	2030	2035	2040	2045	2050	2025-2050
Commercial Sector Capital Costs	-	24.79	21.55	6.60	8.09	4.01	219.17
Commercial Sector Operational Costs	18.60	(28.13)	(49.70)	(75.50)	(85.56)	(83.91)	(1,417.04)
Industrial Sector Total Costs	-	17.45	34.55	56.01	66.74	77.74	1,123.70
Total Costs	18.60	14.11	6.40	(12.89)	(10.73)	(2.17)	(74.17)

Cumulative Cost of Implementation from 2025-2050 (Million 2025 USD): \$(74.17)

Cost data sources include:

- [NREL Slope Scenario Planner](#) to estimate state-level system costs under the Best-Available Energy Efficiency in Buildings scenario.
- [US Census](#) to scale statewide results to the Richmond MSA.
- [Dominion Energy's Evaluation, Measurement, and Verification Report](#) to estimate costs per MWh saved from Dominion's residential and non-residential energy efficiency programs, used to allocate the share capital costs attributable to commercial building retrofits.

Industrial Buildings

Costs associated with the GHG reductions modeled for the industrial sector were calculated using marginal abatement cost data from DOE's Pathways to Commercial Liftoff: Industrial Decarbonization report. For each industry type represented within the Richmond MSA, applicable abatement levers such as electrification of thermal systems, energy efficiency improvements, process emission reductions, and low-carbon fuel switching were assigned representative costs per metric ton of CO₂e reduced. These values were weighted

based on each subsector's emissions profile and the relative contribution of each intervention to total modeled abatement potential, resulting in a weighted average cost of abatement (\$/MTCO₂e) for each industrial subsector.

Table B8: Weighted Average Cost of Abatement by Industrial Sector (\$/MTCO₂e)

Industrial Sector	\$/MTCO ₂ e
Light Industry (Food, Beverage, Tobacco, Transport & Warehouse, Educational Services, Public Administration)	57.42
Paper & Pulp	34.33
Chemicals	26.11
Metals	81.58

Examples of capital costs include the incremental expense of replacing fossil fuel systems such as boilers, furnaces, and direct-fired process heaters with electric technologies like heat pumps, resistance, or induction systems, as well as upgrades to motors, compressors, controls, and HVAC equipment. Operational cost impacts reflect modeled energy savings and the transition from fossil fuels to electricity or other low-carbon fuels.

Total abatement costs were estimated by multiplying the weighted cost per MTCO₂e by the emissions reductions modeled under the mitigation scenario. The resulting values represent the combined cost of implementing a diverse set of industrial decarbonization strategies, inclusive of electrification, efficiency, process improvements, and fuel switching.

In many cases, stationary and process emissions in industrial facilities often come from the same equipment, such as furnaces, boilers, and other thermal systems. With this, a single upgrade often reduces both types of emissions at the same time. When a system is electrified, retrofitted, or switched to a low-carbon fuel, it cuts fuel-combustion emissions while also lowering the process-related emissions connected to that equipment. For this reason, the costs for measures B3 and I2 are bundled to avoid double counting and to reflect that one intervention typically delivers both sets of reductions. Total cost results for industrial are shown in Table B7Table B10. Table B9 below shows the total costs by industrial sub-sector.

Table B9: Measure B4 (Industrial) Annual and Cumulative Cost of Implementation (2025\$ Million)

	2025	2030	2035	2040	2045	2050	2025-2050
Light Industry, Food, Beverage, Tobacco	-	8.82	17.48	28.33	33.75	39.31	569.00
Paper, Pulp, Mining	-	3.31	6.56	10.64	12.67	14.76	213.66
Chemicals	-	4.17	8.27	13.40	15.96	18.59	269.12
Metals	-	1.14	2.25	3.65	4.35	5.06	73.27
Total Costs	-	17.45	34.55	56.01	66.74	77.74	1,125.04

Cumulative Cost of Implementation from 2025-2050 (Million 2025 USD): \$1,125.04

Cost data sources include:

- [DOE Industrial Decarbonization Liftoff Report \(2023\)](#)
- [DOE Industrial Decarbonization Roadmap \(2022\)](#)
- [EIA Annual Energy Outlook 2025 report](#)
- [NREL Annual Technology Baseline 2024](#)
- [EPA GHGRP \(2022\) facility-level emissions](#)
- [BLS County Employment Data \(2024\)](#)

B4: Strongly encourage the design, building, and operation of residential, commercial, and industrial buildings above current required code.

GHG Methodology

GHG emissions reductions from increasing energy efficiency in new construction were estimated based on projected improvements in state building energy codes. Also incorporated into the new buildings modeling is a range of broader new building electrification. The modeling assumed that Virginia adopts updates to the International Energy Conservation Code (IECC) and the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) 90.1 standards at regular intervals from 2026 through 2050, with code compliance assumed for all new buildings based on a 30-year measure life. New building growth projections were based on available forecasts for the region. A fossil fuel combustion phase-out is also assumed in later projection years, in addition to a certain percentage of buildings assumed to be built to a green buildings code.

Key assumptions include:

- Energy code compliance was assumed for all new buildings based on a 30-year measure lifetime.
- Updated IECC and ASHRAE 90.1 standards are adopted every six years.
- New residential home growth was based on household growth rates from the Weldon Cooper Center for Public Service; commercial construction growth projections were based on population projections scaled to historical commercial growth, with square footage estimates sourced from NREL ComStock data.
- Multi-family residential building energy usage was modeled to be 50% of single-family usage based on EPA studies.
- The residential green buildings standard corresponds to Passive House standards, reflecting all-electrified homes meeting a 13.6 kBtu/ft² site energy use intensity (EUI) and decreasing in line with energy code progression. 1% of new homes are assumed to comply with the standard in 2026, growing linearly to 15% by 2050.
- The commercial green buildings standard corresponds to achieving a Portfolio Manager ENERGY STAR score of 90, reflecting all-electrified buildings meeting a 28.4 kBtu/ft² site EUI and decreasing in line with energy code progression. 1% of new commercial square footage is assumed to comply with the standard in 2026, growing linearly to 25% by 2050.
- Multifamily buildings represent 33% of newly constructed homes in 2026, growing linearly to 50% by 2050.

- Heat pump efficiency growth is based on the residential moderate advancement scenario from the 2018 NREL Electrification Futures study.
- Electrification rates continue based historical trends, until fossil fuel combustion phase-outs for new buildings begin in 2035 for the residential sector and 2040 for the commercial sector.

Limitations include:

- New buildings projections are heavily dependent upon household and commercial square footage growth rates. Changes to these rates will correspond to similar changes in emissions reductions. Commercial square footage growth rates were estimated based on population growth across the region. More detailed studies into labor growth, including the types of projected employment and their correspondence to commercial building growth may give a more accurate estimation of square footage growth.
- New buildings modeling is simplified by only accounting for the fuel usage and EUI per residential home or commercial square foot. In actuality, there are numerous types of housing (detached vs. attached single family homes, multifamily buildings with a variety of units, etc.) as well as many different types of commercial buildings (offices, hospitals, schools, industry, etc.) that the modeling cannot reasonably account for. As such, deviations in energy usage based on the growth rates of different types of buildings are to be expected. EUI is also a simplified annual metric that does not take into account specific building equipment types. The modeling assumed that increases in equipment efficiencies are expected to continue, but future energy consumption may be higher if this assumption changes (such as due to state/federal policies, economic/technological limitations, or other barriers).
- The projected split between single-family and multi-family housing in the region will also affect the energy consumption of new buildings. Further state policies as well as demographic/land usage shifts have the potential to alter these projected trends.

Data sources include:

- Growth projections for households and commercial square footage from the [Weldon Cooper Center for Public Service](#) and NREL's [ComStock](#) dataset.
- Energy usage based on data from Pacific Northwest National Laboratory (PNNL) cost-effectiveness studies for [IECC](#) and [ASHRAE](#) codes, [Passive House standards](#), and [ENERGY STAR estimates](#).
- Heat pump efficiency growth from [NREL's 2018 Electrification Futures study](#).

Cost Approach

For new buildings, costs were split out between upfront costs and operational costs (reflecting energy usage change). Upfront costs were split between code improvements and additional stretch/green buildings code costs. The upfront cost calculations for implementing energy efficiency through code improvements were extrapolated based on the costs and savings estimated in the most recently available PNNL cost-effectiveness studies. For residential buildings, this was IECC 2021; for commercial buildings, ASHRAE 90.1 2019 was used. These costs estimates were multiplied by the number of residential homes (single and multifamily) or commercial square footage in each city/county to reach the totals.

To reflect the additional costs of a stretch/green buildings code, new residential buildings meeting this additional standard were modeled to achieve Passive House EUI requirements. Costs for Passive House implementation were sourced from Passive House Institute U.S. ("Phius") cost data research, with state new

construction cost estimates sourced from Home-Cost. New commercial buildings were modeled to meet EUI standards corresponding to a Portfolio Manager ENERGY STAR score of 90 for the low scenario and the 2019 ASHRAE Advanced Energy Design Guide for Small to Medium Office Buildings - Zero Energy report for the high scenario, with cost estimates derived from studies by Built Environment Plus and BR+A, along with construction cost estimates from RSMeans.

Energy cost savings from new buildings were calculated based on changes in fuel and electricity consumption relative to baseline code-compliant construction. Fuel prices were sourced from EIA and escalated using growth rates from EIA's Annual Energy Outlook 2025, Table B3.

Table B10: Measure B4 Annual and Cumulative Cost of Implementation (2025\$ Million)

	2025	2030	2035	2040	2045	2050	2025-2050
Capital Costs	-	13.15	35.37	50.32	76.05	74.41	1,034.97
Operational Costs	-	(1.45)	(6.00)	(12.83)	(24.93)	(39.07)	(336.09)
Total Costs	-	11.70	29.37	37.49	51.12	35.34	698.88

Cumulative Cost of Implementation from 2025-2050 (Million 2025 USD): \$699

Cost data sources include:

- [Residential](#) and [commercial](#) code upgrade costs from PNNL code cost-effectiveness studies.
- Green buildings code costs from [Phius](#), [Home-Cost](#), [Built Environment Plus](#), and [BR+A](#), and [RSMeans](#).
- Historical [natural gas](#), [electricity](#), and [other fuel](#) prices from EIA reports.
- Projected growth rates for fuel and electricity prices in the South Atlantic region from the [EIA Annual Energy Outlook 2025 report](#).

Renewable Natural Gas

RNG was applied to fuel use in the buildings and industrial sectors to reduce the carbon intensity of remaining gas consumption. RNG can serve as a direct substitute for fossil gas either via direct use onsite or through a book-and-claim process whereby the credits for the carbon attributes are transferred to the assets using them. While not included as a standalone measure, RNG was incorporated as an additional modeling component to support progress toward the MSA's net zero emissions targets. Cumulatively, RNG is projected to avoid 13.86 MMTCO₂e from 2025 through 2050, with these emission reductions accounted for under the buildings sector measures.

GHG Methodology

In the modeling case, RNG (produced via a combination of anaerobic digestion and thermal gasification) is used in the residential, commercial, and industrial settings as a replacement for fossil-derived natural gas sources. For this modeling, RNG is considered to emit only biogenic emissions (carbon from within the natural carbon cycle) and is treated as emissions-free from a Scope 1 perspective.

Key assumptions include:

- RNG was used as a direct replacement for fossil gas and treated as a zero-emissions fuel.
- RNG estimates were sourced from the American Gas Foundation's 2025 Renewable Natural Gas Supply Assessment report, which ICF supported. This report details annual state-level supply of RNG from 2025-2050 under three scenarios, using eight different feedstock types. The modeling reflected use of the report's "Ambitious Emission Reduction" scenario.
- The modeling resulted in a blended pipeline gas emissions factor for the entire state, which was used for the Richmond MSA as a simplifying assumption.
- The BAU scenario does not include any RNG within the energy system.

Limitations include:

- All RNG in this modeling was assumed to emit only biogenic carbon dioxide and thus be carbon free. Actual RNG emissions are low but are dependent on the feedstock and range from 150g CO₂e/MJ to -70g CO₂e/MJ.
- A portion of RNG was used as a feedstock for turquoise hydrogen, an emerging technology.²
- The modeling considered Virginia's in-state RNG production capacity as a proxy for total usage, which was then allocated down to the Richmond MSA through pipeline blending. In reality, the state as well as the Richmond MSA will have access to a wider array of regional RNG production sources, but will also need to compete with other states and private entities in order to source this supply.
- The BAU case was assumed to not use RNG, which was a simplifying assumption made for ease of integration that reflects the current low levels of adoption.
- While RNG is a mature technology, implementation at the scale outlined is currently constrained by economic factors. RNG is not broadly cost competitive compared to fossil gas. To achieve full deployment of the fuels, policies may be needed for further economic support.

Data sources include:

- [American Gas Foundation's Renewable Natural Gas Supply Assessment \(2025\)](#)

Cost Approach

RNG costs were estimated by multiplying annual RNG consumption by the median price reported in the American Gas Foundation's Renewable Natural Gas Supply Assessment. These costs are accounted for within the buildings and industrial sector measures. The estimates reflect only the commodity purchase cost of RNG and do not include infrastructure, delivery, or administrative costs associated with RNG production, certification, or use.

Cost data sources include:

- [American Gas Foundation's Renewable Natural Gas Supply Assessment \(2025\)](#)

² "Turquoise hydrogen" is produced from methane. The primary byproduct of this process is solid carbon, rather than gaseous CO₂.

Hydrogen

Hydrogen was applied to fuel use in the industrial sector to reduce the carbon intensity of remaining natural gas consumption. While not included as a standalone measure, hydrogen was incorporated as an additional modeling component to support progress toward the MSA's net zero emissions targets. From 2025 through 2050, hydrogen adoption in industrial applications is projected to avoid 5.72 MMTCO₂e in cumulative emissions, with these reductions reflected under Measure B4.

GHG Methodology

Hydrogen can serve as a direct substitute for fossil gas either via direct use onsite or through a book-and-claim process whereby the credits for the carbon attributes are transferred to the assets using them. Hydrogen integration is designed to further Richmond's decarbonization goals by replacing existing fossil fuel gas usage with zero-emission hydrogen. In the modeling case, hydrogen (from a combination of blue, green, pink, and turquoise sources) is used to power industrial facilities.³ Hydrogen is currently being estimated as a zero-emissions fuel due to its lack of end-use CO₂ emissions.

Key assumptions include:

- Hydrogen supply projections were based on ICF internal forecasts. From a national model, blue turquoise, green, and pink hydrogen generation was scaled down based on the MSA's industry sector relative consumption of state natural gas and the optimization of IRA tax credits for using RNG as a feedstock in hydrogen production.
- Hydrogen was used as a direct replacement for fossil gas and treated as a zero-emissions fuel.
- The modeling considered the region's hydrogen production capacity as a proxy for total usage. In reality, the region will have access to a wider array of hydrogen production sources but will also need to compete with other regions and private entities in order to source this supply. Policy and economic factors will also influence the fuel's potential long-term development.
- The BAU scenario does not include any hydrogen within the energy system.

Limitations include:

- Assumptions regarding hydrogen development and usage are speculative in nature as a result of the limited amount of commercial-scale production sites currently in operation across the country. ICF's alternative fuel and industry teams frequently update their outlooks for hydrogen production based on regional and national policies, which are incorporated into these results. Hydrogen development generally depends on available incentives and funding, so policy changes can strongly influence the amount of investment that is allocated for this fuel.
- This analysis also does not incorporate the logistical or economic challenges of delivering hydrogen to end users, whether in the form of a pipeline blend under a "book-and-claim" system or through direct delivery to industry hubs. Further analysis regarding the costs and design of the delivery infrastructure is recommended, as the age of gas pipeline infrastructure can determine the hydrogen blending capacity.

³ "Blue hydrogen" is produced from natural gas or other fossil fuels. Gaseous CO₂ is a byproduct of this process. "Green hydrogen" is produced using water and electricity generated from renewable sources like wind or solar. There are no CO₂ emissions associated with this process. "Pink hydrogen" is produced using water and electricity generated using nuclear power. For more information, visit: <https://www.belfercenter.org/research-analysis/colors-hydrogen>.

Data sources include:

- ICF Industrial and Alternative Fuels team datasets

Cost Approach

These costs are accounted for within the industrial sector costs shown in Table B7.

Energy Supply

These measures quantify potential GHG reductions from strategies that decarbonize the region’s electricity supply, including transitioning the grid toward cleaner energy sources and promoting local rooftop solar deployment. All modeled emission reductions are attributed to the expansion of rooftop solar, as no additional actions beyond the BAU scenario were modeled for measure E2. Overall, emissions from this sector are projected to decrease by 3.40 MMTCO₂e from 2025 through 2050.

Table B11: Summary of Energy Sector Measure GHG Reductions MTCO₂e

Measure	Cumulative 2025-2030 GHG reductions	Cumulative 2025-2050 GHG reductions
Accelerate regional solar energy adoption by expanding program participation, streamlining permitting and increasing community awareness and education through a Solar Hub	0.44	3.40
Support the development of grid-scale clean energy development and utility efforts to enhance grid resiliency	NE	NE

E1: Support the adoption of distributed renewable energy resources (e.g., rooftop solar)

GHG Methodology

This measure quantifies the potential GHG reductions associated with increased local grid-connected and rooftop solar deployment in the MSA. This measure builds from existing progress in the region. Beyond GHG emission reductions, solar – particularly onsite systems paired with battery storage – can help lower household energy bills and increase resiliency to grid outages. By 2050, the MSA has about 1.1 GW of installed solar capacity, up from 0.1 GW in 2024. This includes about 200 MW of agrivoltaics, discussed in measure NWL2.

The modeling for this measure is based on NREL datasets identifying rooftop solar technical potential by state, NREL reports on market and economic adoption potential, and estimates of rooftop square footage area for residential and commercial buildings by county from NREL’s ResStock and ComStock datasets.

The modeling process to assess solar adoption uses data on 1) rooftop area available for solar, 2) solar output potential and 3) the adoption rate.

- The available rooftop area is from NREL’s 2016 Rooftop Potential Study, which includes state-level roof area suitable for solar for residential (small) and commercial (medium-large) systems. This is downscaled to the county level using rooftop area for residential and commercial buildings from NREL’s ResStock and ComStock datasets.

- The NREL dataset also provides the kW/m² solar output potential for the roof area.
- Using the county rooftop area and solar output potential, NREL defines a technical potential for rooftop solar. NREL DG Solar and Storage Outlook, EFS 2021 provides adoption scenarios. The aggressive “Advanced PV + Battery” adoption scenario was selected, which achieves a 20% adoption rate (of technical potential) as an average across the MSA, and battery storage equivalent to about 7% of solar capacity.
- The avoided emissions from solar were estimated based on the grid emissions factor.

Limitations include:

- Using the NREL data and adoption rate for rooftop solar is an imperfect proxy to estimate the potential for solar growth in the region. In reality, systems will have varying sizes, and large (>20 MW) front-of-the-meter installations can increase the pace of solar deployment compared to residential rooftop installations (which average 7-8 kW per home).
- Actual adoption rates will be influenced by a range of factors, including the cost-effectiveness of solar installations, the efficiency of permitting and regulatory approval processes, and the ease of grid interconnection. Ongoing market uncertainties—such as fluctuations in clean energy tax incentives, tariffs, and broader economic conditions—will play a significant role in determining the real-world impact of this measure.

Data sources include:

- [NREL’s 2016 Rooftop Potential Study](#)
- [NREL DG Solar and Storage Outlook, EFS 2021](#)
- EIA [RECS](#) and [CBECS](#)
- NREL [ResStock](#) and [ComStock](#)

Cost Approach

To estimate the cost of deploying solar, NREL’s 2024 Annual Technology Baseline was used for forecasts of capital and operating costs for residential and commercial distributed solar systems. These costs were applied to the incremental capacity added in each year of the forecast. These costs were applied to the incremental new capacity added in each year of the forecast. In addition, potential bill savings were estimated based on electricity retail rates from EIA-861, which were projected through 2050 based on EIA’s Annual Energy Outlook (AEO) trends. The bill savings drive significant potential for lower costs with rooftop solar due to lower electricity bills. Bill savings are a key driver for the payback period for rooftop solar systems, which can range from 5-15 years depending on the system size and electricity rate.

Table B12: Measure E1 Annual and Cumulative Cost of Implementation (2025\$ Million)

	2025	2030	2035	2040	2045	2050	2025-2050
Capital Costs	70.50	53.27	44.33	37.52	33.90	30.27	1,127.61
Operational Costs	0.73	3.57	5.60	7.08	8.56	9.68	155.98
Bill Impacts (Avoided Costs)	(4.59)	(15.59)	(28.02)	(39.81)	(51.71)	(66.88)	(1,798.89)
Total Costs	64.29	27.07	(6.21)	(35.14)	(65.10)	(96.69)	(515.30)

Cumulative Cost of Implementation from 2025-2050 (Million 2025 USD): \$(515.30)

Cost data sources include:

- [2024 NREL Annual Technology Baseline](#) for moderate scenario capital expenditure (CAPEX) and fixed Operating & maintenance (O&M) costs for residential and commercial distributed solar resources
- [EIA-861](#) for average 2024 residential and commercial retail electricity rates in VA
- [EIA AEO 2025 Table 3.5](#) for projected growth rates of electricity prices in the South Atlantic region

E2: Support the development of grid-scale clean energy development and utility efforts to enhance grid resiliency.

GHG Methodology

In the BAU scenario, grid electricity emission factors for Virginia counties were based on Virginia State CPRG modeling, reflecting the VCEA mandate for utilities to achieve net zero emissions by 2050. As a result, no additional actions beyond the BAU scenario were modeled.

A key component of the VCEA is deploying clean energy resources across the state and ensuring a reliable grid. This necessitates collaboration, with localities supporting resource deployment in a sustainable manner and ensuring complementary priorities are met (e.g., promoting biodiversity alongside clean energy projects and using under-utilized land for project siting). This measure is most appropriate for state agencies, local governments, nonprofits, and regional entities.

Now, more than ever, the electric grid is facing a wave of challenges creating significant uncertainty that permeates through modeling, decision-making, and policies. These uncertainties will have a significant impact on the region's ability to successfully implement VCEA clean energy targets.⁴ Key uncertainties include:

- **Load growth and data center dynamics:** Rapid expansion and rising energy intensity drive uncertainty in both load levels and peak demand timing. Building sector energy efficiency and managed EV charging solutions can help mitigate impacts on peak load and are critical focus areas as these sectors electrify.
- **Emerging technology and innovation** (e.g., small modular nuclear reactors, long duration battery storage): Timing and cost of deployment are uncertain, depending on technology development, regulatory approval, supply chain readiness, and investment from utilities or private developers.
- **Resource availability and cost:** Supply chain volatility, interconnection costs, and fuel cost drive uncertainties for the costs of new energy resources.
- **Transmission system infrastructure:** Congestion and limited transfer capacity within Pennsylvania-New Jersey-Maryland Interconnection (PJM) may delay siting and lean energy projects. Long lead times for permitting and development of new transmission infrastructure pose a risk to achieving VCEA renewable energy targets.
- **VCEA implementation:** The VCEA applies only to investor-owned utilities; private entities such as data centers can develop their own on-site fossil fuel generation. The VCEA also includes a reliability exception, under which utilities can petition the SCC for relief from VCEA targets if they can demonstrate a reliability

⁴ The [Dominion Energy 2025 Update to the 2024 Integrated Resource Plan \(2025 IRP update\)](#) evaluated multiple portfolios that incorporate VCEA requirements. Dominion highlights the challenges of complying with VCEA's net zero GHG target (\$10.1-1308 E) while incorporating assumptions related to reasonable capacity deployment levels, affordability concerns, and reliability concerns.

or security threat. The purpose of this is to maximize the state's energy reliability and resilience and ensure an adequate energy supply during the transition to renewable energy sources. The broader grid and resource interconnection concerns, in addition to the cost to site and build new resources are key factors that will determine the successful implementation of the VCEA targets.

The Virginia Comprehensive Climate Action Plan contains more information on how the state plans to address energy reliability and GHG reduction goals.

Cost Approach

Costs were not quantified for this measure.

Industry

These measures quantify GHG emission reductions from actions that lower emissions from IP. Collectively, these measures are projected to reduce emissions by 7.26 MMTCO₂e from 2025 through 2050.

Table BI3: Summary of Industry Sector Measure GHG Reductions MTCO₂e

Measure	Cumulative 2025-2030 GHG reductions	Cumulative 2025-2050 GHG reductions
Support local production and use of low-embodied carbon materials through clean procurement frameworks.	NE	NE
Support emissions reductions from IP.	0.44	7.26

II: Support local production and use of low-embodied carbon materials through clean procurement frameworks.

GHG Methodology

Embodied carbon refers to the GHG emissions associated with the extraction, manufacturing, transportation, installation, and disposal of building materials. Reducing embodied carbon typically involves clean procurement practices, such as prioritizing materials with lower lifecycle emissions (e.g., green steel, low-carbon concrete, and recycled-content materials) and adopting procurement frameworks that favor verified low-embodied carbon products.

While GHG reductions were not quantified for this measure due to limited region-specific data, the Richmond MSA could reduce embodied emissions by adopting low-carbon procurement practices, such as requiring Environmental Product Declarations (EPDs) for public construction projects, setting performance-based GWP limits for high-impact materials, and participating in state or national “Buy Clean” initiatives. These approaches encourage suppliers to disclose material impacts and support market demand for low-carbon products. Expanding the use of recycled-content materials, low-carbon concrete mixes, and cleaner steel production pathways would further reduce lifecycle emissions from local infrastructure and building projects.

Data sources include:

- [U.S. DOE \(2024\). Embodied Carbon Reduction in New Construction](#)
- [U.S. EPA \(2024\). Low Embodied Carbon Materials](#)
- [NRDC \(2022\). A Design to State and Local Low-Carbon Concrete Procurement](#)

Cost Approach

Costs were not quantified for this measure.

I2: Support emissions reductions from Industrial Processes.

GHG Methodology

Process emissions result from the chemical and physical transformations inherent to industrial production, such as fermentation, calcination, chemical pulping, or glass melting, that release CO₂ independent of fuel combustion. In this analysis, total process emissions were reduced by 30% by 2050 to represent the cumulative impact of feasible technology and material interventions across key industrial subsectors. These reductions reflect improvements in production efficiency, material substitution, and emissions capture rather than structural shifts in output or activity.

Key assumptions include:

- A uniform 30% reduction in process emissions was applied across all modeled industries to represent a conservative estimate of achievable reductions by midcentury.
- Modeled reductions reflect the cumulative impact of practical interventions that can scale within existing industrial systems, such as increased recycling, process optimization, and feedstock substitution that lowers inherent CO₂ generation.
- For the minerals sector (e.g., glass), reductions were attributed to increased cullet use in glass manufacturing and efficiency improvements from advanced furnace technologies like oxyfuel systems.
- For the pulp and paper sector, reductions stemmed from enhanced chemical recovery, greater fiber recycling, and operational improvements that reduce chemical demand and waste generation.
- Process emissions in light industry and food and beverage are relatively small; modest reductions were applied to capture improved process controls and the phaseout of high-global-warming-potential refrigerants.
- Production volumes were held constant across sectors, and reductions result solely from technological and material improvements rather than changes in industrial output.

Limitations include:

- The use of a single reduction factor does not capture variability in process design, technology readiness, or site-level abatement potential.
- Process-level data are limited across many subsectors, and some reduction pathways remain at early commercial or pilot stages.
- Reductions were modeled as linear through 2050 and do not reflect timing or sequencing of technology adoption.

- Non-CO₂ process gases (e.g., CH₄, N₂O) were excluded from process-specific modeling.

Data sources include:

- U.S. DOE. Industrial Decarbonization Roadmap. Office of Energy Efficiency and Renewable Energy, 2022.
- U.S. DOE. Pathways to Commercial Liftoff: Industrial Decarbonization. Loan Programs Office, 2024.
- U.S. EPA. GHGRP, 2023 Data Summary.

Cost Approach

Lifecycle abatement costs for the industrial sector were calculated using outputs from the energy modeling and marginal abatement cost data from DOE's Pathways to Commercial Liftoff: Industrial Decarbonization report. For each industry type represented within the MSA, applicable abatement levers such as electrification of thermal systems, energy efficiency improvements, process emission reductions, and low-carbon fuel switching were assigned representative costs per metric ton of CO₂e reduced. These values were weighted based on each subsector's emissions profile and the relative contribution of each intervention to total modeled abatement potential, resulting in a weighted average lifecycle cost of abatement (\$/MTCO₂e) for each industrial subsector.

Examples of capital costs include the incremental expense of replacing fossil fuel systems such as boilers, furnaces, and direct-fired process heaters with electric technologies like heat pumps, resistance, or induction systems, as well as upgrades to motors, compressors, controls, and HVAC equipment. Operational cost impacts reflect modeled energy savings and the transition from fossil fuels to electricity or other low-carbon fuels.

Total lifecycle abatement costs were estimated by multiplying the weighted cost per MTCO₂e by the emissions reductions modeled under the mitigation scenario. The resulting values represent the combined cost of implementing a diverse set of industrial decarbonization strategies, inclusive of electrification, efficiency, process improvements, and fuel switching.

The costs for process emission reductions are bundled with Measure B4.

Cost data sources include:

- [DOE Industrial Decarbonization Liftoff Report \(2023\)](#)
- [DOE Industrial Decarbonization Roadmap \(2022\)](#)
- [EIA Annual Energy Outlook 2025 report](#)
- [NREL Annual Technology Baseline 2024](#)
- [EPA GHGRP \(2022\) facility-level emissions](#)
- [BLS County Employment Data \(2024\)](#)

Natural & Working Lands

This sector evaluated opportunities to reduce emissions and enhance carbon sequestration through sustainable agricultural practices, soil carbon management, and restoration and protection of natural and working lands. Measures in this sector addressed both direct emission sources (such as fertilizer use and livestock methane) and carbon sinks (such as forest and wetland restoration). The first set of measures increase carbon sequestration through nature-based solutions, including preserving existing natural and working lands, managing land use changes proactively, and expanding equitable tree canopy coverage and

access to public green spaces. Additional measures reduce emissions from agricultural sources by promoting shared land use between renewable energy and farming activities, expanding urban agriculture and regional food systems, increasing adoption of soil conservation and nutrient management practices, and increasing adoption of feed additives. Table B14 shows the cumulative emission reductions modeled for each measure. Together, these measures are projected to decrease emissions by 22.02 MMTCO₂e from 2025 through 2050.

Table B14: Summary of Natural & Working Lands Sector Measure GHG Reductions MMTCO₂e

Measure	Cumulative 2025-2030 GHG reductions	Cumulative 2025-2050 GHG reductions
Remove carbon through nature-based solutions, including preserving existing natural working lands and proactively managing land use changes.	-	17.16
Support or incentivize shared land use with renewable energy and agricultural activities.	0.01	0.41
Expand urban agriculture and develop region-wide and inter-regional food system distribution.	NE	NE
Increase equitable tree canopy coverage and access to public green spaces.	0.07	3.29
Increase soil conservation and nutrient management practices in agriculture	0.04	0.78
Support livestock management strategies that reduce emissions	0.00	0.39

NWL1: Remove carbon through nature-based solutions, including preserving existing natural working lands and proactively managing land use changes.

GHG Methodology

Baseline ecosystem carbon stocks were estimated across key land cover types found across the Richmond MSA, including deciduous, mixed, and evergreen forests, and wetlands. Baseline above-ground biomass, below-ground biomass, and soil organic carbon stocks were calculated for each land cover type from 1990 to 2022 consistent with IPCC methodology and using the most recent available data. Above-ground biomass values were converted to carbon using literature-based biomass-to-carbon ratios, and below-ground biomass was estimated using root-to-shoot ratios from the literature and converted to carbon using the same approach.

After establishing baseline carbon stocks, increases in sequestration from improved land management practices were modeled. The analysis assumed that 25% of each land cover type would transition to improved management, increasing linearly from 2030 to 2050. A 1.3 improvement factor, based on IPCC (2006) guidance for grasslands, was applied to estimate enhanced carbon storage under improved management. The resulting 2050 carbon stock serves as the new baseline sequestration level for the MSA. Increased

sequestration was calculated as the difference between the baseline and improved-management carbon stock values.

Key assumptions include:

- Biomass to carbon ratio of 0.47 was applied to grasslands from IPCC (2006), and 0.50 was applied to forests and wetlands (United States Forest Service (USFS) and USDA).
- Above to below-ground biomass ratios (root to shoot ratios) were taken from the IPCC guidance for all land cover types. The mixed forest land cover type was assumed to be the average ratio of deciduous and evergreen.
- 25% of each land cover type transitions to improved management from 2030–2050 in a linear trajectory.

Limitations include:

- Forest and wetland areas are assumed to remain constant due to high conservation effectiveness, with no land conversion.
- All modeled land areas are assumed to be available for improved management practices.
- The 1.3 improvement factor is a generalized estimate and does not differentiate by land-management practice or land-cover type.
- Land-cover change (conversion to/from modeled types) would alter results.

Data sources include:

- [National Land Cover Dataset \(NLCD\)](#) to estimate land cover data
- USDA [Forest Biomass across the Lower 48 states and Alaska](#) to approximate forest biomass
- [Gridded Soil Survey Geographic \(gSSURGO\) Database](#) to evaluate soil carbon stock

Cost Approach

Costs were estimated using the CAST’s cost profiles dataset for Virginia. The dataset provides default unit cost estimates for each state within the Chesapeake Bay Watershed and reflects expenses incurred across both public and private entities. The dataset does not include the cost of technical assistance. The land management category was divided into two cost estimates: forest management and wetlands management. For forests, the costs calculated include forest harvesting practices and agriculture and developed forest buffers. For wetlands, costs include both wetland preservation and enhancement.

Table B15: Measure NWL1 Annual and Cumulative Cost of Implementation (2025\$ Million)

	2025	2030	2035	2040	2045	2050	2025-2050
Capital Costs	-	-	1.69	1.50	1.32	1.17	29.86
Operational Costs	-	-	0.22	0.20	0.17	0.15	3.94
Total Costs	-	-	1.92	1.69	1.50	1.32	33.80

Cumulative Cost of Implementation from 2025-2050 (Million 2025 USD): \$33.80

Cost Data Sources:

- [CAST - Cost Profiles](#)

NWL2: Support and incentivize shared land use with renewable energy and agricultural activities.

GHG Methodology

A spatial analysis was conducted using land-use and agricultural datasets to identify areas within the Richmond MSA suitable for agrivoltaics deployment. Grazing lands were determined based on livestock density data, and croplands were screened for suitability based on compatibility with agrivoltaic systems (e.g., shade-tolerant crops). Suitable acreage was multiplied by assumed solar capacity per acre to estimate potential energy generation. By 2050, nearly 200 MW of agrivoltaic installations were estimated to be deployed across the MSA.

Key assumptions include:

- Only shade-tolerant crops and pastureland for grazing livestock are considered suitable for agrivoltaics.
- Average solar capacity assumptions (MW/acre):
 - 0.19 - Sheep
 - 0.19 - Honey
 - 0.16 - Berries
 - 0.15 – Grapes
- Adoption rates by 2050:
 - Berries, Honey, & Grapes – 10%
 - Sheep – 50%

Limitations include:

- Average MW/Acre assumptions were taken from real agrivoltaics systems; however, these were averaged from all over the country, not specific to the Mid-Atlantic region. The modeling did not differentiate by utility versus smaller scale operations but assumed the same MW/acre output and therefore the same agrivoltaics set-up for each operation.
- Some state-level crops/livestock data from U.S. Department of Agriculture (USDA) QuickStats were unavailable and needed to be estimated by using averages.

Data sources include:

- USDA Quick Stats
- National Land Cover Database (NLCD)
- ArcGIS Pro and Excel
- AgriSolar Atlas for MW/Acre average solar capacity
- VA Apiary Stocking Rate
- VA Sheep Stocking Rate

Cost Approach

To estimate the cost of deploying agrivoltaics systems, NREL’s 2024 Annual Technology Baseline was used to forecast capital and operating costs for commercial distributed solar systems, which were assumed to be representative of ground-mounted systems integrated with agricultural operations. These costs were applied to the incremental new agrivoltaics capacity added in each year of the forecast. In addition, potential bill savings were estimated based on statewide electricity retail rates from EIA-861, which were projected through 2050 based on trends from EIA’s Annual Energy Outlook. The integration of solar generation with agricultural production can reduce operating costs by offsetting electricity consumption for farm equipment, irrigation, and other end uses, making bill savings a key driver of the economic viability of agrivoltaics systems.

Table BI6: Measure NWL2 Annual and Cumulative Cost of Implementation (2025\$ Million)

	2025	2030	2035	2040	2045	2050	2025-2050
Capital Costs	-	10.88	10.80	11.20	12.62	14.38	258.72
Operational Costs	-	0.22	0.74	1.24	1.82	2.47	27.16
Bill Impacts (Avoided Costs)	-	(1.70)	(6.96)	(12.76)	(21.37)	(31.35)	(303.28)
Total Costs	-	9.40	4.58	(0.32)	(6.92)	(14.50)	(17.40)

Cumulative Cost of Implementation from 2025-2050 (Million 2025 USD): \$(17.40)

Cost data sources include:

- [2024 NREL Annual Technology Baseline](#) for moderate scenario CAPEX and fixed O&M costs for commercial distributed solar resources
- [EIA-861](#) for average 2024 commercial retail electricity rates in VA
- [EIA AEO 2025 Table 3.5](#) for projected growth rates of electricity prices in the South Atlantic region

NWL3: Expand urban agriculture and develop region-wide and inter-regional food system distribution.

GHG Approach

Emission reductions from this measure were not quantified due to lack of existing data on local food production and consumption in the MSA. However, qualitative evidence suggests several meaningful pathways through which this measure can reduce emissions:

- Local food production and farm-to-school initiatives can reduce GHG emissions primarily by shortening food supply chains, lowering the distance food travels from farm to plate (“food miles”), and reducing reliance on energy-intensive transportation, refrigeration, and packaging associated with conventional, long-distance food systems. Sourcing produce locally and seasonally typically decreases fuel and energy use per unit of food delivered.
- Urban agriculture further contributes to emissions reduction through reuse of organic waste and composting, which lowers methane emissions from landfills, and by reducing fertilizer and irrigation

inputs when regenerative or closed loop growing systems are used. In addition, urban green spaces created by gardens and farms enhance local vegetation cover, providing modest carbon sequestration and reducing urban heat island effects.

- Farm-to-school programs can also indirectly reduce emissions by cutting food waste in cafeterias through increased student engagement with fresh, local foods and composting initiatives. Reducing food waste prevents methane formation from organic decomposition and decreases the need for upstream agricultural production.

Data sources include:

- [USDA Climate Hubs](#)
- [Elahi Mirza, et al, 2025. "Urban agriculture and sustainability: A systematic review and thematic trends"](#)

Cost Approach

Costs from this measure were not quantified.

NWL4: Increase equitable tree canopy coverage and access to public green spaces.

GHG Methodology

Given the region's existing urban development and tree cover, there is significant potential to enhance carbon sequestration by increasing tree canopy coverage within urban areas. The measure was estimated by comparing the baseline tree canopy area with a scenario that achieves locality-specific or regional canopy goals by 2050.

Baseline tree canopy area was calculated using the Chesapeake Bay Program's 1-meter resolution land cover dataset. Tree cover pixels were identified within 2020 Census-defined urban areas for each county in the MSA using ArcGIS. The baseline represents the current extent of urban tree canopy.

For the measure scenario, a 2050 tree canopy goal of 50% was assumed for the region. The target canopy area was calculated based on these goals. The increase in canopy area was then used to estimate additional carbon sequestration.

Key assumptions include:

- By 2050, regional tree canopy expands to 50%.

Limitations include:

- Assumes all urban areas can support increased canopy, which may not reflect on-the-ground constraints (e.g., impervious surfaces, land use conflicts).
- Sequestration rates are generalized and may not reflect species-specific or site-specific variability.
- Does not account for potential canopy loss due to development, pests, or climate impacts.
- Assumes linear growth in canopy area, which may not reflect actual implementation timelines.

Data sources include:

- U.S. Census Bureau [Urban and Rural Areas Census data for 2010 and 2020](#). Urban area boundary polygons were used to calculate the extent of tree cover located within urban areas.
- [Chesapeake Bay Program 1m Land Cover Dataset](#) was used to calculate baseline tree canopy area across the MSA, identifying tree canopy pixels within 2020 Census-defined urban areas.
- Carbon sequestration potential rates of settlement trees in Virginia are determined using the [2023 US GHG Inventory Report](#) table 6-125 “*Estimated Annual Carbon Sequestration, Tree Cover, and Annual Carbon Sequestration per Area of Tree Cover for settlement areas in the United States by State and the District of Columbia*”.

Cost Approach

Costs were estimated by using the CAST cost profiles dataset for Virginia. The dataset provides default unit cost estimates for each state within the Chesapeake Bay Watershed. All costs are expressed in 2025 dollars and reflect expenses incurred across both public and private entities. The dataset does not include the cost of technical assistance. The urban tree expansion measure costs include tree planting on developed lands.

Table B17: Measure NWL4 Annual and Cumulative Cost of Implementation, in Millions of Real 2025 USD

	2025	2030	2035	2040	2045	2050	2025-2050
Total Costs	-	1.39	1.23	1.08	0.96	0.85	25.92

Cumulative Cost of Implementation from 2025-2050 (Million 2025 USD): \$25.92

Cost data sources include:

- [CAST - Cost Profiles](#)

NWL5: Increase soil conservation and nutrient management practices in agriculture.

GHG Methodology

This measure quantifies emission reductions from increasing the adoption of both nitrogen inhibitors and cover crops. Modeling approaches for each category are discussed below.

Nitrification Inhibitor Adoption

Nitrification Inhibitors (NI) are chemical compounds that inhibit the nitrification process, which can prolong the retention time of nitrogen (N) in the soil. This mechanism increases nitrogen use efficiency (NUE), reducing N losses and GHG emissions. This category supports agricultural GHG emissions reduction by enhancing NUE, reducing nitrogen fertilizer inputs, and subsequent N₂O emissions, which informs broader agricultural emissions reduction efforts.

Annual GHG emissions reduction impacts from increased nitrification inhibitor adoption were estimated by comparing BAU emissions with the mitigation scenario assuming a 6% increase in adoption area annually

until a maximum adoption rate of 80% is reached. The measure was applied to soybeans, corn, cotton, and wheat crops and used national crop specific adoption rates based on USDA data were assumed for 2025.

For direct and indirect emissions, the mitigation scenario projecting annual metric tons (MT) nitrogen from synthetic fertilizer applied was multiplied by the increasing annual proportion of fertilizer applied with NI and a NI reduction factor. This proportion of total emissions was reduced by 10% to accommodate an assumed 10% increase in NUE. This was added to the remaining proportion of N₂O emissions from N fertilizer that is applied without NIs. This was then compared to the BAU scenario (no increasing adoption) estimate and the difference between the BAU scenario and the mitigation scenario (emissions avoided that would otherwise occur) was applied to the agricultural soils category of the BAU.

Crop planted areas for corn, soybeans, and wheat were projected using historical production data from USDA NASS. Average annual rates of change in production were derived from USDA Baseline Projections which account for market trends, trade and other demand shifts, and production trends. National averages for the percentage of acres receiving N fertilizer were used to isolate applicable acres. Current adoption rates of NIs were established using data from the USDA Agricultural Resource Management Survey (ARMS).

Key assumptions include:

- National average crop-specific fertilizer application (lbs/acre) rate utilized in place of state specific values as state level rates were not available.
- Assumed percent reduction in N₂O from NI application for each applicable crop based on USDA Marginal Abatement Cost Curve (MACC) Report.
- Reduction in total N inputs of 10% due to enhanced NUE based on USDA MACC Report.
- Current adoption of NI estimated based on USDA Economic Research Service (ERS) report: Cover Crop Trends, Programs, and Practices in the United States (2021).
- Increased adoption of NI over time: Maximum adoption reaches 80% for corn in 2042, cotton in 2044, and for wheat and soybeans in 2045.

Limitations include:

- NI adoption rates: Current NI adoption rates were estimated USDA National data, which may not fully capture all NI applications in Richmond. Crop planted acreage projections assume a gradual decline over time, reflecting urbanization trends but not accounting for potential shifts in agricultural practices.

Data sources include:

- [USDA National Agricultural Statistics Service \(NASS\)](#)
- [USDA National Agricultural Statistics Service ARMS](#)

Cover Crop Adoption

Cover crops are plants grown primarily to enhance soil health, reduce erosion, lower GHG emissions, and increase carbon sequestration. They also affect soil nitrous oxide (N₂O) emissions by enabling more plant uptake of nitrogen in the soil, reducing soil nitrogen available for nitrification and denitrification processes that result in nitrous oxide. As a key sustainable agriculture practice, they improve soil fertility and structure, contributing to better crop yields and reduced environmental impact. By incorporating the GHG emissions impacts of projected cover crop adoption, this measure provides a scalable and viable agricultural strategy for reducing emissions. The Mid-Atlantic region's long-standing engagement in cover cropping, particularly in

Maryland, demonstrates its feasibility, offering an effective pathway to lower agricultural-sector emissions through carbon sequestration and reduced N₂O emissions.

Annual GHG emissions reduction impacts from increased cover crop adoption were estimated by comparing BAU emissions with the mitigation scenario assuming a 4% increase in adoption area annually, ramping up from 16% to a maximum of 100%.

Current cover cropping applicable acres were estimated based on the annual harvested area (acres) of field crops and vegetables in 2022 based on USDA NASS datasets. Future harvested areas were projected using observed rates of change. The BAU scenario assumes cover crop adoption remains constant at the 2017 level of 16%, meaning 16% of eligible acres continue using cover crops, sourced from 2021 USDA ERS data⁵ for Virginia's percent of harvested cropland.

Emissions calculations incorporate soil carbon sequestration (MTCO₂e) and reductions in N₂O emissions from decreased nitrogen fertilizer application. Fossil fuel emissions from agricultural equipment used for planting and maintaining cover crops were also factored into the analysis. The total emissions impact was determined by comparing GHG levels in each modeled year under the BAU scenario (no change in cover crop adoption) and the mitigation scenario through 2050.

Key assumptions include:

- Current adoption of cover crops on 16% of applicable crop acres in region based on USDA ERS Cover Crops Report data for Virginia.
- Applicable crop acres assumed to exclude pasture as they are not generally planted annually.
- Maximum adoption is assumed to be reached in 2046.
- Utilize Soil Carbon Sequestration and N₂O Reduction Factor (MTCO₂e) from USDA MACC Report.
- Additional fuel use is 0.92 gallons per acre for planting and cultivating activities, which results in 9.7 kgs CO₂e per cover crop acre emitted from fuel use based on EPA GHG Emission Factor Hub emission data. A scheduled phase-in of 100% renewable diesel (RD) by 2050 was assumed, which partially offset fuel use emissions.

Limitations include:

- Assumptions and Simplifications – Cover Crop Details: Soil carbon sequestration and N₂O reduction emission factors for the Mid-Atlantic region were derived from published USDA reports on cover cropping systems and feasibility. The modeling assumes that 75% of cover crops are nonlegume species, while 25% are legumes—an oversimplification of the MSA's cover cropping landscape, yet broadly representative of U.S. and regional adoption practices. Sequestration depends on the rate of adoption and assumes all acres planted that are not pastureland are available for cover cropping in any given year.
- Sensitivity to External Factors – Cover Crop Adoption: Future cover crop adoption rates may fluctuate based on policy incentives and agricultural market dynamics. The ten-year harvested acreage rate of change from USDA NASS was chosen as the most representative of future trends, reflecting expected declines due to increasing urbanization. These projections align with USDA Baseline Projections estimates for national crop area changes.

⁵ https://ers.usda.gov/sites/default/files/_laserfiche/publications/100551/EIB-222.pdf?v=84007

- Weather Dependence – cover crop sequestration depends on weather in any given year – if there is limited precipitation due to drought, crops will not grow, and soil organic carbon will not be sequestered. There may be increasing droughts and other relevant weather events due to climate change in the future. Heavy precipitation events will spike N₂O emissions which would negate some of the net sequestration.

Data sources include:

- USDA NASS Quick Stats
- Fertilizer Use and Price Economic Research Service
- USDA National Baseline Projections, 2024-2034
- ARMS Farm Financial and Crop Production Practices - Tailored Reports: Crop Production Practices
- USDA Marginal Abatement Cost Curve Estimate Methodology Report
- IPCC 2019 Refinement, Chapter 11: N₂O Emissions from Managed Soils, and CO₂ Emissions from Lime and Urea Application
- Cover Crop Trends, Programs, and Practices in the United States, USDA ERS
- EPA Emission Factors for Greenhouse Gas Inventories
- DOE Alternative Fuels Data Center: Renewable Diesel

Cost Approach

Nitrification Inhibitors

For NI, capital costs included any per-acre costs associated with incorporating nitrification inhibitor products into fertilizer applications. These were treated as annualized costs rather than upfront capital investments. Consistent with the USDA MACC Report (2023), no additional capital costs are associated with NI adoption. O&M costs were minimal as NIs are integrated into existing fertilizer application practices. Any additional labor or equipment calibration costs were included in the per-acre cost estimates. Labor costs were based on the USDA MACC Report (Table 4, Appalachia region). Virginia Environmental Quality Incentives Program (EQIP) payments for “nutrient Management” practice (590A-EQIP) were assumed to serve as a proxy for 75% of the total cost to farmers for adopting NIs. A 10% reduction in fertilizer application results in a proportional 10% reduction in fertilizer costs were assumed, consistent with the USDA MACC Report.

Cost distribution was modeled as recurring annual per-acre costs, increasing over time in line with adoption rates. Costs were scaled by crop-specific adoption trajectories and fertilized acreage.

Cover Crops

Consistent with the USDA MACC Report (2023), no capital costs for cover crop adoption were assumed for the state of Virginia. O&M costs include seed costs (species-dependent), labor and fuel for management, planting and termination. These were modeled as annual per-acre costs and scaled with adoption rates. 2025 Virginia EQIP payments for “Cover Crop – Basic” practice (34-EQIP) were assumed to serve as a proxy for 75% of the total costs to farmers for adopting cover crops and scaled this value to 100% of costs in estimates.

Uniform adoption costs across crop types (i.e., no cost differentiation between field crops and vegetables) were assumed. It is important to note that EQIP payment rates do not account for co-benefits from cover crop adoption that may result in cost savings. To incorporate these benefits, the average inflation-adjusted values from the first year of cover cropping, as reported in Table 10 of the USDA MACC Report (2023), were subtracted from EQIP payments.

Cost distribution was modeled as recurring annual per-acre costs, increasing over time in line with adoption rates. Costs were scaled by projected eligible cropland acreage (i.e., the sum of field crops and vegetables).

Table B18: Measure NWL5 Annual and Cumulative Cost of Implementation (2025\$ Million)

	2025	2030	2035	2040	2045	2050	2025-2050
Cover Crop Adoption	-	0.58	1.19	1.82	2.26	2.29	36.34
NI	-	0.24	0.44	0.64	0.85	0.88	13.78
Total Costs	-	0.82	1.64	2.47	3.11	3.17	50.12

Cumulative Cost of Implementation from 2025-2050 (Million 2025 USD): \$50.12

Cost data sources include:

- [USDA Marginal Abatement Cost Curve Estimate Methodology Report](#)
- [Virginia Environmental Quality Incentives Program](#)

NWL6: Support livestock management strategies that reduce emissions.

GHG Methodology

This category involves the use of feed additives to reduce enteric methane emissions from beef and dairy cattle. These additives inhibit microbial processes in the rumen that produce methane, thereby lowering GHG emissions from livestock. The inclusion of this category targets enteric fermentation, a significant source of agricultural GHG emissions, by leveraging scientifically supported, feed-based emissions reduction strategies. This quantification provides a data-driven projection of emissions reductions achievable through phased adoption of Monensin (2026-2035) and 3-Nitrooxypropanol (3-NOP) (2036-2050), based on livestock population trends and additive efficacy.

To estimate the GHG emissions reduction potential of feed additives in livestock production, baseline population data for beef forage cattle, beef feedlot cattle, and dairy cows were pulled from the CAST. Data were pulled for the relevant counties from the “Base Conditions Report” report type and “2023 Progress” scenario. The per head emission factor is an important driver for emissions reductions estimates and so beef cattle population data was further disaggregated for mitigation modeling into the feedlot and foraging proportion of cattle (both groups excluding calves). The feedlot beef cattle population was calculated by multiplying the population of beef cattle in the MSA by the national proportion of feedlot cattle to the total beef cattle population. The foraging beef cattle population was calculated by multiplying the population of beef cattle in the Richmond MSA by national proportion of bulls to the total beef cattle population. Future livestock population estimates were projected using national average annual growth rates from the USDA Baseline Projections, which account for market trends, trade and other demand shifts, and production trends.

To calculate enteric fermentation emissions, the applicable population was multiplied by the proportion receiving either Monensin or 3-NOP depending on the ear, and the respective feed additive emission reduction factor. This was added to the remaining proportion of the applicable population that did not receive any mitigation feed additive, which was multiplied by the standard per head emission factor. Phased

adoption of Monensin was assumed from 2026-2035, ramping up from 3% to 30%. Due to current cost and consumer perception barriers, the adoption of 3-NOP was not assumed to start until 2035, ramping up from 5% to 100%. Adoption of the two strategies is phasic as there is insufficient scientific evidence to suggest that impacts on enteric fermentation emissions would be additive if implemented at the same time (despite that science may later show they are additive). Emissions reductions per head were applied based on literature values of 3.0% to 8.0% for Monensin, with the conservative value of 3.0% being used, and 38.5% for 3-NOP. The total emissions reductions were calculated as the difference in enteric methane emissions between the BAU and the mitigation scenario, expressed in MTCO₂e.

Key assumptions include:

- Assumed adoption rates would be applicable to 100% of dairy, feedlot and beef cattle, excluding calves. This broad applicability reflects the potential for sector-wide implementation once adoption barriers are addressed.
- Assume that effects of Monensin and 3-NOP are not additive due to lack of consensus of research on combined feed additives and associated effects, therefore when 3-NOP adoption ramps up, assume zero effect from Monensin.
- Monensin is assumed to be market-ready with low implementation costs. Adoption ramps from 3% in 2026 to 30% by 2035.
- 3-NOP is FDA-approved but faces consumer and cost-related barriers. Adoption begins in 2036, increasing from 5% to 100% by 2050.
- These adoption curves reflect realistic market penetration based on regulatory status, economic feasibility, and producer behavior.

Limitations include:

- The analysis assumes that 100% of beef forage cattle, beef feedlot cattle (excluding calves), and dairy cattle are eligible for feed additive treatment. In practice, variability in farm management practices, regional feed availability, and animal health considerations may limit full adoption. This simplification was used to estimate the maximum technical potential of the measure and can be refined with more granular, region-specific adoption data.
- The analysis assumes that Monensin and 3-NOP effects on enteric fermentation emissions are not additive. The model conservatively assumes that the methane-reducing effects of Monensin and 3-NOP are not additive, despite emerging evidence suggesting potential synergy. This simplification avoids overestimating emissions reduction potential in the absence of definitive scientific consensus.
- Monensin is market ready and there is a low cost to implementation; methods assume adoption from 2026-2035. 3-NOP is FDA approved however consumer hesitation and cost barriers remain which deter producers from implementation; methods assume adoption from 2036-2050. Adoption of Monensin (2026–2035) and 3-NOP (2036–2050) is modeled using linear ramp-up scenarios of 3-30% and 5-100%, respectively. These projections do not account for potential disruptions such as supply chain issues, regulatory changes, or shifts in consumer demand. While these assumptions provide a structured framework for long-term planning, future iterations could incorporate dynamic adoption models based on economic or behavioral drivers. Assumed impact on GHG emissions is based on literature (% reduction per animal head with feed additive). GHG reduction percentages per animal are based on literature averages, which may not reflect performance under diverse real-world conditions (e.g., diet composition, animal

genetics, climate). These values were selected to align with established methodologies (e.g., USDA MACC) and provide a consistent basis for comparison across emissions reduction strategies.

Data sources:

- [USDA NASS Quick Stats](#)
- [Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2022 | US EPA, Table A-148](#)
- [EPA SIT Agriculture Module](#)
- [USDA Marginal Abatement Cost Curve Estimate Methodology Report](#)
- [Arndt, et al, 2022. “Full adoption of the most effective strategies to mitigate methane emissions by ruminants can help meet the 1.5 °C target by 2030 but not 2050”](#)
- [Hegarty, et al, 2021. “An evaluation of emerging feed additives to reduce methane emissions from livestock”](#)

Cost Approach

Consistent with the USDA MACC Report (2023), no capital costs are associated with feed additive adoption, as feed additives are incorporated into existing feeding systems. O&M costs may include additive costs per head per year (varying by product and dosage), as well as labor and management for additive integration. These were modeled as annual per-head costs, scaled with adoption rates and livestock populations. Cost distribution increased over time in line with the phased adoption of Monensin and 3-NOP. Monensin feed additive costs were based on the USDA MACC Report. “Monensin, Beef” costs were assumed to apply to both beef cattle and dairy cows. 3-NOP feed additive costs were based on Luke and Tonsor (2024) and similarly assumed to apply to beef cattle and dairy cows. A 6.4% increase in feed efficiency from Monensin and 3-NOP use, respectively, was assumed to result in a corresponding decrease in fertilizer costs.

Cost distribution was modeled as recurring annual costs per animal, increasing over time in line with adoption rates. These costs were scaled by livestock population trajectories.

Table B19: Measure NWL6 Annual and Cumulative Cost of Implementation (2025\$ Million)

	2025	2030	2035	2040	2045	2050	2025-2050
Total Costs	-	0.07	0.15	1.40	3.00	3.22	32.41

Cumulative Cost of Implementation from 2025-2050 (Million 2025 USD): \$32.41

Cost data sources include:

- [USDA Marginal Abatement Cost Curve Estimate Methodology Report](#)
- [Luke, J. R., & Tonsor, G. T. \(2024\). “The enteric methane emission conundrum: U.S. beef cattle producer adoption of climate-focused technology”. *Sustainable Production and Consumption*, 364-375.](#)
- [Federal Reserve Bank of St. Louis Table Data – Gross Domestic Product: Implicit Price Deflator.](#)

Transportation

For the transportation sector measures, GHG reductions were quantified for both on-road and off-road sources. Modeled activities include increasing the adoption of ZEVs, decarbonizing ports, reducing VMT, replacing conventional diesel fuel from on-road and off-road vehicles with RD, and transitioning to sustainable aviation fuel (SAF). SAF was incorporated as an additional modeling component to support progress toward the MSA’s net zero emissions targets. Table B20 shows the cumulative emission reductions modeled from each measure. Collectively, these measures are projected to decrease emissions by 40.91 MMTCO₂e from 2025 through 2050.

Table B20: Summary of Transportation Sector Measure GHG Reductions MMTCO₂e

Measure	Cumulative 2025-2030 GHG reductions	Cumulative 2025-2050 GHG reductions
Reduce emissions from port operations through the adoption of low-carbon fuels, electric equipment, and operational changes.	0.07	1.13
Support, incentivize, and provide assistance for the rapid adoption, equitable installation, and use of ZEV.	1.09	25.34
¹ Expand equitable transit access.		
¹ Provide and promote new and expanded opportunities to reduce VMT through micromobility options and micro modal infrastructure (e.g., electric bikes and scooters.).	0.24	2.34
² Renewable diesel	-	10.26
² Sustainable aviation fuel	-	1.84

¹ Quantification was bundled for measures T3 and T4
² RD and SAF were incorporated as additional modeling components to reach net zero targets

T1: Reduce emissions from port operations through the adoption of low-carbon fuels, electric equipment, and operational changes.

GHG Methodology

The Port of Virginia has committed to achieving net-zero carbon emissions by 2040, driven by two primary strategies: (1) replacing diesel-powered cargo-handling equipment with zero-emission electric and hybrid-electric alternatives (reducing Scope 1 emissions) and (2) sourcing 100% clean electricity for port operations (reducing Scope 2 emissions). The Port’s 2024 Sustainability Report outlines detailed actions and assumptions to achieve these targets.

For the Richmond MSA, GHG reductions were modeled based on electrification of port equipment and deployment of battery-storage systems at port facilities. Modeling inputs reflect fleet data and project lists provided by the Virginia Port Authority (VPA), and assume diesel equipment is replaced with zero-emission electric units. All equipment is assumed to be tailpipe-emission-free by 2040 in alignment with VPA commitments. Because the Port achieved 100% clean electricity in 2024 through a long-term power purchase

agreement, no additional Scope 2 emission reductions from clean electricity procurement were modeled for this measure.

Emissions reductions from equipment electrification were estimated using the EPA Diesel Emissions Quantifier (DEQ) tool and EPA GHG equivalency methods. Fleet-specific fuel-consumption data from the Port of Richmond were used in place of national averages to calculate avoided CO₂e from displacing gasoline and diesel use. Battery-storage benefits were quantified by estimating avoided grid electricity consumption and applying projected grid-emission factors.

Key assumptions include:

- All modeled equipment transitions to zero-emission electric alternatives by 2040.
- Annual emissions reductions are based on internal fleet fuel consumption averages.
- Battery storage systems displace grid electricity based on projected utilization factors.

Limitations include:

- Limited publicly available operational data required a high-level assessment of emission reductions and costs.
- The DEQ tool uses generalized emission factors that may not fully reflect Richmond-specific operational profiles.

Data sources include:

- [Port of Virginia 2024 Sustainability Report](#)
- [U.S. Army Corps of Engineers Entrances and Clearances Data](#)
- [U.S. Army Corps of Engineers Waterborne Cargo and Trips Data Files](#)
- [Port of Los Angeles Inventory of Air Emissions \(2021\)](#)
- [EPA Diesel Emissions Quantifier \(DEQ\)](#)

Cost Approach

Costs were evaluated using findings from the Port of Virginia's Decarbonization Strategy and Implementation Report, which developed a high-level cost model for assessing decarbonization initiatives across the state's port facilities. The analysis incorporated asset procurement costs (e.g., vehicle and equipment purchases), operations and maintenance costs associated with fleet operations, energy costs for fuel and electricity use, and infrastructure costs such as charging equipment upgrades.

In 2025 dollars, reported costs were equivalent to \$272 in capital costs per MTCO₂e avoided and \$394 in operational costs per MTCO₂e avoided. These unit cost assumptions were applied to the modeled emission reductions to estimate total implementation costs for decarbonizing ports within the MSA. Table B21 summarizes the annual and cumulative implementation costs for this measure.

Table B21: Measure T1 Annual and Cumulative Cost of Implementation (2025\$ Million)

	2025	2030	2035	2040	2045	2050	2025-2050
Capital Costs	0.89	5.45	9.02	14.88	18.46	22.91	306.48
Operational Costs	1.29	7.91	13.10	21.60	26.80	33.26	444.87
Total Costs	2.18	13.35	22.12	36.48	45.27	56.17	751.35

Cumulative Cost of Implementation from 2025-2050 (Million 2025 USD): \$751.35

Cost data sources include:

- Port of Virginia Decarbonization Strategy and Implementation Report (2021)

T2: Support, incentivize, and provide assistance for the rapid adoption, equitable installation, and use of ZEV.

GHG Methodology

The modeling estimated potential GHG emission reductions from increasing the use of ZEVs, such as battery electric vehicles (BEVs).

Key assumptions include:

- ZEVs exist in the vehicle fleet for the same length of time as internal combustion engine vehicles (ICEVs).
- ZEV activity/use is identical to an ICEV.
- The annual ZEV sales fraction applies to every fuel type.
- ZEV adoption is modeled to occur at the following rates, with a linear ramp-up period:
- 100% of new light duty (LD) vehicle sales are BEV by 2035. This aligns with [California's Advanced Clean Cars II rule](#).
- 100% of new medium and heavy duty (MHD) vehicle sales are BEV by 2050. This aligns with the [Multi-state Medium -and Heavy Duty Zero Emission Vehicle Memorandum of Understanding](#).

Limitations include:

- Successful ZEV adoption requires electric vehicle (EV) charger installation and accessibility. The pace of charging infrastructure deployment, EV model availability at similar costs to ICEVs, and electricity rates will all impact the adoption rate of EVs.

Data sources include:

- EPA Motor Vehicle Emissions Simulator version 5 (MOVES5)

Cost Approach

Costs include both the upfront capital investments required to purchase new vehicles and install new EV supply equipment (EVSE), as well as the recurring fuel and vehicle maintenance costs. Due to the phaseout of

federal tax incentives for EVs, no financial incentives were assumed. Cost estimates represent the net change in total costs between the zero-emission adoption scenario and the BAU scenario.

Vehicle capital costs associated with electrification were estimated by multiplying the projected number of new vehicle purchases in each model year by the average purchase price per vehicle. These costs were differentiated by vehicle class (e.g., passenger car, single-unit short-haul truck, transit bus) and engine type (e.g., internal combustion engine, battery EV). The average cost per vehicle reflects the additional upfront cost of EVs compared to conventional vehicles, accounting for technology improvements and cost declines over time. EVSE capital costs were estimated assuming one level 2 charger per LD EV, one 50 kW fast charger per Class 2b - 6 MHD EV, and one 150 kW fast charger per Class 7 – 8 MHD EV. All capital costs were assumed to occur at the time of vehicle replacement, consistent with adoption curves and equipment lifetime assumptions.

Energy costs and savings associated with electrification and energy efficiency were estimated using projected annual energy use for each fuel type (e.g., gasoline, diesel) by the corresponding projected cost per unit of fuel, derived from EIA’s Annual Energy Outlook 2025. Electricity prices were calculated using electricity prices from residential sector for LD EVs and electricity prices from commercial sector for MHD EVs.

Vehicle maintenance costs were estimated by multiplying the VMT for each vehicle and engine type by an average maintenance cost per mile (\$/mi). These per-mile costs were specific to each powertrain type and reflect differences in maintenance needs between electric and conventional vehicles, such as reduced brake wear and fewer moving parts in electric drivetrains. These per-mile costs were derived from Argonne National Laboratory’s Alternative Fuel Life-Cycle Environmental and Economic Transportation (AFLEET) tool.

Cost data sources include:

- Vehicle capital costs: ICF’s projection of vehicle capital cost by type and fuel using [AFLEET](#)
- Projected fuel and electricity prices: [EIA’s Annual Energy Outlook 2025, Table 3](#)
- Vehicle maintenance cost: [AFLEET](#)

Table B22: Measure T2 Annual and Cumulative Cost of Implementation (2025\$ Million)

	2025	2030	2035	2040	2045	2050	2025-2050
Capital Costs	162.07	809.36	1,370.26	1,576.74	1,739.38	1,879.21	33,647.81
Operational Costs	4.96	(166.36)	(329.13)	(570.87)	(784.21)	(1,061.41)	(12,323.85)
Total Costs	167.03	642.99	1,041.13	1,005.87	955.16	817.80	21,323.96

Cumulative Cost of Implementation from 2025-2050 (Million 2025 USD): \$21,323.96

T3: Promote equitable transit access.

GHG Methodology

Quantification for this measure was bundled with Measure T4.

Cost Approach

Quantification for this measure was bundled with Measure T4.

T4: Provide and promote new and expanded opportunities to reduce VMT through micromobility options and micro modal infrastructure (e.g., electric bikes and scooters.).

GHG Approach

The measures model the resulting GHG emissions reduced if the MSA implements a variety of strategies to reduce VMT, including land use changes, reduction in transit travel times, increased walk and bike access, and uptake of micromobility.

The Trip Reduction Impacts of Mobility Management Strategies (TRIMMS) tool was used to estimate the impact of changes in trip price and length on mode share. Reductions in transit cost, transit and active transportation trip time, and priced workplace parking in urban regions shift transportation mode share away from personal vehicles to public transit and active transportation. TRIMMS outputs are leveraged to estimate VMT percent change. Increasing equitable access was not explicitly modeled.

A VMT reduction schedule was developed that assumes a 9.31% VMT reduction by 2050. Reductions were assumed to begin in 2026 and were linearly interpolated in interim years. VMT, energy consumption, and emissions after ZEV adoption and clean fuels phase in were reduced by the VMT reduction percentage each year for LD vehicles and motorcycles only.

Key assumptions include:

- Free public transportation
- Priced workplace parking in urban areas
- 10% decrease in public transportation trip time
- 30% decrease in pedestrian trip time
- 30% decrease in bike trip time

Limitations include:

- TRIMMS uses regional-average trip characteristics to estimate mode and VMT change and thus does not capture regional variation.
- TRIMMS also relies on the resulting change from policy decisions, rather than the policy itself. For example, TRIMMS leverages changes in trip or access time instead of using miles of expanded transit routes or number of new stops. Therefore, all TRIMMS inputs are assumptions.

Data sources include:

- [2020 Census and 2020 American Community Survey](#) for regional inputs
- [Replica](#) to model both VMT share and current trip costs and time

Cost Approach

A custom cost calculator was developed to estimate the cost per mile of VMT reduced, expressed as \$/mi VMT reduced. This metric was derived from a representative sample of transit and active transportation investment projects implemented across the United States. The calculator aggregates capital and operating

costs associated with these projects and relates them to the amount of VMT reduction achieved, providing a standardized cost-effectiveness measure.

Based on the analysis of representative projects, the estimated capital cost of transit and active transportation investments is \$0.14 per VMT reduced for the project lifetime. This includes infrastructure development such as bike lanes, pedestrian pathways, and e-bike programs.

Operational expenses include the following:

- The operations and maintenance costs of transit investments were estimated at \$1.00 per VMT reduced. This includes ongoing expenses such as transit incentives (free fare), improved transit service operation, and equipment maintenance necessary to sustain the VMT reductions over time.
- Energy savings associated with reduced VMT electrification were estimated using projected annual energy use for each fuel type (e.g., gasoline, diesel) by the corresponding projected cost per unit of fuel, derived from EIA’s Annual Energy Outlook 2025. Electricity prices were calculated using electricity prices from the residential sector for LDV.
- Vehicle maintenance savings were estimated by multiplying the VMT for each vehicle and engine type by an average maintenance cost per mile. These per-mile costs were derived from Argonne National Laboratory’s AFLEET tool and were specific to each vehicle powertrain type.

Cost data sources include:

- [EIA’s Annual Energy Outlook 2025, Table 3](#) to project fuel and electricity costs
- [AFLEET](#) to model vehicle maintenance costs

Table B23: Measures T3 and T4 Annual and Cumulative Cost of Implementation (2025\$ Million)

	2025	2030	2035	2040	2045	2050	2025-2050
Capital Costs	-	37.39	76.76	118.71	164.33	215.65	2,627.20
Operational Costs	-	187.06	402.26	646.44	914.04	1,213.28	14,333.10
Total Costs	-	224.45	479.02	765.15	1,078.38	1,428.93	16,960.30

Cumulative Cost of Implementation from 2025-2050 (Million 2025 USD): \$16,960.30

On-Road Renewable Diesel

GHG Methodology

Even with aggressive electrification, there will still be conventional vehicles on the roads in 2050. Alternative diesel fuels are one option to reduce emissions from remaining ICEVs. Renewable diesel is a “drop-in” fuel, meaning it can be blended with or used in place of conventional diesel without modifications to the vehicle. Because renewable and conventional diesel have similar combustion emissions, a life-cycle emissions factor was used to capture emissions reductions that occur earlier in the production chain.

This modeling assumes that all diesel consumption for on-road transportation will be transitioned to renewable diesel by 2050.

Key assumptions include:

- 100% of the diesel supply is composed of renewable diesel by 2050
- RD adoption begins in 2031 and grows linearly through 2050.
- Assumes that the carbon intensity of RD is 65% lower than conventional diesel, per the Alternative Fuels Data Center assumption for RD.
- There is enough RD available in the region to supply the demand.

Limitations include:

- The assumption of 65% reduction in carbon intensity is based on California's low carbon fuel standard (LCFS) average and studies completed by Argonne National Laboratory. The actual carbon intensity reduction could be different for the MSA depending on the feedstocks used to produce RD.

Data sources include:

- [Alternative Fuels Data Center: Renewable Diesel](#)

Cost Approach

The incremental cost of renewable diesel was evaluated by calculating the difference in unit price between RD and conventional diesel, then multiplying that difference by the projected volume of RD consumed. This approach quantifies the cost premium associated with using RD in place of conventional fuel.

To reflect the higher cost of renewable diesel prior to the implementation of regulatory incentives or market-based programs, a cost of \$4.80 per gallon for RD was assumed. This represents the estimated cost of alternative fuels in the absence of subsidies and credits to capture the full economic burden of alternative fuel adoption in a pre-regulatory context. Costs for RD used in both on-road and off-road vehicles are presented in Table B24.

Table B24: On-Road RD Annual and Cumulative Cost of Implementation (2025\$ Million)

	2025	2030	2035	2040	2045	2050	2025-2050
Total Costs	-	-	77.17	119.07	126.66	106.61	1,976.23

Cumulative Cost of Implementation from 2025-2050 (Million 2025 USD): \$1,976.23

Cost data sources include:

- [EIA's Annual Energy Outlook 2025, Table 3](#) to forecast conventional diesel price
- ICF's estimation of RD cost is based on existing pricing reports, e.g. [Clean Cities and Communities Alternative Fuel Price Report, January 2025](#)

Off-Road Renewable Diesel

GHG Methodology

This measure models blending renewable diesel with conventional diesel for off-road transportation use. RD is a “drop-in” fuel, meaning it can be blended with or used in place of conventional diesel without modifications to the existing diesel equipment. This measure assumes that all diesel consumption for off-road transportation will be transitioned to RD by 2050. Similar to on-road, RD adoption begins in 2031 and grows linearly through 2050. A 65% carbon intensity reduction factor was applied to the share of diesel converted to RD, thus reducing emissions from RD’s share of overall diesel consumption by 65%.

Key assumptions include:

- All diesel consumption for off-road transportation will be transitioned to RD by 2050.
- RD adoption begins in 2031 and grows linearly through 2050.
- A 65% carbon intensity reduction factor was applied to the share of diesel converted to RD, thus reducing emissions from RD’s share of overall diesel consumption by 65%.

Limitations:

- The assumption of 65% reduction in carbon intensity is based on California’s LCFS average. The actual carbon intensity reduction could be different for the MSA depending on the feedstocks used to produce RD.

Data sources include:

- [Alternative Fuels Data Center: Renewable Diesel](#)

Cost Approach

The incremental cost of renewable diesel was evaluated by calculating the difference in unit price between RD and conventional diesel, then multiplying that difference by the projected volume of RD consumed. This approach

Similar to on-road, To reflect the higher cost of RD prior to the implementation of regulatory incentives or market-based programs, a cost of \$4.8 per gallon for RD was assumed. This represents the estimated cost of alternative fuels in the absence of subsidies and credits to capture the full economic burden of alternative fuel adoption in a pre-regulatory context. Costs for RD are shown in Table B24.

Cost Data Sources:

- Conventional diesel price forecast: [EIA’s Annual Energy Outlook 2025, Table 3](#)
- ICF’s estimation of RD cost is based on existing pricing reports, e.g. [Clean Cities and Communities Alternative Fuel Price Report, January 2025](#)

Sustainable Aviation Fuel

The best option to decarbonize aviation available today is to replace petroleum-based jet fuel with biomass- or waste-based fuel, commonly referred to as SAF. SAF is a chemical equivalent to conventional jet fuel but releases a fraction of the emissions from a lifecycle perspective because the carbon released was recently sequestered by its feedstock – typically a crop, waste oil or other biomass. This is similar from an emissions

accounting perspective to RD used in Measure T1. The barrier to SAF uptake is production cost, which are at least two times the cost of conventional jet fuel. A number of incentives like the Federal Renewable Fuel Standard and California's Low Carbon Fuel Standard offset the cost of SAF but are likely insufficient to induce demand at scale.

To further offset the costs, some states like Illinois and Washington have implemented a SAF tax credit. The purpose of a SAF tax credit is to provide direct cash to the producer or off-taker (the airline) to reduce or eliminate the price premium for SAF. To model SAF uptake, additional tax credits were assumed to be made available over time at a level sufficient to lead to higher levels of SAF blending.

GHG Methodology

Potential GHG reductions from an additional SAF incentive were estimated by comparing BAU jet fuel emissions to emissions under a scenario with increased SAF adoption. Emissions were evaluated on a lifecycle basis, meaning the carbon intensity of a gallon of fuel includes emissions associated with crude extraction, feedstock cultivation, transportation, refining, distribution, and combustion. Because SAF and conventional jet fuel have similar combustion emissions, a life-cycle analysis is important for capturing emissions reductions that occur earlier in the production chain.

To estimate SAF adoption at different incentive levels, RD market dynamics were used as a proxy⁶. A time-series analysis aligned historical incentives, diesel market prices, and RD production costs to predict production volumes based on profitability trends. The strongest relationship occurred at a 13-quarter lag, suggesting that profitability typically takes approximately three years to translate into new production capacity.

Profitability was forecasted using ICF projections for key components of SAF production costs and revenue streams. A third-party provider supplied feedstock price forecasts, which represent a major share of production costs. These data were combined with internal analysis of cost of capital and other operating expenses. Revenue assumptions were also informed by crude oil price projections and the Renewable Fuel Standard, both of which constitute large portions of producer revenue.

Key assumptions include:

- SAF tax incentive that results in close to 100% SAF blend by 2050. A constant \$0.40/gallon SAF tax credit is assumed.
- Blend restrictions are resolved: Currently the American Society for Testing and Materials has approved pathways for SAF production that only allow a 50% blend of SAF with conventional jet fuel. The modeling contemplates a future where SAF is close to 100% of the jet fuel pool. While technically feasible, it would require a SAF producer to undergo the necessary steps to acquire qualification for higher blends.
- Feedstocks are available: The current SAF industry is dominated by HEFA (Hydroprocessed Esters and Fatty Acids) production pathways that use soybean oil, used cooking oil or other crops or waste oils as a feedstock.⁷ These feedstocks are in high demand currently because of the expansion in the RD and SAF industries. As demand for HEFA feedstocks approaches supply constraints, it is anticipated that other pathways like alcohol to jet (ATJ), which uses ethanol to produce jet fuel, would be utilized. Feedstocks of

⁶ RD is a suitable proxy for SAF because both rely on HEFA pathways, share feedstocks, and operate under similar incentive structures. Their recent emergence, high blend potential (e.g., RD reaching 70% in California), and status as drop-in fuels requiring no infrastructure or engine modifications make RD's trajectory a valuable indicator for SAF market development.

⁷ The HEFA production process for SAF involves hydroprocessing vegetable oils, animal fats, or used cooking oil. The feedstocks are first deoxygenated and then the resulting hydrocarbons are hydrocracked and isomerized to meet jet fuel specifications, after which the SAF is blended with conventional jet fuel.

ethanol and corn (to produce the ethanol) have spare but finite capacity. Electrification of the on-road transportation sector may free up feedstocks as demand for RD and ethanol falls. Rather than model these various dynamics in the feedstock markets, the modeling assumes that feedstocks will not be a constraint to industry expansion nor that they will significantly rise in price in real dollar terms.

- SAF Industry Development will mirror RD Development given the same profitability profile. Because the SAF industry has low production to date, it is difficult to use past data for SAF to develop a view of the future. Therefore, it became necessary to find a corollary to SAF that had a stronger data history to analyze. RD has many characteristics that make it a helpful corollary which are articulated above. For these reasons, the modeling relied on RD production history to develop a theory around what will be required for SAF industry expansion.

Limitations include:

- The aviation sector does not reach net zero emissions despite using 100% SAF. For the aviation industry to claim carbon neutrality, it will be necessary to implement other measures like carbon capture and sequestration or carbon offset credits from other economic sectors.
- RD as a proxy market for SAF:
 - In the relevant incentives like the California LCFS, diesel is an obligated fuel, meaning that if a refiner blends RD, they both avoid generating a deficit by producing less diesel and generate a credit. Jet fuel is not obligated, so blending SAF only provides a credit and does not avoid any deficits. This feature essentially doubles the value of RD in comparison to SAF in these incentives and makes rapid expansion of RD very valuable to regulated parties. This difference was accounted for by awarding LCFS value to RD for both the avoided deficits and the credits, which expands the calculated profitability when the relationship between profitability and production is analyzed. When this is applied to SAF production outlooks, the model essentially demands that incentive value rises to the same levels as if SAF was being credited for both avoided deficits and credits.
 - Over the course of RD's rapid expansion, the fuel was certified to be blended to 100% levels, meaning there was no regulatory limit to diesel purchased at the pump from being entirely renewable. The safety considerations inherent in the aviation sector make the process for such certification much more complex. Today almost all SAF pathways are certified for 50% blends. Given the low percentage of SAF in the market today, this is not a barrier to expansion in the industry, but at the levels contemplated in this study, certification will have to be granted for 100% blends by around the mid-2030s.
- Initial volumes of SAF production were assumed to be produced using HEFA pathways. That technology pathway is one of a number of possible ways to produce SAF including ATJ and Fischer Tropsch (FT). Currently, HEFA is the only pathway that actually produces SAF at commercial scale, although there have been significant developments for other pathways. FT pathways do not reach commercial viability during the forecast period and that ATJ pathways develop in a similar pattern to HEFA was assumed. Technological development of FT pathways faster than anticipated could result in outcomes different from the current analysis.

Data sources include:

- CARB
- U.S. EIA
- OPIS
- Fastmarkets

Cost Approach

The incremental cost of SAF implementation was estimated by multiplying the projected SAF consumption by the cost difference between SAF and conventional jet fuel. To reflect the High cost of SAF prior to the influence of federal incentives and market scaling, the modeling used a production cost of \$7.00 per gallon. This metric represents the estimated cost of producing SAF using current technologies and feedstocks, such as HEFA or alcohol-to-jet pathways. SAF production costs are significantly higher than conventional jet fuel due to limited commercial-scale production, feedstock availability, and complex refining processes. For conventional jet fuel, the modeling relied on price forecasts from the EIA's Annual Energy Outlook 2025.

To account for policy-driven cost reductions, the analysis accounted for the SAF tax credits established to facilitate SAF adoption. The tax credit is designed to incentivize SAF production and adoption by offsetting part of the cost differential with conventional fuels.

Table B25: Measure SAF Annual and Cumulative Cost of Implementation (2025\$ Million)

	2025	2030	2035	2040	2045	2050	2025-2050
Total Costs	-	-	-	50.12	45.98	41.96	659.73

Cumulative Cost of Implementation from 2025-2050 (Million 2025 USD): \$659.73

Cost data sources include:

- EIA's Annual Energy Outlook 2025, Table 3

Waste

GHG emission reductions were quantified for actions that reduce the amount of waste sent to landfills, advance circular economy pathways for locally recovered materials, and improve the energy and emissions performance of wastewater treatment facilities. Collectively, these measures are projected to reduce emissions by 1.77 MMTCO₂e from 2025 through 2050.

Table B26: Summary of Waste Sector Measure GHG Reductions MMTCO₂e

Measure	Cumulative 2025-2030 GHG reductions	Cumulative 2025-2050 GHG reductions
Decrease amount of waste sent to landfills.	0.01	1.73
Assess the potential for a local circular economy with the collection of local plastics and paper waste that are processed in local industries for re-use.	NE	NE
Support efficiency upgrades at wastewater treatment plants.	0.0001	0.04

W1: Decrease amount of waste sent to landfills.

GHG Methodology

The methane commitment method from the Global Protocol for Community-Scale Greenhouse Gas Emission Inventories (GPC) was applied to calculate GHG reductions from diverting organics and recyclable waste. The percentage of waste diverted to recycling and composting was derived from historical statewide waste disposal data, and a waste characterization study was used to determine the share of landfilled waste that is recyclable and compostable.

Waste diversion was assumed to begin in 2030, increasing linearly from 0% in 2029 to 80% in 2050. These diversion rates were applied to calculate annual tonnage of recyclable and compostable material diverted from landfill disposal. The resulting diverted tonnage values were then used as inputs to the GPC methane commitment equation to estimate emissions under the measure scenario.

Key assumptions include:

- Waste diversion rates increases linearly from 0% diverted in 2029 to 80% diverted in 2050.

Limitations include:

- This methodology does not calculate the added emissions due to increased composting and recycling.

Data sources include:

- [GPC methane commitment method](#)

Cost Approach

For organic waste diversion, the ReFED Solutions Database was used to acquire data specific to Virginia, to determine annual diversion potential in tons and annual GHG reduction potential in MTCO₂e. Three action types from the database were used in the cost analysis: 1) Recycle Anything Remaining, 2) Reshape Consumer Environments, and 3) Strengthen Food Rescue. Each action type contributes a different share to the overall diversion potential. Recycle Anything Remaining contributes 32%, Reshape Consumer Environments contributes 62%, and Strengthen Food Rescue contributes 6%. Each action has a different cost per metric ton of GHG reduced, ranging from \$19 to \$303, depending on the strategy. Finally, the weighted average cost per metric ton of GHG reduced was calculated, using the diversion share and cost per ton GHG for each action for each state. The result per ton for the average implementation cost for diverting one ton of organic waste was \$124.22. The implementation cost was applied to each jurisdiction’s waste diverted quantity. For the baseline recycling cost reference, a unit cost of \$126 per ton of recycling was used as a reference, based on the New York City Independent Budget Office (2017).

Table B27: Measure W1 Annual and Cumulative Cost of Implementation (2025\$ Million)

	2025	2030	2035	2040	2045	2050	2025-2050
Total Costs	-	0.61	3.81	7.29	11.03	15.05	157.21

Cumulative Cost of Implementation from 2025-2050 (Million 2025 USD): \$157.21

Cost data sources include:

- [NYC Independent Budget Office Recycling Cost](#)
- [ReFED Solutions Database](#)

W2: Assess the potential for a local circular economy with the collection of local plastics and paper waste that are processed in local industries for re-use.

GHG Methodology

Emission reductions were not quantified for this measure. While circular economy strategies can reduce emissions significantly by avoiding upstream extraction, manufacturing, and transportation emissions, these reductions fall primarily within Scope 3 supply-chain emissions, which are not included in the community-wide inventory boundary for this plan.

This measure illustrates potential partnership and implementation pathways for expanding localized material recovery and re-manufacturing capacity in the region. A circular economy approach emphasizes keeping materials in use for as long as possible through reuse, recycling, and reprocessing, reducing demand for energy-intensive virgin materials and minimizing lifecycle emissions associated with production and disposal (EPA, 2024). In the Richmond MSA, post-consumer paper, cardboard, and plastics collected through local waste systems could be processed or re-manufactured locally, decreasing the need for long-distance hauling and reducing transportation-related emissions. These activities could also strengthen local supply chains for recycled-content materials.

Data sources include:

- [U.S. EPA. What is a Circular Economy?](#)
- [ICLEI USA. U.S. State and Local Governments Collaborate to Reduce Plastic Pollution.](#)

Cost Approach

Costs were not quantified for this measure.

W3: Support efficiency upgrades at wastewater treatment plants.

GHG Methodology

To calculate GHG reductions from wastewater treatment plants, EPA's State-Level Non-CO₂ Greenhouse Gas Data Tool was used to identify the potential for methane and nitrous oxide reductions in Virginia. A percentage reduction potential was calculated for the state, with reductions assumed to begin in 2030 and increase linearly to reach the full reduction potential by 2050.

This approach is limited by the lack of facility-specific wastewater treatment data for Virginia. As a result, it is uncertain whether the full reduction potential identified in EPA's tool can be feasibly achieved by wastewater treatment plants in the MSA.

Key assumptions include:

- State-level methane and nitrous oxide reduction potentials from EPA’s tool are representative of wastewater treatment facilities within the MSA.
- Emission reductions begin in 2030 and increase linearly through 2050.
- Reduction technologies and operational practices assumed by EPA are technically feasible and available to MSA wastewater treatment plants over the study period.

Limitations include:

- Lack of facility-specific data for wastewater treatment plants in Virginia may lead to over- or under-estimation of actual reduction potential.
- EPA’s reduction potentials may not fully reflect local treatment technologies, plant sizes, or operational conditions within the MSA.

Data sources include:

- [EPA’s State-Level Non-CO₂ Greenhouse Gas Data Tool](#)

Cost Approach

Costs were calculated by applying the unit cost per metric ton of CO₂e reduced, as reported in EPA’s State-Level Non-CO₂ Mitigation Potential, to the modeled emission reductions.

Table B28: Measure W3 Annual and Cumulative Cost of Implementation (2025\$ Million)

	2025	2030	2035	2040	2045	2050	2025-2050
Total Costs	-	0.17	1.06	1.99	2.97	3.99	42.55

Cumulative Cost of Implementation from 2025-2050 (Million 2025 USD): \$42.55

Cost data sources include:

- [EPA’s State-Level Non-CO₂ Greenhouse Gas Data Tool](#)

Co-Pollutant Quantification Methodology

National Emissions Inventory (NEI) 2022 Inventory and BAU Projection Methodology

The EPA NEI 2022 serves as the foundational dataset for constructing the emissions inventory and developing BAU projections across the Richmond MSA. The workflow integrates EPA’s National Emissions Inventory data,

crosswalked to U.S. Greenhouse Gas Inventory categories, and extended through 2050 using consistent, category-level growth assumptions from NEI projections.

Data Assembly and Structure

The process begins by compiling county-level emissions data from EPA’s NEI Data Retrieval Tool. Only counties within the MSA boundary are extracted and combined into a raw dataset. Columns containing helper formulas automatically map NEI source codes to higher-level categories used elsewhere in the model.

Once formatted, the raw dataset supports a standardized output of three summary tables:

- Total emissions by county
- Emissions by pollutant type
- Emissions by sector

These form the baseline representation of 2022 emission levels across the MSA.

Category Disaggregation

To make the NEI data compatible with GHG inventory structures, sectoral and source reallocation occurs within the Disaggregation tab. NEI’s detailed categories are mapped to broader U.S. GHG Inventory sectors including Industrial Processes and Product Use (IPPU), Mobile, Agriculture, Forestry and Other Land Use (AFOLU), Stationary, Waste, and Other. This step uses line-specific formulas referencing a Lookup table that maintains the correspondence between NEI source categories and inventory-level groupings.

Disaggregation ensures consistent categorization across pollutants, sectors, and inventory years. Error-checking functions confirm that reallocated categories are correctly linked and that no data gaps occur during crosswalk updates.

The Lookup tab acts as the central crosswalk engine, referencing all three NEI source description levels and mapping them to dual-level inventory groupings. It is periodically updated to reflect evolving NEI source classifications. New or unrecognized source codes identified during data imports are highlighted, categorized, and integrated into all dependent tabs to maintain integrity across the disaggregation and projection workflows. The mapping to inventory sector categories were provided by EPA.

Table 29. Co-pollutant Emissions by Sector and Pollutant

Category	CO	NOx	VOC	PM ₁₀	PM _{2.5}	SO ₂	NH ₃
AFOLU	19,361.7	1,423.6	96,522.8	3,987.0	2,145.9	120.8	3,495.6
IPPU	2,640.1	2,544.5	11,966.7	7,097.8	1,922.2	756.8	637.6
Mobile	101,098.4	10,746.1	6,608.9	939.5	488.1	64.4	818.3
Stationary	15,113.2	6,771.7	1,985.1	4,054.7	3,791.4	481.6	415.8
Waste	8,629.4	408.6	1,492.4	1,350.0	1,164.9	213.8	595.1

Category	CO	NOx	VOC	PM ₁₀	PM _{2.5}	SO ₂	NH ₃
Other	327.3	7.7	82.5	4,188.7	772.0	0.6	0.0
Total	147,170.1	21,902.3	118,658.5	21,617.8	10,284.6	1,638.0	5,962.3

Co-Pollutant Quantification Approach by Sector

Criteria Air Pollutants (CAPs) were quantified because they are common pollutants with widespread public health impacts, causing respiratory and cardiovascular diseases, asthma aggravation, and premature death. Their reductions are directly linked to clear public health benefits and regulatory air quality standards, supported by well-established emissions factors and monitoring methods. CAPs include ozone, particulate matter (PM_{2.5}, PM₁₀), carbon monoxide (CO), nitrogen oxides (NO_x), sulfur dioxide (SO₂), and lead.

Hazardous Air Pollutants (HAPs), in contrast, tend to be emitted in smaller quantities with more complex sources and lack widely available emissions factors, making their reductions harder to quantify and often smaller in overall impact. HAPs include over 180 chemicals including benzene and mercury making them harder to quantify. Although HAPs are not quantitatively represented, they will still be reduced through GHG reduction measures. Reducing energy use in buildings by increasing efficiency and transitioning to cleaner energy sources lowers the need for burning fossil fuels, which in turn can decrease emissions of toxic air pollutants like formaldehyde, benzene, and other hazardous substances. When more EVs are used and VMT decrease, emissions of HAPs from gasoline and diesel engines, such as 1,3-butadiene, acetaldehyde, and benzene, are also reduced. These shifts generally improve both outdoor and indoor air quality, lessen the public's exposure to a variety of indoor and outdoor toxins, and support better respiratory and overall health outcomes, particularly in densely populated or heavily trafficked areas.

Buildings

For energy efficiency or fuel-switching measures in the commercial, residential, and industrial buildings sectors, less fuel is used in both new and existing buildings. This not only reduces most GHG emissions but also decreases emissions of other harmful pollutants that are released during fuel combustion. The following methodology was used to quantify co-pollutant emission reductions in the building sectors:

- **Quantify Fuel Saved:** Determine the amount of each fuel type saved by comparing the baseline scenario to the mitigation scenario.
- **Apply Emission Factors:** Use standard EPA AP-42 emissions factors for each fuel type to estimate how much NO_x, SO₂, Lead, CO, VOC, and PM would have been emitted if the fuel had been used.
- **Calculate Emissions Reductions:** Multiply the amount of each fuel saved by its corresponding emission factor to estimate the avoided emissions for each pollutant.

Transportation

For Richmond's on-road transportation sector, co-pollutant reductions were quantified using emission factors derived from 2020 EPA NEI data and VMT estimates. Emission factors were calculated by dividing total 2020 emissions by total 2020 VMT, disaggregated by county, pollutant, vehicle type, and fuel type, resulting in mass per mile (e.g., metric tons CO per diesel truck mile).

For the mitigation scenario, these emission factors are applied to projected VMT through 2050 to estimate gross emissions under the mitigation pathway. Specifically, the emissions factor (EF) for each pollutant and vehicle/fuel category is multiplied by the corresponding VMT in the mitigation scenario. The resulting emissions are then subtracted from the 2020 NEI-based BAU emissions to estimate net reductions in co-pollutants attributable to the mitigation strategy.

Richmond's off-road calculations only include emissions reductions for converting conventional jet fuel to SAF in the aviation sector. For Aviation, the methodology uses an emissions factor approach. Gross emissions reductions are calculated by multiplying the amount of jet fuel saved (from baseline minus mitigation scenario) by Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model emissions factors for conventional jet fuel. Emissions from SAF are also calculated from GREET factors. The SAF emissions are subtracted from the gross emissions reductions to calculate net emissions reductions.

Waste

Waste reduction measures lead to less waste ending up in landfills. This not only reduces greenhouse gas emissions but also decreases emissions of other harmful pollutants, specifically NO_x, CO, and PM_{2.5}, that are released when landfill gas is flared.

- Quantify Waste Diverted: Determine the amount of waste that is prevented from entering landfills due to the waste reduction measure.
- Estimate Methane Generation Avoided: Calculate how much methane would have been produced by this diverted waste if it had been landfilled.
- Apply Emission Factors: Use standard EPA emission factors to estimate how much NO_x, CO, VOC, and PM_{2.5} would have been emitted from flaring the methane generated by the landfilled waste.

Natural & Working Lands

For Richmond's natural and working lands sector, co-pollutant removals are quantified using data from the i-Tree Landscape Module⁴⁷, accessed county by county. Annual pollutant removal estimates are converted from pounds to metric tons and downscaled to a per-tree basis using the total number of trees in the MSA, as quantified in the natural working lands (NWL) measure modeling output.

These per-tree removal rates are then multiplied by the number of new trees projected to be planted across the MSA under the mitigation scenario aggregated by locality. This approach yields cumulative co-pollutant removal estimates attributable to tree planting efforts, representing added benefits from natural sequestration and air quality improvements.

Electricity Demand Changes

Mitigation measures such as building and transportation electrification and solar installations lead to changes in electricity demand. This in turn changes how power plants across the broader regions – within and outside of the MSA – operate. Because the changes in power plants occur across a broader region and not just within the MSA, these co-pollutant emission changes are reported separately, although a portion would likely occur within the region.

The net electricity demand increases with measure implementation of building and transportation electrification, leading to increased co-pollutant emissions. This is a potential disbenefit to communities that

live around power plants that increase their output to meet this increased electricity demand and emphasizes the importance of measures focusing on increasing the amount of clean energy capacity deployed.

The net change in co-pollutant emissions across the broader power grid was estimated based on projected changes in the electricity grid mix. These projections were informed by data from EPA's National Emissions Inventory, EIA's form EIA-923, and power sector modeling data from the Virginia State CPRG plan, which reflect the increased demand.

Factors

The tables below contain the factors and sources used for this analysis.

Table B30: Building and Industry Fuels Emissions Factors

Fuel	Notes	Units	NOx	SO ₂	PM	CO	Lead	VOC
Natural Gas	Uncontrolled small boiler or controlled (recirculation) large boiler	Boiler Ef (lb/10 ⁶ scf)	100	0.6	7.6	84	0.0005	5.5
Natural Gas	Residential furnace	Ef lb/10 ⁶ scf	94	0.6	7.6	40	0.0005	5.5
Natural Gas	Assume large industrial boiler, low NOx burner	Ef lb/10 ⁶ scf	140	0.6	7.6	84	0.0005	4.68
Fuel Oil	<100 MMBTU	Boiler Distillate oil fired Ef (lb/1000 gal)	20	7.1	2	5	0.0015	0.46
Fuel Oil	>100 MMBTU	Boiler #2 oil fired Ef (lb/1000 gal)	24	7.1	2	5	0.0015	0
Fuel Oil	>100 MMBTU	Boiler (assume #6 oil) fired Ef (lb/1000 gal)	47	78.5	7.815	5	0.0015	0
LPG	Source: AP 42 Source: AP 42	Propane Ef (lb/1000 gal)	13	0.05	0.7	7.5	0	0.8
Coal	Source: AP 42, spreader stoker, bituminous	Common in medium sized boilers, assuming use in industrial buildings (lb/ton)	11	76	66	5	0	0
Other	These represent a 55/45 split of coal/oil boilers	Lb/MMBtu	0.33	1.26	0.15	0.03	0	0.003

Table B31: Conversion and Heat Factors

Fuel Type	Value	Units	Source
Natural gas	1036	BTU/scf	EIA
Distillate oil heating value	140	MMBTU/1000 gal	EPA
Residual oil heating value	150	MMBTU/1000 gal	EIA
Propane heating value	91.5	MMBTU/1000 gal	EIA

Table B32: Sulfur (S) Content Estimates

Fuel Type	Value	Unit
Assumed S content of distillate oil	0.05	% by weight (500 ppm)
Assumed S content of propane	0.5	% by weight
Assumed S content of 6 oil	0.5	% by weight

Table B33: Aviation Emissions Factors from GREET1 2024⁸

Pollutant	HEFA SAF EF (g/MJ)	Petroleum Conventional Jet EF (g/MJ)
CO	0.06942	0.060
NO _x	0.20216	0.2329
PM ₁₀	0.009	0.003
PM _{2.5}	0.009	0.003
VOC	0.0380	0.0093
SO _x	0.0010	0.0132

Table B34: Waste Emissions Factors from EPA AP-42⁹

Control Device	Notes	Units	NO _x	PM (Primary)	CO	VOC
Flare	Emission rates for secondary compounds exiting control devices	Lb/10 ⁶ dscf Methane	40	17	750	4.1

Benefits Assessment

As part of the benefits analysis, Richmond assessed the different benefits impacts the measures are projected to have on different sectors – namely in the form of health impacts and avoided costs.

⁸ JetFuel_WTWa tab, “Passenger Aircraft, Singl Aisle (SA): HEFA from Soybean” table; JetFuel_WTWa tab, “Passenger Aircraft, Singl Aisle (SA): Petroleum Conventional Jet” table

⁹ <https://www3.epa.gov/ttnchie1/ap42/ch02/final/c02s04.pdf>

Ecosystem Services

Impacts from the natural and working lands sector were derived from the i-Tree landscape model. The i-Tree Landscape module is a web-based tool that spatially estimates ecosystem services provided by trees across different landscapes, such as urban or rural areas. It uses tree cover data, leaf area index, weather, pollution levels, and local population data to estimate benefits like air pollution removal and stormwater management. Specifically, it quantifies how much air pollutants such as nitrogen dioxide, sulfur dioxide, ozone, carbon monoxide, and particulate matter are removed by trees, using deposition rates and leaf surface area. It also estimates stormwater runoff reduction by calculating how trees intercept rainfall based on canopy cover and local weather conditions.

Table B35: Total NWL Co-pollutant Removals, 2025-2050

Pollutant	Cumulative Removals (MT)
NOx	35,218
SO ₂	20,585
PM	73,548
CO	5,945
Lead	35,218
VOC	n/a

Table B36: NWL Avoided Stormwater Runoff Added Monetary Benefit of 50% Tree Canopy Cover (\$2025)

Region	2050 Monetary Value
Total MSA	\$34,226,505

The results highlight the significant co-benefits of natural and working lands investments in the region, both for air quality and water management. Cumulatively, trees are projected to remove tens of thousands of metric tons of pollutants such as PM, NOx, SO₂, and CO between 2025 and 2050, improving public health and regional air quality. In addition, expanding tree canopy cover yields substantial economic value for stormwater management, with avoided runoff benefits reaching millions of dollars in several counties, particularly Chesterfield, Henrico, and Richmond City. The results show that urban tree canopy expansion and forest conservation strategies provide not only greenhouse gas mitigation but also measurable local benefits in air pollution reduction and infrastructure cost savings.

Health Impacts

Table B37 below presents the cumulative health benefits and associated monetary values resulting from quantified co-pollutant reductions in the MSA between 2025 and 2050. These estimates are derived from the EPA Co-Benefits Risk Assessment (COBRA) model and reflect the total change in incidence, the number of avoided cases, for each health impact category. The monetary benefits represent the economic value of these avoided outcomes, including reduced mortality, fewer hospital visits, and improved productivity through fewer missed school and workdays. This summary provides an MSA-wide overview, which is followed by sector-specific results detailing pollutant reductions and health impacts at a more granular level.

At the MSA level, the table provides a range of estimates, low and high, for both health outcomes and their monetized benefits for mortality. These ranges reflect uncertainty in the underlying epidemiological and economic assumptions, such as the sensitivity of populations to air pollution and the valuation of avoided health outcomes. The low estimate represents a more conservative scenario, while the high estimate assumes stronger health effects and higher economic valuations. This range helps contextualize the potential variability in benefits.

Table B37: Cumulative Monetary Health Benefits (Million \$2025) and Incident Reductions, 2025-2050

Health Impact	Cumulative Monetary Benefits (2025-2050)	Cumulative Incidence Reduction (2025-2050)
Mortality	\$ 7,467 - \$ 12,740	511 - 876
Hospital Visits	\$ 7	1,212
Missed School/Work or Restricted Activity	\$ 273	427,548
Cardiovascular Conditions	\$ 19	227
Respiratory Conditions	\$ 270	380,885

In the sector-specific results that follow, only the low-end estimates from COBRA are shown. This approach is intended to maintain a conservative and cautious interpretation of the data. By focusing on the lower bound of potential benefits, the analysis avoids overstating impacts while still capturing the meaningful health and economic gains associated with co-pollutant reductions.

Commercial and Residential Buildings

In the Buildings sector, the modeled strategies have led to significant cumulative reductions in key pollutants from 2025 to 2050. The residential and commercial buildings sector has the highest cumulative reductions for NOx. These reductions are primarily driven by a suite of building-focused strategies aimed at improving energy efficiency and electrification. Measures included in this modeling are; provide technical and financial assistance to achieve net-zero operations for municipal and school buildings, increase resident education of incentives for energy efficiency home improvements and electric appliances, increase energy efficiency in existing commercial and industrial buildings, strongly encourage residential, commercial, and industrial buildings to be above current code requirements, and manage data center growth and regional impacts.

Table B38: Total Residential and Commercial Buildings Co-pollutant Reductions, 2025-2050

Pollutant	Cumulative Reductions (MT)
NOx	32,023.58
SO ₂	1,476.88
PM	2,498.70
CO	18,180.36
Lead	0.40
VOC	1,715.07

Translated into health impact quantification, using the results provided from COBRA, the building residential sector is estimated to achieve substantial public health benefits between 2025 and 2050. These include avoided mortality valued at approximately \$3 billion, along with reductions in hospital visits, missed school and workdays, cardiovascular conditions, and respiratory conditions.

Table B39: Residential Buildings COBRA Benefits, 2025-2050

Health Impact	Cumulative Monetary Benefits (\$)	Cumulative Incidence Reduction
Mortality	\$2,195,187,077	150
Hospital Visits	\$1,835,501	391
Missed School/Work or Restricted Activity	\$106,643,963	118,486
Cardiovascular Conditions	\$3,907,070	48
Respiratory Conditions	\$100,247,057	128,900

The buildings-commercial sector shows strong health co-benefits, with cumulative mortality benefits estimated at \$1.84 billion, slightly lower than the residential sector. It also shows comparable gains in hospital visits, missed activity days, and respiratory conditions.

Table B40: Commercial Buildings COBRA Benefits, 2025-2050

Health Impact	Cumulative Monetary Benefits (\$)	Cumulative Incidence Reduction
Mortality	\$1,839,241,364	126
Hospital Visits	\$1,531,810	328
Missed School/Work or Restricted Activity	\$89,894,045	99,126
Cardiovascular Conditions	\$3,240,985	40
Respiratory Conditions	\$84,422,546	108,346

Industrial Buildings

In the industrial buildings sector, fuel-switching and increased energy efficiency measures reduce the use of high-emission fuels such as fuel oil, propane and coal while increasing reliance on natural gas. The largest cumulative reductions occur for SO₂, with over 32,000 MT reduced, followed by PM at nearly 20,000 MT. NO_x and CO also decline significantly. Minor reductions are observed from lead and VOCs, reflecting the sector's transition away from high-emission fuels. These changes are driven by building measures aimed at improving energy efficiency and electrification.

Table B41: Total Industrial Buildings Co-pollutant Reductions, 2025-2050

Pollutant	Cumulative Reductions (MT)
NO _x	7,032.49
SO ₂	32,377.69

Pollutant	Cumulative Reductions (MT)
PM	19,944.84
CO	1,982.30
Lead	0.11
VOC	54.51

The industrial buildings sector shows strong health co-benefits, with cumulative mortality benefits estimated at \$3.33 billion, higher than both the residential and commercial sectors. It results in a substantial amount of reductions in hospital visits, missed activity days, and respiratory conditions. Buildings remain a key contributor to MSA-wide health improvements. It is important to note that benefits for the buildings-industrial sector may be skewed due to a misalignment with COBRA's default baseline emissions. The calculated reduction in 2030 to 2050 are larger than COBRA's default emissions baseline for SO₂ and PM_{2.5}. For this reason, the COBRA output assumes a reduction equal to the COBRA baseline, which yields large benefits as a result.

Table B42: Industrial Buildings COBRA Benefits, 2025-2050

Health Impact	Cumulative Monetary Benefits (\$)	Cumulative Incidence Reduction
Mortality	\$3,325,082,575	228
Hospital Visits	\$3,805,152	471
Missed School/Work or Restricted Activity	\$69,476,869	204,623
Cardiovascular Conditions	\$11,364,386	139
Respiratory Conditions	\$79,024,874	136,360

Transportation

In the Transportation sector, the modeled strategies have led to substantial cumulative reductions. The largest CO emission reductions come from the transportation sector due to decreased tailpipe emissions in the on-road sector. However, emissions from SAFs outweighs the on-road co-benefit. Switching from conventional jet fuel to SAF may decrease GHGs, but CO and PM emissions increase. The transportation sector also includes additional measures to increase efficiency for both on and off-road transportation including: supporting equitable ZEV adoption, expand transit access, promoting micromobility options like e-bikes and scooters, and increasing the use of low-carbon transportation materials.

Table B43: Total Transportation Co-pollutant Reductions, 2025-2050

Pollutant	Cumulative Reductions (MT)
NOx	4,092.35
SO ₂	1,281.40
PM	262.36
CO	20,724.19
VOC	47.07

As seen below in Table B44 On-Road transportation accounts for the majority of CO emission reductions due to residents switching to ZEVs with less tail-pipe exhaust.

Table B44: On-road Transportation Co-pollutant Reductions, 2025-2050

Pollutant	Cumulative Reductions (MT)
NOx	2,201.56
SO ₂	49.43
PM	71.76
CO	20,336.14

In contrast, the majority of SO₂ and PM emissions result from Aviation activities due to the combustion process of conventional jet fuel. Reducing the reliance on conventional jet fuel through SAF fuel switching causes these reductions.

Table B45: Off-road Transportation Co-pollutant Reductions, 2025-2050

Pollutant	Cumulative Reductions (MT)
NOx	1,890.78
SO ₂	1,231.97
PM	190.60
CO	388.06
VOC	47.07

The transportation sector is notably less impactful than the buildings sector in terms of health-related co-benefits from pollutant reductions. It's lower than all sectors apart from Waste in cumulative monetary benefits with the highest benefit being \$511 million for mortality. Transportation is also relatively low in incidence reductions. However, this sector still sees public health gains through air quality improvements.

Table B46: Total Transportation Sector COBRA Benefits, 2025-2050

Health Impact	Cumulative Monetary Benefits (\$)	Cumulative Incidence Reduction
Mortality	\$511,492,028	35
Hospital Visits	\$431,662	91
Missed School/Work or Restricted Activity	\$24,943,714	27,560
Cardiovascular Conditions	\$910,443	11
Respiratory Conditions	\$23,430,122	30,098

Waste

In the waste sector, the modeled strategies have led to modest cumulative reductions in pollutants from 2025 to 2050. These reductions are achieved through strategies that improve waste management practices, encouraging reuse and recycling, and reduce methane and fossil fuel emissions. Modeled measures include reducing GHG emissions from waste and wastewater treatment.

Table B47: Waste Co-pollutant Reductions, 2025-2050

Pollutant	Cumulative Reductions (MT)
NOx	79.70
PM	33.87
CO	1,494.36
VOC	1,715.07

The waste sector yields less health benefits in comparison to other sectors. Cumulative monetary values are low across all categories, with mortality benefits totaling \$9.61 million and negligible gains in hospital visits and missed activity days. Incidence reductions are similarly limited, suggesting that co-pollutant reductions in this sector have a relatively small impact on public health outcomes. While not a major driver of MSA-wide benefits, the Waste sector may still offer localized improvements.

Table B48: Waste COBRA Benefits, 2025-2050

Health Impact	Cumulative Monetary Benefits (\$)	Cumulative Incidence Reduction
Mortality	\$9,608,557	1
Hospital Visits	\$10,040	2
Missed School/Work or Restricted Activity	\$292,893	566
Cardiovascular Conditions	\$27,618	0
Respiratory Conditions	\$301,013	453

Electricity Demand Changes

In the electricity sector, demand has increased from various measures. This increase in demand leads to an increase in co-pollutant emissions from power plants and therefore is a disbenefit to the local community surrounding electricity generating power plants in the region. The disbenefit reduces over time as the grid shifts to a greater share of clean energy resources.

Table B49: Electricity Co-pollutant Emissions Increase, 2025-2050

Pollutant	Cumulative Reductions (MT)
CO	(778.31)
NH ₃	(129.45)
NOx	(2,303.95)
PM	(954.99)
SO ₂	(197.61)
VOC	(171.89)

Note: Negative values indicate net increases in emissions

The electricity sector yields health disbenefits, with mortality disbenefits estimated at \$413 million. Health incidences also increase, showing the negative impact on public health outcomes due to an increase in emissions.

Table B50: Electricity COBRA Benefits, 2025-2050

Health Impact	Cumulative Monetary Benefits (\$)	Cumulative Incidence Reduction
Mortality	\$(413,133,007)	(28)
Hospital Visits	\$(369,488)	(72)
Missed School/Work or Restricted Activity	\$(18,444,837)	(22,814)
Cardiovascular Conditions	\$(838,830)	(10.2)
Respiratory Conditions	\$(17,592,554)	(23,272)

Note: Negative values indicate disbenefits and increased incidence

Appendix C: Workforce Analysis

Assessing the readiness of the workforce to support implementation of the measures is a critical step to successful implementation. The technical appendix provides a detailed workforce gap analysis methodology, identifies certifications and credentials that employers require for priority occupations, catalogs education and training providers in the region, and presents a workforce solution framework. Labor Market Data Tables contain complete labor market statistics, certification requirements, and training program details for all 60 occupations analyzed, serving as a technical reference for stakeholders engaged in workforce planning and program development. The workforce gap analysis uses data on projected growth (the number of workers needed to fill new growth), separations (employees leaving the workforce/occupation), and hires to estimate the shortage or surplus of workers for each of the 60 occupations. The workforce gap analysis only considers existing conditions in the labor market and does not factor in additional demand for workers that implementing the measures could generate.

Key Findings

A total of 60 occupations could be impacted by the implementation of Richmond's Air Quality Plan measures, ranging from engineering, construction and skilled trades, production, transportation, and agricultural jobs. In total, these occupations represent roughly 82,500 jobs, or 11.2% of 738,000 total jobs in the Richmond metropolitan statistical area (MSA).

The workforce gap analysis uses data from Lightcast on projected growth, separations, and hires to estimate the shortage or surplus of workers in each of the 60 occupations. The workforce gap analysis only considered existing conditions in the labor market and did not incorporate assumptions based on additional demand for workers that could be generated if the measures are implemented.

From a workforce perspective, the Richmond region is well-positioned to implement its measures. Overall, the region has enough workers in its labor market to meet the demands of implementing the measures, with greater worker surpluses than worker shortages.

Workforce Shortages

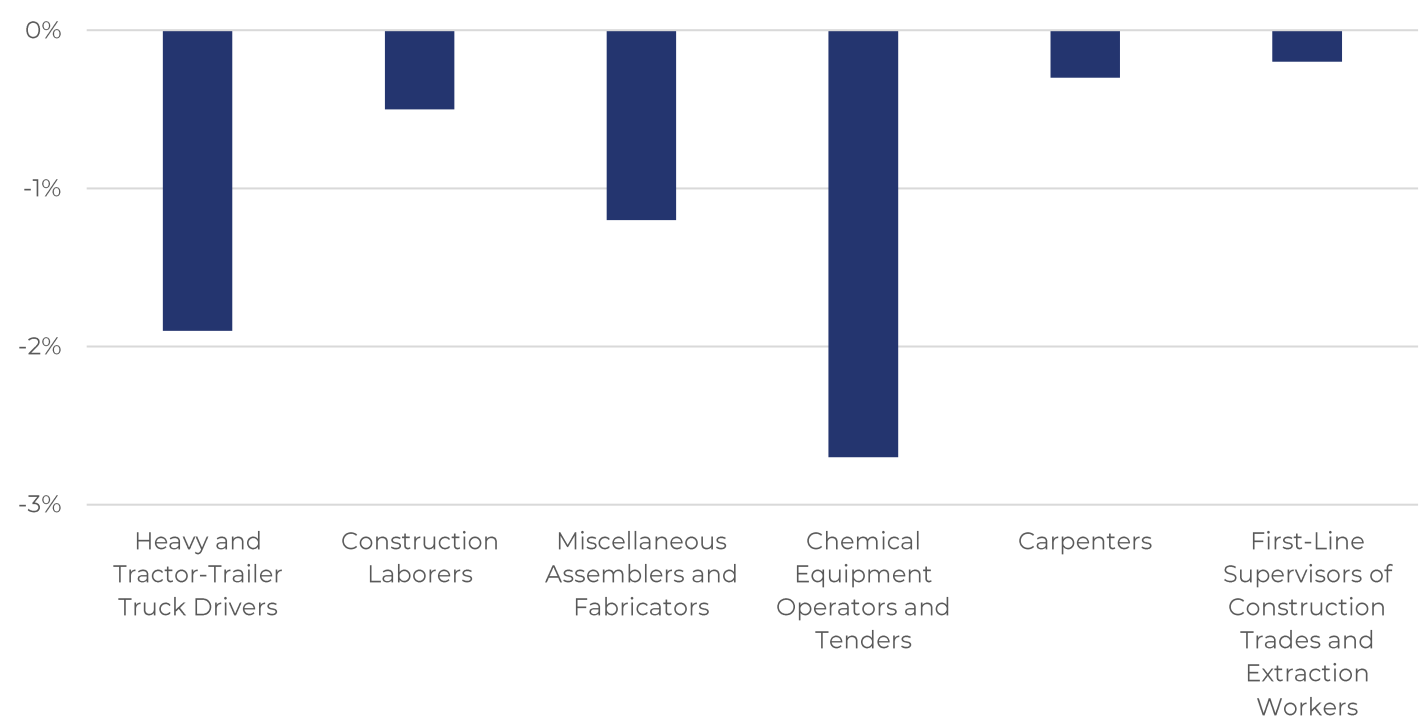
- There is a shortage of 219 **Heavy Tractor-Trailer Truck Drivers**, an occupation which will be critical for the implementation of the measures across the plan. This represents 1.9% of the total number of Heavy Tractor-Trailer Truck Drivers in the MSA and is the greatest shortage of any occupation in the region by number.
- There is a shortage of 13 **Chemical Equipment Operators**, an occupation which will support implementation of the measures in the industry sector. This represents 2.7% of the total number of Chemical Equipment Operators and is the greatest shortage of any occupation in the region by percentage.
- Other occupations with minor estimated shortages include Construction Laborers (32 workers, or 0.5% of total employment), Carpenters (12 workers, or 0.3% of total employment), First-Line Supervisors of Construction (10 workers, or 0.2% of total employment), and Miscellaneous Assemblers and Fabricators (31 workers, or 1.2% of total employment).

Shortages can be driven by many factors, not just a lack of skills or availability of training. Even when workers have the necessary skills and experience, a range of structural and economic barriers can limit their ability to find and keep stable employment. **Strict job requirements**—such as rigid degree mandates or years of experience thresholds—can exclude qualified candidates and narrow opportunities for advancement. **High housing costs** can force workers to live far from job centers, increasing commute times and reducing work-life balance. Meanwhile, the rising **costs of childcare and transportation** can make full-time employment financially unsustainable, especially for parents and lower-wage workers. Together, these factors contribute to higher turnover, reduced labor force participation, and ongoing challenges in worker retention across multiple industries.

Table C1: Occupations with the Largest Shortages (2025)

SOC Code	Occupation	Relevant Sector	Shortage or Surplus 2025	
			Potential Workforce Shortage	Shortage (% of Total Employment)
53-3032	Heavy and Tractor-Trailer Truck Drivers	Waste	-219	1.9%
47-2061	Construction Laborers	Buildings	-32	0.5%
51-2098	Miscellaneous Assemblers and Fabricators	Industry	-31	1.2%
51-9011	Chemical Equipment Operators and Tenders	Industry	-13	2.7%
47-2031	Carpenters	Industry, Buildings	-12	0.3%
47-1011	First-Line Supervisors of Construction Trades and Extraction Workers	Transportation, Buildings	-10	0.2%

Figure C1: Shortage as percent of total employees (2025)



Workforce Surpluses

Workforce surpluses in the region are more significant than the shortages. Laborers and Freight, Stock, and Material Movers is estimated to have the largest surplus, 636 workers or 5.5% of the total workforce in that occupation. Many surpluses are jobs with high turnover and occupations that may be part-time jobs, so the data may not reflect a long-term shortage in the occupation.

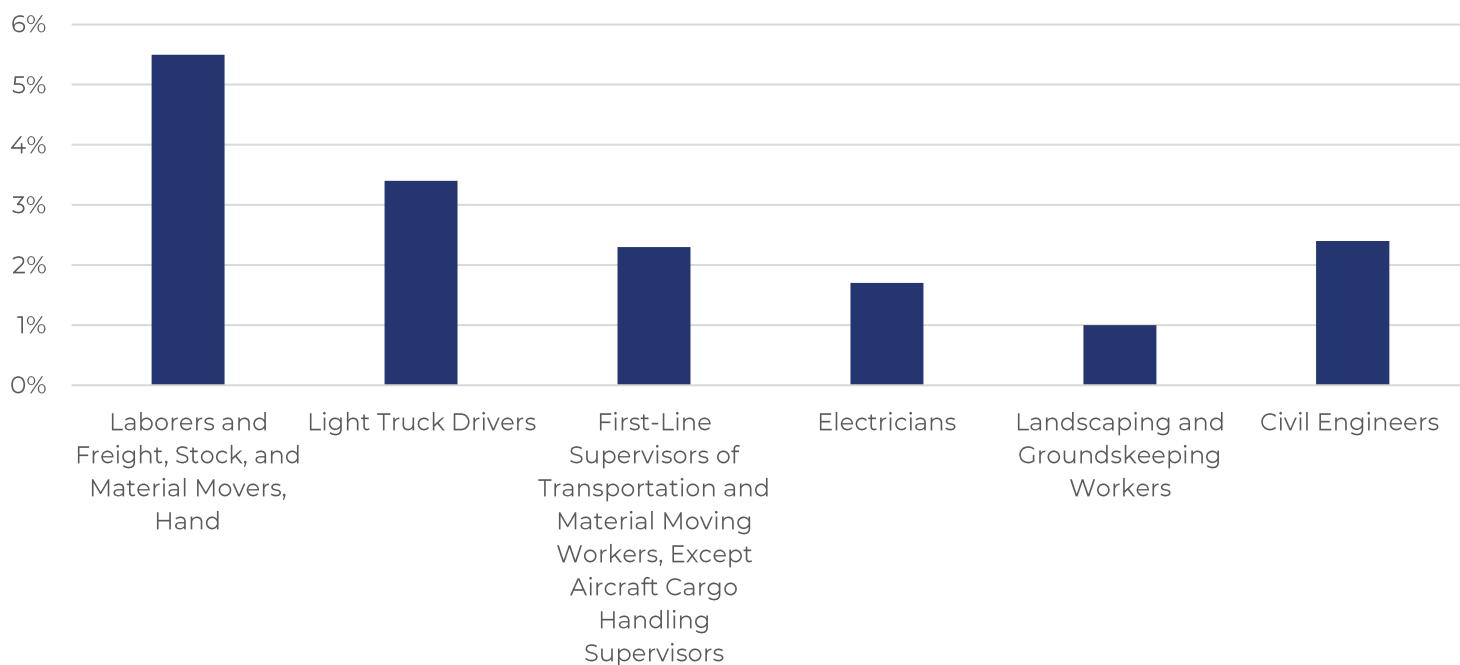
Surpluses also are estimated for Light Truck Drivers, Supervisors or Transportation and Material Moving Workers, Electricians, Landscaping Workers, and Civil Engineers.

It is important to note that a surplus in the occupation does not mean that there will not be shortages or difficulties hiring for jobs specific to the energy transition. While there may be a sufficient number of electricians in the MSA, the data does not provide a level of granularity to assess whether enough of them can support electric vehicle (EV) charging infrastructure, for example. The same goes for engineers and heating, ventilation, and air conditioning (HVAC) technicians that might not have the knowledge or experience to design and maintain green or all-electric buildings.

Table C2: Occupations with Largest Surplus (2025)

SOC Code	Occupation	Relevant Sector	Shortage or Surplus (2025)	
			Potential Workforce Surplus	Surplus (% of Occupational Employment)
53-7062	Laborers and Freight, Stock, and Material Movers, Hand	Transportation	636	5.5%
53-3033	Light Truck Drivers	AFLOU	185	3.4%
53-1047	First-Line Supervisors of Transportation and Material Moving Workers, Except Aircraft Cargo Handling Supervisors	Transportation	70	2.3%
47-2111	Electricians	AFOLU, Transportation, Buildings, Energy	64	1.7%
37-3011	Landscaping and Groundskeeping Workers	AFLOU	57	1.0%
17-2051	Civil Engineers	Buildings	56	2.4%

Figure C2: Surplus as percent of total employees (2025)



Solutioning Framework

While not quantified in this assessment, implementation will drive demand for greater activity across all sectors, with the largest potential growth in energy, buildings, and transportation – the same sectors responsible for most modeled greenhouse gas reductions. As the pace of the energy transition increases, this added demand will exacerbate existing shortages and workforce challenges. While many of these occupations already exist within the region, increasing the scale and pace of climate-related investment will create new competition for workers. Without proactive training and recruitment strategies, the region could face delays in project implementation, higher labor costs, and reduced local benefit capture.

- **Energy:** Expansion of renewable generation, grid modernization, and distributed energy resources will drive new positions in electrical, mechanical, and construction trades.
- **Buildings:** Energy efficiency retrofits and electrification will create sustained demand for heating, ventilation, and air conditioning (HVAC) technicians, electricians, and energy auditors.
- **Transportation:** Electrification of vehicles and charging infrastructure deployment will increase need for electrical lineworkers, electric vehicle (EV) maintenance technicians, and manufacturing roles tied to battery systems. Transit expansion plans will require additional heavy duty vehicle drivers.
- **Industry:** Efficiency upgrades and process innovation will require engineers, maintenance staff, and technicians trained in new industrial control systems.
- **Waste:** Growth in organics diversion, methane recovery, and advanced treatment facilities will create opportunities in materials management and plant operations.
- **Agriculture and Natural Lands:** Habitat restoration, reforestation, and regenerative agricultural practices will expand employment in land management, equipment operation, and environmental services.

Shortages can be driven by many factors, not just a lack of skills or availability of training. Even when workers have the necessary skills and experience, a range of structural and economic barriers can limit their ability to find and keep stable employment. For example, students that graduate from local programs and universities may not be able to afford to live and stay in the region. In addition, strict job requirements—such as rigid degree mandates or years of experience thresholds—can exclude qualified candidates and narrow opportunities for advancement. High housing costs can force workers to live far from job centers, increasing commute times and reducing work-life balance. Meanwhile, the rising costs of childcare and transportation can make full-time employment financially unsustainable, especially for parents and lower-wage workers. Together, these factors contribute to higher turnover, reduced labor force participation, and ongoing challenges in worker retention across multiple industries.

The most significant workforce gaps are expected in skilled trades and technical occupations that support clean energy and infrastructure deployment. These gaps are driven by three interrelated factors:

1. **Aging Workforce:** Many skilled trades are facing retirements faster than replacements are entering the field.
2. **Training Capacity Constraints:** Existing technical programs and apprenticeships are operating near capacity and may require expansion to meet future demand.
3. **Awareness and Access Barriers:** Young workers and underrepresented populations often lack exposure to clean energy and climate-resilience career pathways.

Bridging these gaps will require coordinated efforts among employers, training providers, and workforce councils to align programs with implementation timelines.

Addressing workforce barriers requires a coordinated, multi-stakeholder approach recognizing the interconnected nature of economic, social, and policy challenges. Collaboration among employers, government agencies, educational institutions, and community organizations will be needed to build supportive ecosystems for workers. Employers can adapt by offering more flexible job requirements, remote or hybrid options, and family-friendly benefits, while public agencies can invest in affordable housing, childcare infrastructure, and transportation access. Educational institutions and workforce boards can align training programs with real-time industry needs, ensuring that skill-building efforts translate into viable employment pathways. Lasting progress depends on shared responsibility—no single employer or sector can address these barriers alone—but through coordinated investment and policy alignment, communities can create conditions where workers and businesses thrive together.

Future discussion will be needed across the region with employers in key occupations to better understand their specific challenges in hiring and retaining workers, what programs and solutions they already have in place to address barriers, and to discuss how they could be involved in more regional collaborative programs and initiatives to support their needs.

Although Richmond’s workforce shortages are relatively minor today in the assessed occupations, addressing these shortages will ensure successful implementation of the Air Quality Plan. While workforce shortages and barriers go beyond skills and training, those are still fundamental elements of workforce development and will be critical to ensure the workforce is ready to meet the challenges of implementation. In addition to the broader framework for support outlined above, the following strategies can directly support workforce development goals:

- Reskill and upskill workers from occupations where there are surpluses to occupations with shortages.
 - Surplus labor provides an opportunity for the region to retrain and redeploy workers into emerging fields aligned with Air Quality Plan priorities. For example, Laborers and Freight, Stock, and Material Movers (with relatively large surpluses) can be reskilled as Construction Laborers (an occupation with significant shortages). Light Truck Drivers could also be reskilled as Heavy and Tractor-Trailers.
 - Often these transitions can be made with minimal additional training.
- Apprenticeships, reskilling opportunities, and flexible certification pathways can help ensure a steady pipeline of qualified workers.
- Developing partnerships with educational institutions, training providers, employers, and government agencies can foster dynamic skill-development programs.

Addressing workforce shortages and surpluses is central to the success of the measures. By anticipating labor market trends, investing in workforce development, and embracing innovative workforce solutions, the region can secure the expertise needed.

Gap Analysis Methodology

This section outlines the methodology for each component of the workforce analysis. This analysis integrates labor market data from Lightcast to project future workforce gaps and informs strategic planning. It also forms a foundation for the subsequent sections, where labor gaps, certifications, education and training providers, and workforce solutions are examined to address occupational shifts and ensure alignment with measures.

Workforce Analysis Approach/Methodology

The first step in the workforce analysis was the identification of occupations that might be impacted by the implementation of the measures. Each mitigation measure was linked to relevant industry and occupational codes using the North American Industry Classification System (NAICS) and the Standard Occupational Classification (SOC) framework. This mapping identified the primary and secondary occupations associated with activities such as renewable energy deployment, building retrofits, vehicle electrification, and land restoration. For example, the measure “Expand Utility-Scale Renewables” was mapped to NAICS 221114 (Solar Electric Power Generation) and corresponding SOC codes for construction laborers, electricians, and power plant operators. Similar linkages were developed for all measures to create a comprehensive crosswalk between emissions reduction strategies and the occupational categories they influence. The impacted occupations are listed in Table C9 of the Workforce Data Appendix.

To quantify the employment baseline for the identified occupations, data from Lightcast (formerly EMSI), Bureau of Labor Statistics (BLS) Occupational Employment and Wage Statistics (OEWS), and Virginia Employment Commission (VEC) were used for the Hampton Roads Metropolitan Statistical Area. Data included historic and projected employment, employment concentration, wages, typical education and training requirements, turnover rates, the number of hires, and openings. Projected employment growth was then estimated by applying national or state-level clean energy job multipliers, derived from studies conducted by NREL, DOE, and BW Research Partnership Energy Employment Reports. These multipliers were adjusted to reflect local market conditions, existing industrial capacity, and regional specialization factors.

Workforce gaps were determined by comparing projected growth in employment, occupational separations (using the turnover rate), and new hires for each occupation. In the analysis, new hires represent supply, and new growth and separations represent estimated demand. The difference between workforce supply and demand represents the gap, which can either be negative (indicating a shortage) or positive (indicating a surplus).

The analysis next compared occupational skill requirements with available regional training programs, apprenticeships, and certification pathways. Results identified areas where current training supply was sufficient and where capacity or curriculum updates would be needed to meet workforce requirements. This evaluation considered both quantitative metrics (number of graduates, program enrollment, completion rates) and qualitative inputs (curriculum content and industry alignment). Regional training data were collected from the VCCS, Hampton Roads Workforce Council, and local apprenticeship programs registered through the Virginia Department of Labor and Industry. Additionally, information from Lightcasts's real-time job posting analytics on the certifications that employers seek when hiring for a selected set of priority occupations relevant to the measures was used. The priority occupations included: EV Maintenance; Energy Auditor; Construction Laborer; Roof Top Solar Installers; Heat Pump Installers; HVAC; Farmers; Landscaping Workers; Electricians; Electrical Engineers; Heavy Tractor-Trailer Drivers; and Bus Drivers for Transit. Data from the Integrated Postsecondary Education Data System (IPEDS) from the National Center for Education

Statistics (NCES) was also used to identify education and training providers in the metropolitan statistical area (MSA) that have programs that led to credentials requested by the occupations.

Employment Trends

A total of 60 occupations by the implementation of the Air Quality Plan measures, including construction and skilled trades, transportation, energy production and distribution, and agricultural jobs. In total, these occupations represent roughly 82,500 jobs, or 11.2% of 738,000 total jobs in the Richmond MSA.

Table C3 shows the occupations that have grown the most in employment over the past 10 years. Heavy Tractor-Trailer Drivers lead in growth, adding 1,802 jobs in the past ten years at an 18.3% growth rate. This is followed by Construction Trade Supervisors, Transportation and Material Moving Supervisors, Construction Laborers, Laborers and Freight, Stock and, and Material Movers, and Compliance Officers, all which added over 1,000 workers in the past ten years. These roles are especially critical for supporting the Buildings and Transportation components of the measures. For a full breakdown of employment trends across all 60 occupations, refer to Table C10.

Table C3: Occupations with the Greatest Job Growth

SOC	Description	Relevant Sectors	2015 Jobs	2025 Jobs	Change	% Change
53-3032	Heavy and Tractor-Trailer Truck Drivers	Waste	9,822	11,624	1,802	18.3%
47-1011	First-Line Supervisors of Construction Trades and Extraction Workers	Transportation, Buildings	3,301	4,636	1,335	40.4%
53-1047	First-Line Supervisors of Transportation and Material Moving Workers, Except Aircraft Cargo Handling Supervisors	Transportation	1,847	3,050	1,203	65.1%
47-2061	Construction Laborers	Buildings	5,047	6,204	1,157	22.9%
53-7062	Laborers and Freight, Stock, and Material Movers, Hand	Transportation	10,542	11,673	1,131	10.7%
13-1041	Compliance Officers	Buildings	1,248	2,316	1,068	85.6%

Table C4 provides an overview of occupations in the Richmond MSA that have undergone the most significant reductions in employment between 2015 and 2025. Notably, carpenters have experienced the steepest decline, losing 372 positions over the decade, a considerable drop of 9.4%. This downward trend is likely the result of shifting demands within the construction and building sectors.

Table C4: Occupations with the Greatest Job Loss

SOC	Description	Relevant Sectors	2015 Jobs	2025 Jobs	Change	% Change
47-2031	Carpenters	Industry, Buildings	3,964	3,592	-372	-9.4%
47-2071	Paving, Surfacing, and Tamping Equipment Operators	Transportation	537	233	-304	-56.6%
53-7081	Refuse and Recyclable Material Collectors	Waste	669	375	-294	-43.9%
49-9052	Telecommunication Line Installers and Repairers	Buildings	898	621	-277	-30.8%
47-3012	Helpers--Carpenters	Industry, Buildings	410	157	-253	-61.7%
51-8021	Stationary Engineers and Boiler Operators	Energy	342	123	-219	-64.0%

Table C5 provides an overview of the occupations within the Richmond MSA that are expected to experience the greatest projected job growth from 2025 to 2035. This is led by Laborers and Freight, Stock, and Material Movers, Heavy and Tractor-Trailer Truck Drivers, and Light Truck Drivers, which are expected to add 1,035, 789, and 730 jobs, respectively, over the next ten years in the Richmond MSA.

This projected growth underscores a broader trend within the region's labor market, reflecting the ongoing importance of logistics, transportation, and material handling sectors to the local economy. These occupations play a vital role in supporting supply chains and facilitating the movement of goods throughout the area.

Table C5: Occupations with the Greatest Projected Job Growth

SOC	Description	Relevant Sectors	2025 Jobs	2035 Jobs	Change	% Change
53-7062	Laborers and Freight, Stock, and Material Movers, Hand	Transportation	11,673	12,708	1,035	8.9%
53-3032	Heavy and Tractor-Trailer Truck Drivers	Waste	11,624	12,413	789	6.8%
53-3033	Light Truck Drivers	AFLOU	5,381	6,111	730	13.6%
53-1047	First-Line Supervisors of Transportation and Material Moving Workers, Except Aircraft Cargo	Transportation	3,050	3,279	229	7.5%

SOC	Description	Relevant Sectors	2025 Jobs	2035 Jobs	Change	% Change
	Handling Supervisors					
37-3011	Landscaping and Groundskeeping Workers	AFLOU	5,511	5,735	224	4.1%
47-2061	Construction Laborers	Buildings	6,204	6,414	210	3.4%

Table C6 highlights the occupations with the greatest projected decline in jobs between 2025 and 2035. This is led by Telecommunication Line Installers and Repairers, Electricians, and Electrician Helpers, which are expected to decline by 119, 92, and 72 jobs, respectively, over the next ten years in the Richmond MSA.

Table C6: Occupations with the Greatest Projected Job Decline

SOC	Description	Relevant Sectors	2025 Jobs	2035 Jobs	Change	% Change
49-9052	Telecommunication Line Installers and Repairers	Buildings	621	502	-119	-19.2%
47-2111	Electricians	AFOLU, Transportation, Buildings, Energy	3,801	3,709	-92	-2.4%
47-3013	Helpers—Electricians	AFOLU, Transportation, Buildings, Energy	574	502	-72	-12.5%
47-2031	Carpenters	Industry, Buildings	3,592	3,540	-52	-1.4%
49-9051	Electrical Power-Line Installers and Repairers	energy	531	484	-47	-8.9%
47-2181	Roofers	Buildings	480	436	-44	-9.2%

Gap Analysis

The gap analysis evaluates the difference between workforce supply and employer demand. As outlined in the methodology, demand refers to both projected job growth and the need to replace workers who retire or change occupations, while supply is defined as the actual number of hires made by employers. The gap analysis takes into account the increased demand for these jobs that may result from implementing the measures, it only considers current conditions.

Table C7 shows the occupations that are estimated to have the greatest workforce shortages in 2025 for the Richmond MSA. The region has very good equilibrium in its labor market for the occupations, with only some relatively minor shortages or surpluses of workers.

Table C7: Occupations with the Greatest Projected Workforce Shortages (2025)

Occupation	Relevant Sector	Projected Employment	Projected Supply	Projected Demand Subtotals		Projected Shortage	
			Hires	Growth ¹	Separations	Workforce	% of Occupational Employment
Heavy and Tractor-Trailer Truck Drivers	Waste	11,624	8,395	244	8,370	-219	1.9%
Construction Laborers	Buildings	6,204	4,031	85	3,978	-32	0.5%
Miscellaneous Assemblers and Fabricators	Industry	2,572	2,014	27	2,017	-31	1.2%
Chemical Equipment Operators and Tenders	Industry	471	128	4	137	-13	2.7%
Carpenters	Industry, Buildings	3,592	1,711	20	1,703	-12	0.3%
First-Line Supervisors of Construction Trades and Extraction Workers	Transportation, Buildings	4,636	1,743	38	1,715	-10	0.2%
Chemical Plant and System Operators	Industry	236	59	2	63	-6	2.5%
Farmers, Ranchers, and Other Agricultural Managers	AFOLU	882	89	8	87	-6	0.7%
Operating Engineers and Other Construction Equipment Operators	Transportation, Buildings	2,491	1,273	41	1,236	-4	0.2%
Helpers—Carpenters	Industry, Buildings	157	337	1	339	-3	1.8%

¹Growth refers to number of new jobs

Table C8 shows the occupations that are estimated to have the greatest surpluses in workers in 2025 for the Richmond MSA. Although, it is projected that there will be enough labor for these occupations to effectively implement the measures, as noted above the gap analysis does not include the labor force demand that the measures may generate.

The occupation with the largest surplus of workers is Laborers and Freight, Stock, and Material Movers. These workers primarily work in warehouses and other storage facilities and for transportation companies. Workers in this occupation will be needed to implement measures in the transportation sector. Labor surpluses also exist in a variety of other sectors and include Light Truck Drivers, Supervisors of Transportation and Material Moving Workers, and Electricians.

Assessing labor surpluses provides insight into where there could be opportunities for workers to transition their skills from one occupation to another that may be in greater demand. For example, Light Truck Drivers and Laborers and Freight, Stock, and Material Movers, where there are surpluses of workers, can transition to Heavy and Tractor-Trailer Truck Drivers, where there is a shortage, often with minimal additional training. The gap analysis will inform Richmond's workforce development strategies, ensuring that they focus on areas with the greatest need. See Table C13 in the Workforce Data Appendix for the gap analysis for all occupations.

Table C8: Occupations with the Largest Estimated Workforce Surpluses (2025)

Occupation	Sector	Projected Employment	Projected Supply	Projected Demand Subtotals		Projected Surplus	
			Hires	Growth	Separations	Workforce	% of Occupational Employment
Laborers and Freight, Stock, and Material Movers, Hand	Transportation	11,673	14,253	317	13,300	636	5.5%
Light Truck Drivers	AFLOU	5,381	5,013	180	4,648	185	3.4%
First-Line Supervisors of Transportation and Material Moving Workers, Except Aircraft Cargo Handling Supervisors	Transportation	3,050	1,797	74	1,654	70	2.3%
Electricians	AFOLU, Transportation, Buildings, Energy	3,801	1,738	8	1,667	64	1.7%
Landscaping and Groundskeeping Workers	AFLOU	5,511	4,004	86	3,861	57	1.0%
Civil Engineers	Buildings	2,326	870	32	782	56	2.4%

Occupation	Sector	Projected Employment	Projected Supply	Projected Demand Subtotals		Projected Surplus	
			Hires	Growth	Separations	Workforce	% of Occupational Employment
Bus Drivers, Transit and Intercity	Transportation	571	199	7	146	47	8.2%
Compliance Officers	Buildings	2,316	742	17	688	36	1.6%
Helpers—Electricians	AFOLU, Transportation, Buildings, Energy	574	970	(7)	944	33	5.8%
Electrical, Electronic, and Electromechanical Assemblers, Except Coil Winders, Tapers, and Finishers	Transportation	640	332	18	284	30	4.8%

Effective management of workforce imbalances involves proactive measures, such as targeted recruitment, training, and education initiatives. Partnerships between government, industry, and educational institutions can help align labor supply with emerging demands, ensuring that the region is equipped to meet goals. Understanding and addressing workforce shortages and surpluses is crucial for successful implementation of the Air Quality Plan.

Certifications

A comprehensive analysis was conducted to evaluate the most sought-after skills and certifications for key occupations (see Table C14, Table C15,

Table C16, Table C17, Table C18, Table C19, Table C20, Table C21, Table C22, Table C23, Table C24, and Table C25). This review focused on roles such as EV maintenance technicians, energy auditors, construction laborers, rooftop solar installers, heat pump installers, HVAC specialists, farmers, landscaping workers, electricians, electrical engineers, heavy tractor-trailer drivers, and transit bus drivers. Real-time job posting data from Lightcast for the Richmond MSA provided insight into employer requirements for these positions.

For many jobs, employers are consistently seeking candidates with specific certifications and skills. This trend is especially notable for electric vehicle mechanics, energy auditing, rooftop solar installation, and building trades such as electricians, HVAC technicians, and heat pump installers.

Key certifications include the Electric Vehicle Fundamentals (EVF) Certification for EV mechanics, the Certified Energy Auditor (CEA) for energy auditors, the Photovoltaic Installation Professional (PVIP) Certification for solar installers, the Environmental Protection Agency (EPA) Section 608 Technician Certification for HVAC and heat pump specialists, and the Journeyman Electrician License for electricians.

Conversely, employers hiring for occupations such as construction laborers, landscapers, and agricultural workers typically do not require formal certifications.

For a detailed breakdown of the top certifications required for each key occupation, see the Workforce Data Appendix, Tables C14-C25.

Education and Training Providers

Education and training providers across the Richmond MSA have been identified as key resources for supplying the credentials and certifications prioritized by employers in the key occupations. The Richmond area has a wide variety of existing training and education programs (see Table C26, Table C27, Table C28, Table C29, Table C30, Table C31, Table C32, Table C33,

Table C34, Table C35, and Table C36).

While the region boasts a strong array of training programs for traditional building trades, there are notably fewer options in newer fields like energy auditing, rooftop solar installation, and EV maintenance. For building trades, a variety of pathways are available, including high school and technical education, community colleges, apprenticeship programs, and private training providers.

However, specialized training in energy auditing, rooftop solar, and EV maintenance is currently concentrated in just a few community colleges. These colleges will play a pivotal role in bridging workforce gaps by updating curricula, incorporating the latest technologies, and expanding programs to align with industry and implementation demands.

See the Workforce Data Appendix, Tables C26-C36, for a comprehensive list of educational and training providers relevant to each major occupation.

Workforce Solutions

Addressing the workforce challenges associated with implementation will involve three key components: 1) developing solutions and partnerships; 2) developing partnerships; and 3) setting, tracking, and continually refining goals. The labor market and workforce gap analysis identified some of the current needs that should be addressed to successfully implement the Air Quality Plan:

Workforce shortages in key occupations, including:

- Heavy and Tractor-Trailer Truck Drivers
- Construction Laborers
- Carpenters

A lack of training opportunities for key skills and credentials in the region, including:

- EVF Certification for EV mechanics
- CEA for energy auditors
- PVIP Certification for solar installers
- EPA Section 608 Technician Certification for HVAC and heat pump specialists
- Journeyman Electrician License for electricians

The need to upskill and reskill workers, including:

- Laborers and Freight, Stock, and Material Movers, Hand
- Light Truck Drivers
- Electricians

The focus of the following workforce solutions is addressing these workforce and training needs.

Developing Solutions and Partnerships

Effective workforce development demands collaboration among a diverse array of stakeholders. Forming partnerships with colleges and training providers offering programs in key occupations can help meet the emerging needs. Building new partnerships and strengthening existing ones are crucial for successful

implementation. It is vital to make workforce education and training accessible to current workers, as well as those seeking to transition from other fields.

To develop solutions to address workforce challenges it is important to build new partnerships for effective implementation. The Richmond MSA features a rich landscape of education and training resources, particularly for traditional building trades. Pathways include high school and technical education programs, community colleges, apprenticeships, and private institutions. Yet, in emerging fields like energy auditing, rooftop solar, and EV maintenance, specialized training is currently limited to a few community colleges. Expanding these offerings and updating curricula with the latest technology is key to closing workforce gaps.

Preparing the future workforce might involve early education and outreach, developing tailored training materials for apprenticeships and pre-apprenticeships, and connecting with local businesses and contractors about upcoming opportunities and evolving workforce needs. Using these strategies will equip workers for the changes brought by implementation.

Leveraging these resources will help prepare the workforce for the changes brought about by implementation of the measures.

Setting, Tracking, and Continually Refining Goals

Setting, tracking, and continually refining goals throughout the implementation will be important to measure Richmond's success in addressing the projected workforce shortages and implementing measures. Metrics might include:

- Number of jobs created in a given occupation
- Number of workers trained in a given program
- Training programs developed in a given sector

By tracking these benchmarks, stakeholders can measure progress and maintain alignment with priorities throughout the process.

Workforce Data Appendix

Occupations Impacted by Air Quality Plan Measures

Table C9: Occupations Impacted by Measures

SOC	Occupation	Relevant Sectors
11-9013	Farmers, Ranchers, and Other Agricultural Managers	AFOLU
13-1041	Compliance Officers	Buildings
17-2051	Civil Engineers	Buildings
17-2071	Electrical Engineers	Buildings
17-2081	Environmental Engineers	Buildings
17-2141	Mechanical Engineers	Buildings
17-2161	Nuclear Engineers	Energy
19-1013	Soil and Plant Scientists	AFOLU
19-1032	Foresters	AFLOU
19-3051	Urban and Regional Planners	Buildings
19-4071	Forest and Conservation Technicians	AFOLU
37-3011	Landscaping and Groundskeeping Workers	AFLOU
37-3013	Tree Trimmers and Pruners	AFLOU
45-2092	Farmworkers and Laborers, Crop, Nursery, and Greenhouse	AFOLU
45-2093	Farmworkers, Farm, Ranch, and Aquacultural Animals	AFLOU
45-2099	Agricultural Workers, All Other	AFLOU
45-4011	Forest and Conservation Workers	AFOLU
47-1011	First-Line Supervisors of Construction Trades and Extraction Workers	Transportation, Buildings
47-2031	Carpenters	Industry, Buildings
47-2061	Construction Laborers	Buildings
47-2071	Paving, Surfacing, and Tamping Equipment Operators	Transportation
47-2073	Operating Engineers and Other Construction Equipment Operators	Transportation, Buildings
47-2111	Electricians	AFOLU, Transportation, Buildings, Energy
47-2131	Insulation Workers, Floor, Ceiling, and Wall	Buildings
47-2152	Plumbers, Pipefitters, and Steamfitters	Buildings, Energy

SOC	Occupation	Relevant Sectors
47-2181	Roofers	Buildings
47-2231	Solar Photovoltaic Installers	AFOLU, Buildings, Energy
47-3012	Helpers--Carpenters	Industry, Buildings
47-3013	Helpers--Electricians	AFOLU, Transportation, Buildings, Energy
47-3015	Helpers--Pipelayers, Plumbers, Pipefitters, and Steamfitters	Buildings, Energy
47-4011	Construction and Building Inspectors	Buildings
49-2093	Electrical and Electronics Installers and Repairers, Transportation Equipment	Transportation
49-2095	Electrical and Electronics Repairers, Powerhouse, Substation, and Relay	Energy
49-2096	Electronic Equipment Installers and Repairers, Motor Vehicles	Transportation
49-9021	Heating, Air Conditioning, and Refrigeration Mechanics and Installers	Buildings
49-9031	Home Appliance Repairers	Buildings
49-9051	Electrical Power-Line Installers and Repairers	energy
49-9052	Telecommunication Line Installers and Repairers	Buildings
49-9081	Wind Turbine Service Technicians	Energy
51-2028	Electrical, Electronic, and Electromechanical Assemblers, Except Coil Winders, Tapers, and Finishers	Transportation
51-2098	Miscellaneous Assemblers and Fabricators	Industry
51-7042	Woodworking Machine Setters, Operators, and Tenders, Except Sawing	Industry
51-8011	Nuclear Power Reactor Operators	Energy
51-8012	Power Distributors and Dispatchers	Energy
51-8013	Power Plant Operators	Buildings, Energy
51-8021	Stationary Engineers and Boiler Operators	Energy
51-8031	Water and Wastewater Treatment Plant and System Operators	Waste
51-8091	Chemical Plant and System Operators	Industry
51-9011	Chemical Equipment Operators and Tenders	Industry
53-1047	First-Line Supervisors of Transportation and Material Moving Workers, Except Aircraft Cargo Handling Supervisors	Transportation
53-3032	Heavy and Tractor-Trailer Truck Drivers	Waste
53-3033	Light Truck Drivers	AFLOU
53-3052	Bus Drivers, Transit and Intercity	Transportation

SOC	Occupation	Relevant Sectors
53-5011	Sailors and Marine Oilers	Transportation
53-5021	Captains, Mates, and Pilots of Water Vessels	Transportation
53-5031	Ship Engineers	Transportation
53-7021	Crane and Tower Operators	Transportation, Buildings
53-7041	Hoist and Winch Operators	Transportation
53-7062	Laborers and Freight, Stock, and Material Movers, Hand	Transportation
53-7081	Refuse and Recyclable Material Collectors	Waste

Labor Market Data

Table C10 shows the percentage change in employment for five-year periods over the past ten years and the projected change over the next ten years for the Richmond MSA.

Table C10: Percent Change in Employment

SOC	Description	Relevant Sectors	Percent Change 2015-2020	Percent Change 2020-2025	Percent Change 2025-2030	Percent Change 2030-2035
11-9013	Farmers, Ranchers, and Other Agricultural Managers	AFOLU	40.7%	-14.3%	3.0%	1.6%
13-1041	Compliance Officers	Buildings	64.6%	12.8%	1.4%	0.4%
17-2051	Civil Engineers	Buildings	18.6%	19.3%	2.9%	0.9%
17-2071	Electrical Engineers	Buildings	0.5%	39.3%	1.5%	-0.7%
17-2081	Environmental Engineers	Buildings	-15.6%	-36.7%	2.2%	-0.6%
17-2141	Mechanical Engineers	Buildings	-0.8%	-19.5%	7.9%	3.3%
17-2161	Nuclear Engineers	Energy	-42.6%	-35.8%	10.6%	2.9%
19-1013	Soil and Plant Scientists	AFOLU	65.7%	73.3%	4.4%	0.8%
19-1032	Foresters	AFLOU	48.0%	6.9%	1.8%	4.2%
19-3051	Urban and Regional Planners	Buildings	6.5%	22.6%	2.1%	0.7%
19-4071	Forest and Conservation Technicians	AFOLU	-39.4%	15.5%	1.0%	-1.0%
37-3011	Landscaping and Groundskeeping Workers	AFLOU	-0.3%	7.3%	3.3%	0.7%
37-3013	Tree Trimmers and Pruners	AFLOU	20.5%	-26.8%	1.7%	-1.0%
45-2092	Farmworkers and Laborers, Crop, Nursery, and Greenhouse	AFOLU	9.5%	22.2%	3.1%	1.2%

SOC	Description	Relevant Sectors	Percent Change 2015-2020	Percent Change 2020-2025	Percent Change 2025-2030	Percent Change 2030-2035
45-2093	Farmworkers, Farm, Ranch, and Aquacultural Animals	AFLOU	21.1%	-7.2%	3.3%	2.1%
45-2099	Agricultural Workers, All Other	AFLOU	23.1%	34.7%	7.0%	4.3%
45-4011	Forest and Conservation Workers	AFOLU	26.3%	15.7%	6.6%	2.3%
47-1011	First-Line Supervisors of Construction Trades and Extraction Workers	Transportation, Buildings	15.9%	21.2%	0.6%	-1.3%
47-2031	Carpenters	Industry, Buildings	-1.0%	-8.5%	0.2%	-1.6%
47-2061	Construction Laborers	Buildings	3.2%	19.1%	2.9%	0.5%
47-2071	Paving, Surfacing, and Tamping Equipment Operators	Transportation	-21.6%	-44.7%	3.5%	1.0%
47-2073	Operating Engineers and Other Construction Equipment Operators	Transportation, Buildings	-0.3%	20.6%	3.3%	0.3%
47-2111	Electricians	AFOLU, Transportation, Buildings, Energy	6.8%	2.1%	-0.7%	-1.7%
47-2131	Insulation Workers, Floor, Ceiling, and Wall	Buildings	67.7%	92.7%	1.2%	-0.1%
47-2152	Plumbers, Pipefitters, and Steamfitters	Buildings, Energy	5.2%	-0.8%	1.0%	-1.2%
47-2181	Roofers	Buildings	2.0%	-2.7%	-4.7%	-4.6%
47-2231	Solar Photovoltaic Installers	AFOLU, Buildings, Energy	197.7%	-63.7%	10.9%	7.5%
47-3012	Helpers--Carpenters	Industry, Buildings	-33.0%	-43.0%	-0.7%	-2.7%
47-3013	Helpers--Electricians	AFOLU, Transportation, Buildings, Energy	-6.8%	-17.0%	-6.7%	-6.3%
47-3015	Helpers--Pipelayers, Plumbers, Pipefitters, and Steamfitters	Buildings, Energy	-17.8%	-8.5%	0.3%	-0.6%
47-4011	Construction and Building Inspectors	Buildings	23.8%	31.4%	0.7%	-0.8%

SOC	Description	Relevant Sectors	Percent Change 2015-2020	Percent Change 2020-2025	Percent Change 2025-2030	Percent Change 2030-2035
49-2093	Electrical and Electronics Installers and Repairers, Transportation Equipment	Transportation	-39.3%	56.6%	0.7%	0.1%
49-2095	Electrical and Electronics Repairers, Powerhouse, Substation, and Relay	Energy	-18.0%	1.6%	-1.0%	-2.1%
49-2096	Electronic Equipment Installers and Repairers, Motor Vehicles	Transportation	-17.4%	-10.7%	-8.2%	-9.6%
49-9021	Heating, Air Conditioning, and Refrigeration Mechanics and Installers	Buildings	13.7%	21.4%	2.3%	0.2%
49-9031	Home Appliance Repairers	Buildings	-31.1%	-6.8%	-8.3%	-5.5%
49-9051	Electrical Power-Line Installers and Repairers	energy	-10.9%	4.8%	-4.5%	-4.5%
49-9052	Telecommunication Line Installers and Repairers	Buildings	-5.4%	-26.9%	-12.2%	-8.0%
49-9081	Wind Turbine Service Technicians	Energy	150.5%	20.9%	-1.8%	-3.0%
51-2028	Electrical, Electronic, and Electromechanical Assemblers, Except Coil Winders, Tapers, and Finishers	Transportation	-12.4%	-3.3%	6.1%	2.0%
51-2098	Miscellaneous Assemblers and Fabricators	Industry	-8.7%	6.0%	0.6%	-1.9%
51-7042	Woodworking Machine Setters, Operators, and Tenders, Except Sawing	Industry	25.7%	-39.1%	2.9%	-1.0%
51-8011	Nuclear Power Reactor Operators	Energy	-	-	17.2%	6.5%
51-8012	Power Distributors and Dispatchers	Energy	-49.6%	-12.2%	-3.0%	-3.9%
51-8013	Power Plant Operators	Buildings, Energy	-8.3%	-0.9%	-3.6%	-2.3%
51-8021	Stationary Engineers and Boiler Operators	Energy	-73.0%	33.5%	2.6%	0.3%
51-8031	Water and Wastewater Treatment Plant and System Operators	Waste	5.5%	-1.2%	-1.2%	-2.2%
51-8091	Chemical Plant and System Operators	Industry	17.2%	163.8%	-0.8%	-2.8%

SOC	Description	Relevant Sectors	Percent Change 2015-2020	Percent Change 2020-2025	Percent Change 2025-2030	Percent Change 2030-2035
51-9011	Chemical Equipment Operators and Tenders	Industry	-20.5%	36.9%	-1.8%	-4.8%
53-1047	First-Line Supervisors of Transportation and Material Moving Workers, Except Aircraft Cargo Handling Supervisors	Transportation	30.4%	26.6%	5.5%	1.9%
53-3032	Heavy and Tractor-Trailer Truck Drivers	Waste	8.7%	8.9%	4.9%	1.8%
53-3033	Light Truck Drivers	AFLOU	10.5%	6.4%	9.1%	4.1%
53-3052	Bus Drivers, Transit and Intercity	Transportation	-2.8%	11.2%	2.0%	-0.7%
53-5011	Sailors and Marine Oilers	Transportation	21.8%	-22.4%	0.4%	0.5%
53-5021	Captains, Mates, and Pilots of Water Vessels	Transportation	-15.4%	-8.1%	3.6%	1.4%
53-5031	Ship Engineers	Transportation	23.8%	-22.7%	-0.6%	0.0%
53-7021	Crane and Tower Operators	Transportation, Buildings	-6.5%	-4.8%	4.0%	0.5%
53-7041	Hoist and Winch Operators	Transportation	0.0%	0.0%	0.0%	0.0%
53-7062	Laborers and Freight, Stock, and Material Movers, Hand	Transportation	1.1%	9.5%	6.5%	2.2%
53-7081	Refuse and Recyclable Material Collectors	Waste	-21.6%	-28.5%	3.1%	-0.1%

Source: Lightcast

Table C11 shows the location quotient (LQ) for five-year periods over the past ten years and the projected LQ over the next ten years for the Richmond MSA. The LQ is a statistical measure that represents a region's industrial or occupational concentration compared to the national average. An LQ of 1 indicates the region has the same concentration as the nation, greater than 1 means it is more concentrated, suggesting specialization, and less than 1 signifies lower concentration.

Table C11: Employment Concentration – LQ 2015-2035

SOC	Description	Relevant Sectors	2015 LQ	2020 LQ	2025 LQ	2030 LQ	2035 LQ
11-9013	Farmers, Ranchers, and Other Agricultural Managers	AFOLU	0.29	0.38	0.36	0.38	0.39
13-1041	Compliance Officers	Buildings	1.06	1.39	1.35	1.33	1.32
17-2051	Civil Engineers	Buildings	1.28	1.38	1.49	1.48	1.48

SOC	Description	Relevant Sectors	2015 LQ	2020 LQ	2025 LQ	2030 LQ	2035 LQ
17-2071	Electrical Engineers	Buildings	0.88	0.85	1.19	1.17	1.16
17-2081	Environmental Engineers	Buildings	1.06	0.94	0.74	0.73	0.72
17-2141	Mechanical Engineers	Buildings	0.62	0.59	0.49	0.50	0.51
17-2161	Nuclear Engineers	Energy	1.76	1.13	0.87	0.96	1.00
19-1013	Soil and Plant Scientists	AFOLU	0.39	0.64	0.95	0.95	0.93
19-1032	Foresters	AFLOU	0.90	1.17	1.12	1.12	1.17
19-3051	Urban and Regional Planners	Buildings	1.22	1.23	1.32	1.32	1.32
19-4071	Forest and Conservation Technicians	AFOLU	0.52	0.31	0.36	0.37	0.36
37-3011	Landscaping and Groundskeeping Workers	AFLOU	0.96	0.99	1.03	1.05	1.06
37-3013	Tree Trimmers and Pruners	AFLOU	0.91	1.03	0.75	0.76	0.76
45-2092	Farmworkers and Laborers, Crop, Nursery, and Greenhouse	AFOLU	0.19	0.23	0.29	0.30	0.31
45-2093	Farmworkers, Farm, Ranch, and Aquacultural Animals	AFLOU	0.30	0.37	0.35	0.37	0.38
45-2099	Agricultural Workers, All Other	AFLOU	0.26	0.30	0.32	0.34	0.35
45-4011	Forest and Conservation Workers	AFOLU	0.30	0.37	0.35	0.37	0.38
47-1011	First-Line Supervisors of Construction Trades and Extraction Workers	Transportation, Buildings	1.21	1.27	1.23	1.22	1.21
47-2031	Carpenters	Industry, Buildings	1.02	0.95	0.99	1.04	1.06
47-2061	Construction Laborers	Buildings	0.89	0.90	1.01	1.02	1.02
47-2071	Paving, Surfacing, and Tamping Equipment Operators	Transportation	2.23	2.08	1.13	1.14	1.15
47-2073	Operating Engineers and Other Construction Equipment Operators	Transportation, Buildings	1.27	1.13	1.20	1.21	1.21
47-2111	Electricians	AFOLU, Transportation, Buildings, Energy	0.90	0.87	0.82	0.82	0.82
47-2131	Insulation Workers, Floor, Ceiling, and Wall	Buildings	0.18	0.24	0.39	0.40	0.40
47-2152	Plumbers, Pipefitters, and Steamfitters	Buildings, Energy	1.18	1.16	1.07	1.02	0.99
47-2181	Roofers	Buildings	0.76	0.71	0.64	0.60	0.58

SOC	Description	Relevant Sectors	2015 LQ	2020 LQ	2025 LQ	2030 LQ	2035 LQ
47-2231	Solar Photovoltaic Installers	AFOLU, Buildings, Energy	1.09	1.07	1.02	1.00	0.99
47-3012	Helpers--Carpenters	Industry, Buildings	0.53	1.02	0.23	0.23	0.23
47-3013	Helpers--Electricians	AFOLU, Transportation, Buildings, Energy	2.40	1.99	1.59	1.60	1.60
47-3015	Helpers--Pipelayers, Plumbers, Pipefitters, and Steamfitters	Buildings, Energy	2.31	2.10	1.84	1.72	1.65
47-4011	Construction and Building Inspectors	Buildings	1.22	1.21	1.39	1.38	1.38
49-2093	Electrical and Electronics Installers and Repairers, Transportation Equipment	Transportation	1.89	1.60	1.70	1.66	1.66
49-2095	Electrical and Electronics Repairers, Powerhouse, Substation, and Relay	Energy	0.77	0.70	1.31	1.29	1.28
49-2096	Electronic Equipment Installers and Repairers, Motor Vehicles	Transportation	0.83	0.87	0.94	0.95	0.94
49-9021	Heating, Air Conditioning, and Refrigeration Mechanics and Installers	Buildings	1.31	1.33	0.85	0.86	0.87
49-9031	Home Appliance Repairers	Buildings	1.43	1.18	1.08	1.06	1.05
49-9051	Electrical Power-Line Installers and Repairers	energy	1.40	1.29	1.36	1.34	1.33
49-9052	Telecommunication Line Installers and Repairers	Buildings	1.84	1.54	1.39	1.20	1.09
49-9081	Wind Turbine Service Technicians	Energy	0.22	0.36	0.25	0.21	0.19
51-2028	Electrical, Electronic, and Electromechanical Assemblers, Except Coil Winders, Tapers, and Finishers	Transportation	2.00	1.66	1.42	1.34	1.28
51-2098	Miscellaneous Assemblers and Fabricators	Industry	1.11	0.99	0.98	0.91	0.87
51-7042	Woodworking Machine Setters, Operators, and Tenders, Except Sawing	Industry	0.67	0.53	0.55	0.56	0.57
51-8011	Nuclear Power Reactor Operators	Energy	0.45	0.44	0.41	0.42	0.43

SOC	Description	Relevant Sectors	2015 LQ	2020 LQ	2025 LQ	2030 LQ	2035 LQ
51-8012	Power Distributors and Dispatchers	Energy	0.15	0.21	0.69	0.81	0.88
51-8013	Power Plant Operators	Buildings, Energy	2.69	1.56	1.45	1.43	1.41
51-8021	Stationary Engineers and Boiler Operators	Energy	0.50	0.52	0.54	0.55	0.56
51-8031	Water and Wastewater Treatment Plant and System Operators	Waste	1.88	0.61	0.71	0.72	0.72
51-8091	Chemical Plant and System Operators	Industry	0.61	0.63	0.62	0.62	0.62
51-9011	Chemical Equipment Operators and Tenders	Industry	0.50	0.74	2.88	2.85	2.82
53-1047	First-Line Supervisors of Transportation and Material Moving Workers, Except Aircraft Cargo Handling Supervisors	Transportation	1.08	1.14	1.17	1.20	1.21
53-3032	Heavy and Tractor-Trailer Truck Drivers	Waste	1.15	1.17	1.16	1.19	1.20
53-3033	Light Truck Drivers	AFLOU	1.18	1.14	1.15	1.19	1.20
53-3052	Bus Drivers, Transit and Intercity	Transportation	0.68	0.71	0.64	0.64	0.63
53-5011	Sailors and Marine Oilers	Transportation	0.55	0.71	0.52	0.51	0.52
53-5021	Captains, Mates, and Pilots of Water Vessels	Transportation	0.64	0.84	0.62	0.62	0.63
53-5031	Ship Engineers	Transportation	0.78	0.78	0.74	0.76	0.77
53-7021	Crane and Tower Operators	Transportation, Buildings	0.17	0.19	0.27	0.29	0.31
53-7041	Hoist and Winch Operators	Transportation	1.18	1.23	1.89	1.92	1.94
53-7062	Laborers and Freight, Stock, and Material Movers, Hand	Transportation	0.94	0.85	0.90	0.92	0.94
53-7081	Refuse and Recyclable Material Collectors	Waste	1.20	0.92	0.58	0.59	0.59

Source: Lightcast

Table C12 shows the wages in the Richmond, MSA in 2025 for each occupation. Wages are shown in percentiles, with the median annual earnings representing the 50th percentile.

Table C12: Wages 2025

SOC	Description	Relevant Sectors	Median Annual Earnings	Pct. 10 Annual Earnings	Pct. 25 Annual Earnings	Pct. 75 Annual Earnings	Pct. 90 Annual Earnings
11-9013	Farmers, Ranchers, and Other Agricultural Managers	AFOLU	\$29,108	\$4,627	\$16,280	\$57,412	\$125,763
13-1041	Compliance Officers	Buildings	\$71,465	\$45,902	\$55,386	\$88,711	\$112,328
17-2051	Civil Engineers	Buildings	\$86,378	\$63,070	\$74,435	\$108,113	\$137,073
17-2071	Electrical Engineers	Buildings	\$108,061	\$77,535	\$89,239	\$133,169	\$160,503
17-2081	Environmental Engineers	Buildings	\$88,482	\$66,524	\$74,747	\$106,203	\$128,124
17-2141	Mechanical Engineers	Buildings	\$93,835	\$64,708	\$79,985	\$109,919	\$132,128
17-2161	Nuclear Engineers	Energy	\$100,171	\$72,941	\$83,871	\$124,376	\$150,592
19-1013	Soil and Plant Scientists	AFOLU	\$63,589	\$45,211	\$52,288	\$73,851	\$98,473
19-1032	Foresters	AFLOU	\$67,380	\$42,095	\$54,810	\$79,957	\$98,661
19-3051	Urban and Regional Planners	Buildings	\$70,286	\$53,690	\$60,272	\$84,344	\$102,091
19-4071	Forest and Conservation Technicians	AFOLU	\$40,420	\$31,119	\$34,118	\$51,839	\$72,804
37-3011	Landscaping and Groundskeeping Workers	AFLOU	\$35,406	\$25,856	\$30,197	\$41,911	\$48,758
37-3013	Tree Trimmers and Pruners	AFLOU	\$43,183	\$27,397	\$36,730	\$51,988	\$69,996
45-2092	Farmworkers and Laborers, Crop, Nursery, and Greenhouse	AFOLU	\$31,049	\$24,962	\$25,842	\$38,017	\$47,149
45-2093	Farmworkers, Farm, Ranch, and Aquacultural Animals	AFLOU	\$28,575	\$22,259	\$25,017	\$40,418	\$57,608
45-2099	Agricultural Workers, All Other	AFLOU	\$32,955	\$24,961	\$27,450	\$40,693	\$56,747

SOC	Description	Relevant Sectors	Median Annual Earnings	Pct. 10 Annual Earnings	Pct. 25 Annual Earnings	Pct. 75 Annual Earnings	Pct. 90 Annual Earnings
45-4011	Forest and Conservation Workers	AFOLU	\$33,474	\$24,961	\$26,572	\$42,755	\$55,362
47-1011	First-Line Supervisors of Construction Trades and Extraction Workers	Transportation, Buildings	\$66,178	\$47,069	\$56,612	\$82,703	\$102,155
47-2031	Carpenters	Industry, Buildings	\$48,514	\$32,145	\$39,068	\$58,531	\$68,331
47-2061	Construction Laborers	Buildings	\$37,667	\$28,279	\$32,699	\$44,881	\$50,483
47-2071	Paving, Surfacing, and Tamping Equipment Operators	Transportation	\$48,725	\$35,914	\$41,196	\$53,321	\$65,715
47-2073	Operating Engineers and Other Construction Equipment Operators	Transportation, Buildings	\$48,915	\$38,110	\$42,532	\$57,762	\$66,373
47-2111	Electricians	AFOLU, Transportation, Buildings, Energy	\$58,140	\$36,614	\$45,276	\$72,567	\$82,348
47-2131	Insulation Workers, Floor, Ceiling, and Wall	Buildings	\$51,768	\$38,187	\$42,964	\$62,310	\$70,135
47-2152	Plumbers, Pipefitters, and Steamfitters	Buildings, Energy	\$57,229	\$37,323	\$45,958	\$66,346	\$75,028
47-2181	Roofers	Buildings	\$47,616	\$28,389	\$41,174	\$59,497	\$65,794
47-2231	Solar Photovoltaic Installers	AFOLU, Buildings, Energy	\$41,617	\$35,189	\$37,627	\$47,474	\$56,541
47-3012	Helpers--Carpenters	Industry, Buildings	\$39,535	\$30,571	\$34,145	\$46,762	\$53,579
47-3013	Helpers--Electricians	AFOLU, Transportation,	\$38,000	\$29,970	\$32,965	\$45,699	\$49,945

SOC	Description	Relevant Sectors	Median Annual Earnings	Pct. 10 Annual Earnings	Pct. 25 Annual Earnings	Pct. 75 Annual Earnings	Pct. 90 Annual Earnings
		Buildings, Energy					
47-3015	Helpers--Pipelayers, Plumbers, Pipefitters, and Steamfitters	Buildings, Energy	\$35,725	\$29,049	\$32,894	\$40,792	\$43,889
47-4011	Construction and Building Inspectors	Buildings	\$66,166	\$45,436	\$54,233	\$80,400	\$110,123
49-2093	Electrical and Electronics Installers and Repairers, Transportation Equipment	Transportation	\$97,300	\$58,929	\$84,445	\$105,657	\$116,632
49-2095	Electrical and Electronics Repairers, Powerhouse, Substation, and Relay	Energy	\$94,117	\$52,791	\$59,404	\$105,513	\$112,202
49-2096	Electronic Equipment Installers and Repairers, Motor Vehicles	Transportation	\$42,390	\$38,524	\$40,993	\$50,625	\$55,580
49-9021	Heating, Air Conditioning, and Refrigeration Mechanics and Installers	Buildings	\$54,197	\$37,960	\$45,884	\$64,024	\$77,909
49-9031	Home Appliance Repairers	Buildings	\$48,423	\$30,416	\$42,511	\$61,116	\$70,720
49-9051	Electrical Power-Line Installers and Repairers	energy	\$79,641	\$50,662	\$63,036	\$98,322	\$110,013
49-9052	Telecommunication Line Installers and Repairers	Buildings	\$67,182	\$45,429	\$51,880	\$91,036	\$94,752
49-9081	Wind Turbine Service Technicians	Energy	\$54,220	\$35,657	\$44,589	\$66,729	\$82,761
51-2028	Electrical, Electronic, and	Transportation	\$41,165	\$32,306	\$36,065	\$46,942	\$53,285

SOC	Description	Relevant Sectors	Median Annual Earnings	Pct. 10 Annual Earnings	Pct. 25 Annual Earnings	Pct. 75 Annual Earnings	Pct. 90 Annual Earnings
	Electromechanical Assemblers, Except Coil Winders, Tapers, and Finishers						
51-2098	Miscellaneous Assemblers and Fabricators	Industry	\$36,624	\$29,321	\$32,634	\$44,109	\$51,899
51-7042	Woodworking Machine Setters, Operators, and Tenders, Except Sawing	Industry	\$34,300	\$28,201	\$29,328	\$38,859	\$47,984
51-8011	Nuclear Power Reactor Operators	Energy	\$120,977	\$94,441	\$106,654	\$137,214	\$156,178
51-8012	Power Distributors and Dispatchers	Energy	\$98,702	\$84,155	\$92,448	\$104,930	\$110,696
51-8013	Power Plant Operators	Buildings, Energy	\$61,165	\$43,753	\$48,606	\$96,311	\$108,812
51-8021	Stationary Engineers and Boiler Operators	Energy	\$52,305	\$36,967	\$41,326	\$64,221	\$75,453
51-8031	Water and Wastewater Treatment Plant and System Operators	Waste	\$52,891	\$38,001	\$42,373	\$65,180	\$71,595
51-8091	Chemical Plant and System Operators	Industry	\$34,689	\$29,958	\$31,941	\$38,538	\$44,855
51-9011	Chemical Equipment Operators and Tenders	Industry	\$49,125	\$41,051	\$44,373	\$57,772	\$75,210
53-1047	First-Line Supervisors of Transportation and Material Moving Workers, Except Aircraft Cargo Handling Supervisors	Transportation	\$59,212	\$41,267	\$47,671	\$73,500	\$85,389

SOC	Description	Relevant Sectors	Median Annual Earnings	Pct. 10 Annual Earnings	Pct. 25 Annual Earnings	Pct. 75 Annual Earnings	Pct. 90 Annual Earnings
53-3032	Heavy and Tractor-Trailer Truck Drivers	Waste	\$50,932	\$35,842	\$44,984	\$60,970	\$77,141
53-3033	Light Truck Drivers	AFLOU	\$41,674	\$25,854	\$31,885	\$51,777	\$80,884
53-3052	Bus Drivers, Transit and Intercity	Transportation	\$56,860	\$39,990	\$44,684	\$59,026	\$59,789
53-5011	Sailors and Marine Oilers	Transportation	\$42,008	\$27,098	\$35,425	\$48,316	\$52,201
53-5021	Captains, Mates, and Pilots of Water Vessels	Transportation	\$72,457	\$38,004	\$51,323	\$89,532	\$116,387
53-5031	Ship Engineers	Transportation	\$70,544	\$41,253	\$50,208	\$107,636	\$142,488
53-7021	Crane and Tower Operators	Transportation, Buildings	\$64,613	\$40,488	\$46,495	\$78,474	\$89,527
53-7041	Hoist and Winch Operators	Transportation	Insf. Data	Insf. Data	Insf. Data	Insf. Data	Insf. Data
53-7062	Laborers and Freight, Stock, and Material Movers, Hand	Transportation	\$41,580	\$30,191	\$35,132	\$47,638	\$52,618
53-7081	Refuse and Recyclable Material Collectors	Waste	\$31,989	\$25,542	\$28,122	\$37,156	\$46,759

Source: Lightcast

Table C13 shows the gap analysis for all occupations for the Richmond MSA.

Table C13: Gap Analysis

SOC Code	Occupation	Relevant Sector	Supply 2025 Hires	Demand Subtotals		Shortage or Surplus		
				Growth (New Jobs) 2025	Projected Separations 2025	Potential Workforce Shortage 2025	Potential Workforce Shortage 2035	Shortage/ Surplus as Percent of Total Employment 2025
11-9013	Farmers, Ranchers, and Other Agricultural Managers	AFOLU	89	8	87	-6	0	0.7%
13-1041	Compliance Officers	Buildings	742	17	688	36	53	1.6%

			Supply	Demand	Subtotals	Shortage or Surplus		
SOC Code	Occupation	Relevant Sector	2025 Hires	Growth (New Jobs) 2025	Projected Separations 2025	Potential Workforce Shortage 2025	Potential Workforce Shortage 2035	Shortage/ Surplus as Percent of Total Employment 2025
17-2051	Civil Engineers	Buildings	870	32	782	56	83	2.4%
17-2071	Electrical Engineers	Buildings	335	11	303	21	33	2.2%
17-2081	Environmental Engineers	Buildings	42	2	38	3	4	2.1%
17-2141	Mechanical Engineers	Buildings	206	16	188	2	14	0.4%
17-2161	Nuclear Engineers	Energy	15	3	15	-2	0	3.5%
19-1013	Soil and Plant Scientists	AFOLU	40	1	37	2	3	2.6%
19-1032	Foresters	AFLOU	22	1	20	2	1	2.5%
19-3051	Urban and Regional Planners	Buildings	70	2	62	6	8	2.3%
19-4071	Forest and Conservation Technicians	AFOLU	21	1	18	2	2	3.5%
37-3011	Landscaping and Groundskeeping Workers	AFLOU	4,004	86	3,861	57	103	1.0%
37-3013	Tree Trimmers and Pruners	AFLOU	165	3	159	3	5	1.4%
45-2092	Farmworkers and Laborers, Crop, Nursery, and Greenhouse	AFOLU	601	11	586	4	9	0.5%
45-2093	Farmworkers, Farm, Ranch, and Aquacultural Animals	AFLOU	188	4	183	2	3	0.7%
45-2099	Agricultural Workers, All Other	AFLOU	97	3	94	0	1	0.1%
45-4011	Forest and Conservation Workers	AFOLU	42	3	36	3	6	3.1%
47-1011	First-Line Supervisors of	Transportation, Buildings	1,743	38	1,715	-10	39	0.2%

			Supply	Demand	Subtotals	Shortage or Surplus		
SOC Code	Occupation	Relevant Sector	2025 Hires	Growth (New Jobs) 2025	Projected Separations 2025	Potential Workforce Shortage 2025	Potential Workforce Shortage 2035	Shortage/ Surplus as Percent of Total Employment 2025
	Construction Trades and Extraction Workers							
47-2031	Carpenters	Industry, Buildings	1,711	20	1,703	-12	18	0.3%
47-2061	Construction Laborers	Buildings	4,031	85	3,978	-32	17	0.5%
47-2071	Paving, Surfacing, and Tamping Equipment Operators	Transportation	129	5	125	0	3	0.2%
47-2073	Operating Engineers and Other Construction Equipment Operators	Transportation, Buildings	1,273	41	1,236	-4	26	0.2%
47-2111	Electricians	AFOLU, Transportation, Buildings, Energy	1,738	8	1,667	64	85	1.7%
47-2131	Insulation Workers, Floor, Ceiling, and Wall	Buildings	42	(0)	41	1	1	1.9%
47-2152	Plumbers, Pipefitters, and Steamfitters	Buildings, Energy	1,141	22	1,101	18	42	0.8%
47-2181	Roofers	Buildings	189	(4)	192	1	3	0.3%
47-2231	Solar Photovoltaic Installers	AFOLU, Buildings, Energy	20	1	19	0	0	0.0%
47-3012	Helpers--Carpenters	Industry, Buildings	337	1	339	-3	-1	1.8%
47-3013	Helpers--Electricians	AFOLU, Transportation, Buildings, Energy	970	(7)	944	33	41	5.8%

SOC Code	Occupation	Relevant Sector	Supply		Demand		Subtotals		Shortage or Surplus	
			2025 Hires	Growth (New Jobs) 2025	Projected Separations 2025	Potential Workforce Shortage 2025	Potential Workforce Shortage 2035	Shortage/ Surplus as Percent of Total Employment 2025		
47-3015	Helpers--Pipelayers, Plumbers, Pipefitters, and Steamfitters	Buildings, Energy	635	3	613	18	22	5.2%		
47-4011	Construction and Building Inspectors	Buildings	327	7	300	20	28	2.3%		
49-2093	Electrical and Electronics Installers and Repairers, Transportation Equipment	Transportation	33	0	31	2	2	3.6%		
49-2095	Electrical and Electronics Repairers, Powerhouse, Substation, and Relay	Energy	46	0	40	6	7	4.3%		
49-2096	Electronic Equipment Installers and Repairers, Motor Vehicles	Transportation	25	0	25	0	1	1.0%		
49-9021	Heating, Air Conditioning, and Refrigeration Mechanics and Installers	Buildings	1,361	34	1,299	28	54	1.0%		
49-9031	Home Appliance Repairers	Buildings	121	(5)	115	10	9	4.2%		
49-9051	Electrical Power-Line Installers and Repairers	energy	210	(3)	198	15	17	2.8%		
49-9052	Telecommunication Line Installers and Repairers	Buildings	185	(28)	190	23	10	3.7%		
49-9081	Wind Turbine Service Technicians	Energy	5	(0)	5	0	0	0.0%		

			Supply	Demand	Subtotals	Shortage or Surplus		
SOC Code	Occupation	Relevant Sector	2025 Hires	Growth (New Jobs) 2025	Projected Separations 2025	Potential Workforce Shortage 2025	Potential Workforce Shortage 2035	Shortage/ Surplus as Percent of Total Employment 2025
51-2028	Electrical, Electronic, and Electromechanical Assemblers, Except Coil Winders, Tapers, and Finishers	Transportation	332	18	284	30	47	4.8%
51-2098	Miscellaneous Assemblers and Fabricators	Industry	2,014	27	2,017	-31	1	1.2%
51-7042	Woodworking Machine Setters, Operators, and Tenders, Except Sawing	Industry	85	2	85	-2	1	1.3%
51-8011	Nuclear Power Reactor Operators	Energy	5	1	5	-1	0	5.9%
51-8012	Power Distributors and Dispatchers	Energy	13	(0)	12	2	2	2.3%
51-8013	Power Plant Operators	Buildings, Energy	14	0	12	2	2	2.1%
51-8021	Stationary Engineers and Boiler Operators	Energy	43	0	40	2	2	1.8%
51-8031	Water and Wastewater Treatment Plant and System Operators	Waste	82	1	77	5	7	1.5%
51-8091	Chemical Plant and System Operators	Industry	59	2	63	-6	-2	2.5%
51-9011	Chemical Equipment Operators and Tenders	Industry	128	4	137	-13	-2	2.7%
53-1047	First-Line Supervisors of	Transportation	1,797	74	1,654	70	124	2.3%

			Supply	Demand	Subtotals	Shortage or Surplus		
SOC Code	Occupation	Relevant Sector	2025 Hires	Growth (New Jobs) 2025	Projected Separations 2025	Potential Workforce Shortage 2025	Potential Workforce Shortage 2035	Shortage/ Surplus as Percent of Total Employment 2025
	Transportation and Material Moving Workers, Except Aircraft Cargo Handling Supervisors							
53-3032	Heavy and Tractor-Trailer Truck Drivers	Waste	8,395	244	8,370	-219	-116	1.9%
53-3033	Light Truck Drivers	AFLOU	5,013	180	4,648	185	265	3.4%
53-3052	Bus Drivers, Transit and Intercity	Transportation	199	7	146	47	54	8.2%
53-5011	Sailors and Marine Oilers	Transportation	45	0	42	4	4	3.7%
53-5021	Captains, Mates, and Pilots of Water Vessels	Transportation	48	1	44	3	3	2.6%
53-5031	Ship Engineers	Transportation	18	(0)	16	2	2	4.2%
53-7021	Crane and Tower Operators	Transportation, Buildings	123	3	116	4	5	3.1%
53-7041	Hoist and Winch Operators	Transportation	0	0	0	0	0	0.0%
53-7062	Laborers and Freight, Stock, and Material Movers, Hand	Transportation	14,253	317	13,300	636	761	5.5%
53-7081	Refuse and Recyclable Material Collectors	Waste	263	5	259	-2	4	0.4%

Source: ICF estimates using data from Lightcast

Top Certifications

Table C14: EV Maintenance

Certification
Electric Vehicle Infrastructure Training Program (EVITP)
EVF Certification
Automotive Service Excellence (ASE) xEV Certification
ASE Certification
ASE Advanced Engine Performance Certification
ASE Medium-Heavy Truck Certification
Automobile Parts Specialist Certification
ASE Auto Maintenance and Light Repair Certification
ASE Automobile Service Consultant

Table C15: Energy Auditor

Certification
CEA
Home Energy Professional (HEP) Energy Auditor
Building Energy Assessment (BEAP) certification
Home Energy Auditor InterNACHI
Certified Industrial Energy Auditor (CEIA)
LEED Accredited Professional (AP)
Certified Energy Manager
Building Energy Modeling Professional Certification
Certified Electrical Safety Compliance Professional
Certified Building Commissioning Professional
Professional Engineer (PE) License
Operator Certification
System Operator Certification

Table C16: Construction Laborer

Certification
10-Hour Occupational Safety and Health Administration (OSHA) General Industry Card
Commercial Driver's License (CDL)
CDL Class A License
30-Hour OSHA General Industry Card
NICET Certification (National Institute for Certification In Engineering Technologies)
OSHA Certification
Flagger Certification
ASNT Non-Destructive Tester
10-Hour OSHA Construction Card
Certified Crane Operator
Tanker And Hazmat Combo X Endorsement
Hazmat Endorsement
Tanker Endorsement
Forklift Certification
CDL Class C License
National Center For Construction Education & Research (NCCER) Core Curriculum
NCCER Construction Craft Laborer

Table C17: Roof Top Solar

Certification
NABCEP PVIP Certification
Photovoltaics Installer/Designer (PV2) certification
PVIP Board Certification
PV Installer Specialist (PVIS) Board Certification
PV Technical Sales (PVTs) Board Certification
NABCEP Solar Installation Company Accreditation
SEI Solar Professionals Certificate Program (SPCP)
OSHA Construction Safety for Solar Installers
30-Hour OSHA General Industry Card
10-Hour OSHA General Industry Card
NCCER Electrical
NCCER Solar Photovoltaics

Table C18: Heat Pump

Certification
EPA Section 608 Technician Certification
North American Technician Excellence (NATE) Certification with Heat Pump Installation Specialty
NATE Certification with Heat Pump Service Specialty
HVAC Excellence Heat Pump Service
HVAC Excellence Heat Pump Installer
HVAC Excellence Employment
Ready Heat Pump Certification
EPA Universal Certification
NCCER Certification
3rd Class Power Engineer Certificate
EPA 608 Technician Certification
10-Hour OSHA General Industry Card
HVAC Certification

Table C19: HVAC

Certification
EPA 608 Technician Certification
EPA 608 Certification
HVAC Excellence Certification
NATE Certification
Refrigeration Service Engineers Society (RSES) Certification
HVAC/R Certification
EPA Universal Certification
HVAC Excellence Professional Level Certification
Master HVAC License
10-Hour OSHA General Industry Card
30-Hour OSHA General Industry Card

Table C20: Farmers

Certification
Pesticide Applicator License
Accredited Farm Manager (AFM)

Table C21: Landscapers

Certification
Landscape Industry Certified (LIC) Programs (NALP)
Landscape Industry Certified Horticultural Technician (LIC-HT)
Landscape Industry Certified Lawn Care Technician (LIC-LCT)
Certified Landscape Irrigation Auditor (CLIA)
Certified Irrigation Technician (CIT)
Certified Landscape Irrigation Water Manager
Certified Arborist (ISA):
Certified Professional Landscape Designer (CPLD)
Certified Horticultural Technician (CHT)
Pesticide Applicator License
CDL
CDL Class B License
Herbicide Applicator License

Table C22: Electricians

Certification
Certified Electrical Safety Compliance Professional (CESCP)
Master Electrician Certificate
Certified Electrical Safety Worker (CESW)
Electrical Project Management Institute (EPMI) Certification
Certified Electrical Safety Technician (CEST)
Journeyman Electrician License
Certified Energy Manager
LEED Green Associate
NCCER Solar Photovoltaics
Apprentice Electrician
Green Energy Certification
NCCER Electrical
NCCER Pipeline Electrical & Instrumentation
NICET Certification (National Institute For Certification In Engineering Technologies)
NICET Electrical Power Testing

Table C23: Electrical Engineers

Certification
Bachelor of Science (BS), Electrical Engineering
Bachelor of Engineering (BEng)
PE License
Certified Energy Manager (CEM)
Certified Automation Professional (CAP)
National Institute for Certification in Engineering Technologies (NICET)
LEED Accredited Professional (AP)
Project Management Professional Certification
Certified Information Systems Security Professional
Institute of Electrical and Electronics Engineers (IEEE)
Engineer in Training (EIT)
Certified Power Quality Professional

Table C24: Heavy Tractor-Trailer Drivers

Certification
CDL
CDL Class A License
CDL Class B License
Tanker Endorsement
Transportation Worker Identification Credential (TWIC) Card
Hazmat Endorsement
Tanker And Hazmat Combo X Endorsement
Forklift Certification
CDL Class C License
Doubles Endorsement
DOT Certification
Triples Endorsement
Hazardous Materials Certification
Certified Crane Operator
Flagger Certification
Pallet Jack Certification

Table C25: Bus Drivers Transit

Qualification
CDL
Passenger Endorsement
CDL Class B License
Cardiopulmonary Resuscitation (CPR) Certification
First Aid Certification
CDL Class A License
Automated External Defibrillator (AED) Certification
CDL Class C License

Educational/Training Programs

Table C26: EV Maintenance

Institution	Type	County	Course/Program
Reynolds Community College	Community College	Henrico County	Hybrid Electric Vehicle Technology Course
Richmond Electrician's JATC	Apprenticeship	Richmond city	Electric Vehicle Charging Systems (EVCS-17)

Table C27: Energy Auditor

Institution	Type	County	Course/Program
Brightpoint Community College	Community College	Chesterfield County	Environmental Control Technologies/Technicians, Other

Table C28: Construction Laborer

Institution	Type	County	Course/Program
Brightpoint Community College	Community College	Chesterfield County	Building Construction Certificate
DAW Construction	Apprenticeship	Chesterfield County	Construction Laborer
Supastrip	Apprenticeship	Chesterfield County	Construction Laborer

Institution	Type	County	Course/Program
Gray't Homes & Improvements, Inc.	Apprenticeship	Hanover County	Construction Laborer
THS Construction	Apprenticeship	Hanover County	Construction Laborer
Allan Myers	Apprenticeship	Henrico County	Construction Laborer
Donley's Concrete Group LLC.	Apprenticeship	Henrico County	Construction Laborer
Commonwealth Power LLC	Apprenticeship	Richmond city	Construction Laborer

Table C29: Roof Top Solar

Institution	Type	County	Course/Program
Commonwealth Power LLC	Private Construction	Richmond city	Solar Installer
Brightpoint Community College	Community College	Chesterfield County	Energy Technology CSC
Bridging the Gap in Virginia	Private	Richmond city	Solar Training
Solar Energy Solutions	Apprenticeship	Henrico County	Solar Training

Table C30: Heat Pump and HVAC

Institution	Type	County	Course/Program
Fortis College-Richmond	Community College	Richmond city	Heating, Air Conditioning, Ventilation and Refrigeration Maintenance Technology/Technician
Brightpoint Community College	Community College	Chesterfield County	Heating, Air Conditioning, Ventilation and Refrigeration Maintenance Technology/Technician
Associated Builders and Contractors	Apprenticeship	Richmond city	HVAC
UA Plumbers and Steamfitters Local 10	Apprenticeship	Richmond city	HVAC
Roxbury Mechanical LLC	Apprenticeship	Charles City County	HVAC Technician
Atlantic Constructors	Apprenticeship	Chesterfield County	HVAC Technician
Chesterfield County Dept. of General Services	Apprenticeship	Chesterfield County	HVAC Technician

Institution	Type	County	Course/Program
Chesterfield County Public Schools Facilities and Maintenance Department	Apprenticeship	Chesterfield County	HVAC Technician
Church & Dwight Co.	Apprenticeship	Chesterfield County	HVAC Technician
Cross Creek Mechanical LLC	Apprenticeship	Chesterfield County	HVAC Technician
Dominion Service Company of Richmond	Apprenticeship	Chesterfield County	HVAC Technician
Foster Plumbing & Heating, Inc	Apprenticeship	Chesterfield County	HVAC Technician
Industrial Turnaround Corp.	Apprenticeship	Chesterfield County	HVAC Technician
Ironbridge Heating and Air	Apprenticeship	Chesterfield County	HVAC Technician
JRC Mechanical, LLC	Apprenticeship	Chesterfield County	HVAC Technician
Colonial Plumbing & Heating	Apprenticeship	Colonial Heights city	HVAC Technician
AeroTech Mechanical	Apprenticeship	Hanover County	HVAC Technician
Bantams Plumbing	Apprenticeship	Hanover County	HVAC Technician
Blazer Heating and Air	Apprenticeship	Hanover County	HVAC Technician
Chadwick Air	Apprenticeship	Hanover County	HVAC Technician
Chamberlain Mechanical Services	Apprenticeship	Hanover County	HVAC Technician
Comfort Systems, Inc.	Apprenticeship	Hanover County	HVAC Technician
Culley Mechanical	Apprenticeship	Hanover County	HVAC Technician
Elite Heating and Air llc.	Apprenticeship	Hanover County	HVAC Technician
Empire Mechanical	Apprenticeship	Hanover County	HVAC Technician
Gilman Heating, Cooling and Plumbing	Apprenticeship	Hanover County	HVAC Technician
Green Air Inc.	Apprenticeship	Hanover County	HVAC Technician
Howell's Heating & Air Conditioning	Apprenticeship	Hanover County	HVAC Technician
Karnes & Stanley Heating & Air LLC.	Apprenticeship	Hanover County	HVAC Technician
Patriot Mechanical	Apprenticeship	Hanover County	HVAC Technician

Institution	Type	County	Course/Program
Pole Green Services, Inc.	Apprenticeship	Hanover County	HVAC Technician
Service Plus	Apprenticeship	Hanover County	HVAC Technician
Temperature Control Mechanical Services	Apprenticeship	Hanover County	HVAC Technician
Air Conditioning Equipment Sales, Inc	Apprenticeship	Henrico County	HVAC Technician
Bell, BCI	Apprenticeship	Henrico County	HVAC Technician
Colonial Webb Contractors	Apprenticeship	Henrico County	HVAC Technician
Daikin Applied	Apprenticeship	Henrico County	HVAC Technician
ETEC Mechanical Corporation	Apprenticeship	Henrico County	HVAC Technician
Hobbs and Associates, Inc.	Apprenticeship	Henrico County	HVAC Technician
M & E Contractors, Inc.	Apprenticeship	Henrico County	HVAC Technician
Mechanical Solutions LLC	Apprenticeship	Henrico County	HVAC Technician
Mid-Atlantic Controls Corporation	Apprenticeship	Henrico County	HVAC Technician
Service Experts Heating and Air Conditioning LLC	Apprenticeship	Henrico County	HVAC Technician
Quality 'Plus' Service, Inc.	Apprenticeship	Petersburg city	HVAC Technician
Cii Engineered Systems, Inc.	Apprenticeship	Richmond city	HVAC Technician
Davis & Green, Inc.	Apprenticeship	Richmond city	HVAC Technician
James River Air Conditioning Co.	Apprenticeship	Richmond city	HVAC Technician
JATC Plumbers and Steamfitters Richmond Virginia - Local 10	Apprenticeship	Richmond city	HVAC Technician
Old Dominion Mechanical	Apprenticeship	Richmond city	HVAC Technician
Virginia Commonwealth University Facilities Management	Apprenticeship	Richmond city	HVAC Technician
Virginia Department of Corrections, Correctional Education	Apprenticeship	Richmond city	HVAC Technician
Virginia Department of General Services	Apprenticeship	Richmond city	HVAC Technician
Woodfin Heating Inc. / EMC Mechanical Services	Apprenticeship	Richmond city	HVAC Technician

Institution	Type	County	Course/Program
Reynolds Community College	Community College	Henrico County	HVAC NCCER Certificate
Henrico County Adult Education	Adult Continuing Education	Henrico County	HVAC Technician
Richmond Adult Technical Center	Adult Continuing Education	Richmond City	HVAC Technician
Chesterfield Adult Education	Adult Continuing Education	Chesterfield County	HVAC
Bridging Communities Regional Career and Technical Center	CTE High School	New Kent County	HVACR
Hanover Center for Trades & Technology	CTE High School	Hanover County	HVACR
Henrico Workforce & Career Development	CTE High School	Henrico County	HVACR
Hopewell High School	CTE High School	Hopewell City	HVAC
Dinwiddie High School	CTE High School	Dinwiddie County	HVAC
Bradley Mechanical	Private	Richmond City	HVAC Technician

Table C31: Farming

Institution	Type	County	Course/Program
Reynolds Community College	Community College	Henrico County	Sustainable Agriculture Certificate
Chesterfield Career and Technical Center	CTE	Chesterfield County	Agriculture
Dinwiddie High School	CTE High School	Dinwiddie County	Agriculture Education

Table C32: Landscaping

Institution	Type	County	Course/Program
Virginia Department of Corrections, Correctional Education	Correctional Education	Richmond city	Landscape Worker
Goochland High School	CTE High School	Goochland County	Landscaping

Table C33: Electricians

Institution	Type	County	Course/Program
Centura College-Richmond Main	CTE	Richmond	Electrician
Brightpoint Community College	Community College	Chesterfield County	Electrician
Associated Builders and Contractors	Apprenticeship	Richmond city	Electrician
Richmond Electrician's JATC	Apprenticeship	Richmond city	Electrician
Central Virginia Electrical Contractors Association	Apprenticeship	Richmond city	Electrician
C & C Electrical Service Inc.	Apprenticeship	Charles City County	Electrician
Design Electrical	Apprenticeship	Charles City County	Electrician
River City Industrial, Inc.	Apprenticeship	Charles City County	Electrician
Atlantic Constructors	Apprenticeship	Chesterfield County	Electrician
Bradley Mechanical Co., LLC	Apprenticeship	Chesterfield County	Electrician
Chesterfield County Dept. of General Services	Apprenticeship	Chesterfield County	Electrician
Commonwealth Electrical Services	Apprenticeship	Chesterfield County	Electrician
Commonwealth Wiring Solutions	Apprenticeship	Chesterfield County	Electrician
DuPont De Nemours & Co., E. I.	Apprenticeship	Chesterfield County	Electrician
Eagle Fire, Inc.	Apprenticeship	Chesterfield County	Electrician
Family Electric	Apprenticeship	Chesterfield County	Electrician
Gill, Douglas L., Inc.	Apprenticeship	Chesterfield County	Electrician
Gypsy Hill Electric	Apprenticeship	Chesterfield County	Electrician

Institution	Type	County	Course/Program
HCE OF VIRGINIA INC.	Apprenticeship	Chesterfield County	Electrician
Humphrey Electric Co., Inc.	Apprenticeship	Chesterfield County	Electrician
Industrial Technical Services Inc.	Apprenticeship	Chesterfield County	Electrician
Industrial Turnaround Corp.	Apprenticeship	Chesterfield County	Electrician
J.L. Minter Inc.	Apprenticeship	Chesterfield County	Electrician
JATC Richmond Electricians, Local 666	Apprenticeship	Chesterfield County	Electrician
Johnson Unlimited	Apprenticeship	Chesterfield County	Electrician
P & M Elec Corp	Apprenticeship	Chesterfield County	Electrician
Patriot Electric	Apprenticeship	Chesterfield County	Electrician
Poe Electrical Services	Apprenticeship	Chesterfield County	Electrician
Pyramid Electrical Contractors	Apprenticeship	Chesterfield County	Electrician
R K Newman Electric Services	Apprenticeship	Chesterfield County	Electrician
Rudy L. Hawkins Electrical	Apprenticeship	Chesterfield County	Electrician
S&S Electrical	Apprenticeship	Chesterfield County	Electrician
S.J. Ryan Electric	Apprenticeship	Chesterfield County	Electrician
The Electrical Connection, Inc.	Apprenticeship	Chesterfield County	Electrician
Trademark Services	Apprenticeship	Chesterfield County	Electrician
J.K. Stell Electrical	Apprenticeship	Colonial Heights city	Electrician
Tyler Electric	Apprenticeship	Colonial Heights city	Electrician
Gerdau	Apprenticeship	Dinwiddie County	Electrician

Institution	Type	County	Course/Program
Livewire Logic	Apprenticeship	Dinwiddie County	Electrician
M. D. McCray Electric Co.	Apprenticeship	Dinwiddie County	Electrician
S & S Electrical Contractors, Inc.	Apprenticeship	Dinwiddie County	Electrician
Wayne Cook Electric, Inc.	Apprenticeship	Dinwiddie County	Electrician
Seacom, Inc	Apprenticeship	Goochland County	Electrician
Abbott & Harris Inc.	Apprenticeship	Hanover County	Electrician
Avis electric co., inc.	Apprenticeship	Hanover County	Electrician
B & B Building Systems, Inc.	Apprenticeship	Hanover County	Electrician
BLS Electrical	Apprenticeship	Hanover County	Electrician
Clemens and Company, LLC	Apprenticeship	Hanover County	Electrician
Commonwealth Electric LLC	Apprenticeship	Hanover County	Electrician
Cornerstone electrical inc.	Apprenticeship	Hanover County	Electrician
Electrical Controls & Maintenance, Inc.	Apprenticeship	Hanover County	Electrician
Electrical Services Unlimited	Apprenticeship	Hanover County	Electrician
Excel Electric	Apprenticeship	Hanover County	Electrician
Express Electric Company	Apprenticeship	Hanover County	Electrician
H&F Electric, LLC	Apprenticeship	Hanover County	Electrician
Haven Electrical	Apprenticeship	Hanover County	Electrician
Hazzard Electrical LLC	Apprenticeship	Hanover County	Electrician
Hill Electrical, Inc	Apprenticeship	Hanover County	Electrician
HO Feild Electric	Apprenticeship	Hanover County	Electrician
Houston Electric LLC	Apprenticeship	Hanover County	Electrician
Integrated Security Technologies	Apprenticeship	Hanover County	Electrician
Keeton Electrical Contractor, M.E.	Apprenticeship	Hanover County	Electrician
MW Butler Electrical LLC	Apprenticeship	Hanover County	Electrician
Peak Electrical Services	Apprenticeship	Hanover County	Electrician
Piedmont Electrical	Apprenticeship	Hanover County	Electrician
Pole Green Services, Inc.	Apprenticeship	Hanover County	Electrician

Institution	Type	County	Course/Program
Schermerhorn Electric Company	Apprenticeship	Hanover County	Electrician
Service Electrical Contractors, Inc.	Apprenticeship	Hanover County	Electrician
SmartWire 360	Apprenticeship	Hanover County	Electrician
SW Mills	Apprenticeship	Hanover County	Electrician
Tolley Electrical Corp.	Apprenticeship	Hanover County	Electrician
TRIBBLE ELECTRIC, INC.	Apprenticeship	Hanover County	Electrician
Turner Electrical Service	Apprenticeship	Hanover County	Electrician
VSC Fire & Security	Apprenticeship	Hanover County	Electrician
ACE Electric Inc	Apprenticeship	Henrico County	Electrician
Air Conditioning Equipment Sales, Inc	Apprenticeship	Henrico County	Electrician
Anything Electrical LLC.	Apprenticeship	Henrico County	Electrician
C & L Electric Company Inc.	Apprenticeship	Henrico County	Electrician
CB Chandler Construction Inc.	Apprenticeship	Henrico County	Electrician
Colonial Webb Contractors	Apprenticeship	Henrico County	Electrician
Craven Electrical Services	Apprenticeship	Henrico County	Electrician
DHC Properties LLC	Apprenticeship	Henrico County	Electrician
Electrical & Lighting Solutions, Inc.	Apprenticeship	Henrico County	Electrician
Freedom Forever Virginia, LLC	Apprenticeship	Henrico County	Electrician
Harris Electric Co. of Virginia, Inc.	Apprenticeship	Henrico County	Electrician
Integrity Contracting & Renovations LLC.	Apprenticeship	Henrico County	Electrician
Kanawha Management	Apprenticeship	Henrico County	Electrician
Local Electric Company, Inc.	Apprenticeship	Henrico County	Electrician
Lucky Dog Electrical Service Inc.	Apprenticeship	Henrico County	Electrician
M & E Contractors, Inc.	Apprenticeship	Henrico County	Electrician
Metro Electric	Apprenticeship	Henrico County	Electrician
Mid-Atlantic Controls Corporation	Apprenticeship	Henrico County	Electrician

Institution	Type	County	Course/Program
Pinnacle Living-Cedarfield	Apprenticeship	Henrico County	Electrician
Shibley Enterprises	Apprenticeship	Henrico County	Electrician
Arroman Industries	Apprenticeship	Hopewell city	Electrician
Electriforce, Inc.	Apprenticeship	King and Queen County	Electrician
Eastern Electric Inc.	Apprenticeship	New Kent County	Electrician
Amsted Rail	Apprenticeship	Petersburg city	Electrician
Quality 'Plus' Service, Inc.	Apprenticeship	Petersburg city	Electrician
C.C. Taylor Electric	Apprenticeship	Powhatan County	Electrician
Diversified Electrical Services Inc	Apprenticeship	Powhatan County	Electrician
R J Wade Electric	Apprenticeship	Powhatan County	Electrician
RMS Services	Apprenticeship	Powhatan County	Electrician
Village Building Company	Apprenticeship	Powhatan County	Electrician
Woodstock Management, Inc.	Apprenticeship	Powhatan County	Electrician
Perdue Foods, LLC	Apprenticeship	Prince George County	Electrician
Beckstoffer & Welsh, Inc.	Apprenticeship	Richmond city	Electrician
Commercial One Electrical Contractors	Apprenticeship	Richmond city	Electrician
Commonwealth Power LLC	Apprenticeship	Richmond city	Electrician
Davis & Green, Inc.	Apprenticeship	Richmond city	Electrician
Heritage Electrical Corp.	Apprenticeship	Richmond city	Electrician
James River Air Conditioning Co.	Apprenticeship	Richmond city	Electrician
Kelleher HVAC	Apprenticeship	Richmond city	Electrician
Lauterbach Electric	Apprenticeship	Richmond city	Electrician
Master Electrical Services LLC	Apprenticeship	Richmond city	Electrician
Nationwide Electric Supply Co.	Apprenticeship	Richmond city	Electrician
Old Dominion Mechanical	Apprenticeship	Richmond city	Electrician
RS Industries	Apprenticeship	Richmond city	Electrician
Schneider Electric USA	Apprenticeship	Richmond city	Electrician

Institution	Type	County	Course/Program
U.S. Electric Co.,Inc.	Apprenticeship	Richmond city	Electrician
Virginia Commonwealth University Facilities Management	Apprenticeship	Richmond city	Electrician
Virginia Department of Corrections, Correctional Education	Apprenticeship	Richmond city	Electrician
Virginia Department of General Services	Apprenticeship	Richmond city	Electrician
Woodfin Heating Inc. / EMC Mechanical Services	Apprenticeship	Richmond city	Electrician
Reynolds Community College	Community College	Henrico County	Electrician NCCER Certificate
Brightpoint Community College	Community College	Chesterfield County	Electricity CSC
Brightpoint Community College	Community College	Chesterfield County	Energy Technology CSC
Henrico County Adult Education	Adult Continuing Education	Henrico County	Electrical Technician
Richmond Adult Technical Center	Adult Continuing Education	Richmond City	Electrician
Chesterfield Adult Education	Adult Continuing Education	Chesterfield County	Electrical Technician
Hanover Center for Trades & Technology	CTE	Hanover County	Electrician
Henrico Workforce & Career Development	CTE	Henrico County	Electrician
Richmond Technical Center	CTE	Richmond City	Electrician
Chesterfield Career and Technical Center	CTE	Chesterfield County	Electrician
Dinwiddie High School	CTE High School	Dinwiddie County	Electrician
Powhatan High School	CTE High School	Powhatan County	Electrician
Sussex Central High School	CTE High School	Sussex County	Electrician

Table C34: Electrical Engineers and Technicians

Institution	Type	County	Course/Program
Virginia Commonwealth University	University	Richmond City	Electrical, Electronics and Communications Engineering
J Sargeant Reynolds Community College	Community College	Henrico County	Electrical, Electronic, and Communications Engineering Technology/Technician
Centura College-Richmond Main	Community College	Richmond City	Electrical, Electronic, and Communications Engineering Technology/Technician
Brightpoint Community College	Community College	Chesterfield County	Electrical, Electronic, and Communications Engineering Technology/Technician

Table C35: Heavy Tractor-Trailer Drivers

Institution	Type	County	Course/Program
Estes Logistics	Apprenticeship	Richmond city	Heavy Truck Driver
Virginia Department of Transportation - Construction Division	Apprenticeship	Richmond city	Heavy Truck Driver
Reynolds Community College	Community College	Henrico County	CDL
Brightpoint Community College	Community College	Chesterfield County	CDL
5 Star CDL Training LLC	Virginia Works	Richmond City	CDL
Road Safety CDL Training School	Virginia Works	Petersburg City	CDL
160 Driving Academy - Midlothian	Virginia Works	Chesterfield County	CDL
CDS Tractor Trailer Training	Virginia Works	Chesterfield County	CDL
TJ and Friends Smith System CDL Training LLC	Virginia Works	Chesterfield County	CDL

Table C36: Bus Drivers Transit

Institution	Type	County	Course/Program
Reynolds Community College	Community College	Henrico County	CDL
Brightpoint Community College	Community College	Chesterfield County	CDL

Appendix D: Data Center Background Information and Guidance

Data centers are buildings containing computer servers, storage, and network equipment that provide online services and support for the digital economy such as social media, video streaming, cloud storage and, increasingly, artificial intelligence (AI) and quantum computing. A data center contains various components, including servers, storage devices, networking equipment, power systems, cooling systems, and physical security measures. Emissions from data centers come from the use of fossil fuels to generate electricity. That electricity is either grid-supplied or generated onsite through backup power, typically from diesel generators. In theory, reducing these emissions is simple: Sourcing carbon-free power for electricity supply would eliminate GHG emissions from data center operations. However, developing such resources at the pace and scale required presents a significant challenge, largely due to their requirement for high-reliability energy supply.

Data centers are the primary (but not sole) driver of rising energy demand in the region⁴⁴. However, they also have brought many clean energy projects online in the Mid-Atlantic and generate significant economic benefits to localities, including tax revenue. The goal of this appendix is to provide information that localities can leverage going forward to capture the economic value from data centers while implementing lessons learned from other regions. Data center owners and operators, such as Amazon, Microsoft, and Google (who collectively own over half of hyperscale data centers⁴⁵) and utilities such as Dominion Energy (the primary electric utility serving the MSA) will be critical partners for successfully reducing the GHG impact of data center development in the region.

Data Center Growth in Virginia

Virginia is the world's leading hub for data centers, driven by favorable incentives and zoning policies, access to land and electric power, an extensive underground and undersea fiber optic network, and proximity to federal agencies. Loudoun County, in northern Virginia, is home to the highest concentration of data centers globally and Virginia is expected to be a lead area for continued data center growth in the coming decades.

In the common vernacular, the term data centers may bring to mind humongous buildings on even larger campuses. But data centers can be as small as an IT closet in an office building or over a million square feet, and every size in between. The different types are described in the box to the right. The electricity demand

⁴⁴ See PJM 2025 Load Forecast: <https://www.pjm.com/-/media/DotCom/library/reports-notice/load-forecast/2025-load-report.pdf>

⁴⁵ Cloud data centers get bigger, denser amid AI building boom: <https://www.utilitydive.com/news/cloud-ai-data-center-aws-microsoft-google-oracle/743290/>

from data centers varies depending on their size and use, as does their opportunities to reduce emissions. The concentration of data centers in Virginia, including the recent development of large hyperscale facilities, has led to significant increases in energy demand.

From 2010-2018, most servers could be found in Internal, Edge, or Enterprise data centers. In 2023, hyperscale and colocation data centers accounted for almost 80% of data server energy use⁴⁶. Hyperscale data centers are built by companies that deploy internet services and platforms at massive scale and can exceed 100,000 square feet. The development of more powerful microchips in recent years has led to higher power demand in a smaller footprint, resulting in some hyperscale facilities using hundreds of megawatts of electricity – enough to power hundreds of thousands of homes.

Hyperscale data centers are experiencing rapid growth. Clusters of colocation and hyperscale type data centers emerge as data centers companies strategically position themselves close to their clients and cloud services users to ensure high availability and low response times. Factors such as proximity to population centers, electricity cost, network infrastructures, and local utility prices influence their location choices. Virginia hosts the highest electricity demand associated with data centers in the U.S., serving as the primary hub for both colocation and hyperscale data centers, followed by California and Texas⁴⁷.

Data center developers and owners/operators are necessary partners for localities where data centers are interested in locating. Many of the region's data centers are already applying best practices to maximize energy efficiency and manage energy demands. To manage costs, many colocation and hyperscale data centers are designed to be as highly efficient as possible, but may not apply for certification programs such as

Data Center Types at a Glance

- **Edge data centers** are smaller facilities that are located closer to end users at the edge of a network to provide low-latency computing. They offer the same services as a traditional data center but have a smaller footprint.
- **Enterprise data centers** are owned or leased by a single organization and used to support that organization's internal IT needs. Enterprise data centers can be a full-capacity data hall built for a specific customer within a colocation data center or an on-premise data center built by an organization. Enterprise facilities are built to suit that organization's needs.
- **Internal data centers** are typically integrated into larger buildings and managed by businesses with their own IT systems.
- **Colocation data centers** provide space, power, cooling, and connectivity for the servers and other hardware of multiple organizations. The organizations that rent space at these facilities are known as tenants. Space in a colocation data center is often leased by the rack, cabinet, cage or room. These facilities are also referred to as multi-tenant data centers.
- **Hyperscale data centers** are usually built by or for one organization to meet the specific technical, operational, and pricing requirements of a hyperscale customer.

⁴⁶ Lawrence Berkeley National Laboratory. (2024). 2024 United States Data Center Energy Usage Report. Retrieved from https://eta-publications.lbl.gov/sites/default/files/2024-12/lbnl-2024-united-states-data-center-energy-usage-report.pdf?utm_source=substack&utm_medium=email

⁴⁷ Lawrence Berkeley National Laboratory. (2024). 2024 United States Data Center Energy Usage Report. Retrieved from https://eta-publications.lbl.gov/sites/default/files/2024-12/lbnl-2024-united-states-data-center-energy-usage-report.pdf?utm_source=substack&utm_medium=email

ENERGY STAR or similar. This is an area where localities can encourage existing and prospective data centers to go a little further.

The following background information is compiled from multiple resources, including:

- Lawrence Berkeley National Lab’s (LBNL) Center of Expertise for Energy Efficiency in Data Centers <https://datacenters.lbl.gov/>
- Graphics from: LBNL [2024 United States Data Center Energy Usage Report](#), December 2024
- “As generative AI asks for more power, data centers seek more reliable, cleaner energy solutions” [Deloitte](#)

Data Center Types

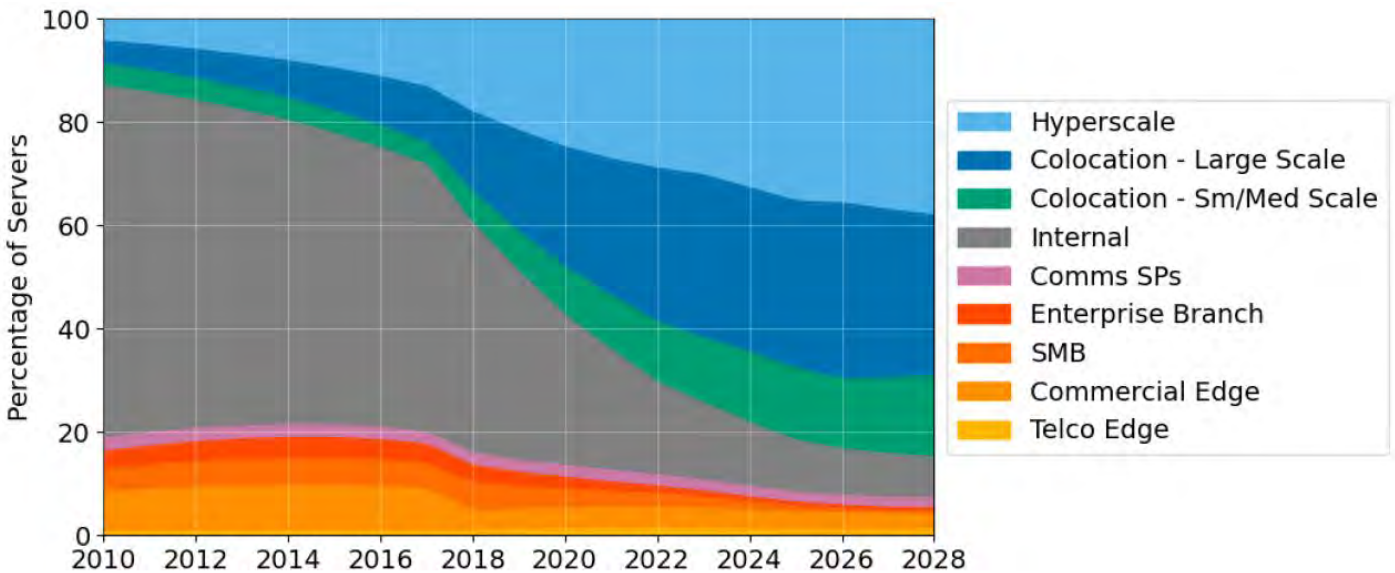
There are multiple ways to categorize data centers, including based on IT equipment, ownership (internal vs service provider), or the facility space type. Different space types can have varying operational characteristics and cooling systems. The LBNL report categorizes them by space type: small, with an average square footage of less than 150; midsize, with an average square footage of 2,700 – 6,900; or large-scale, with average square footages of 11,000 for the colocation space types and 30,000 for hyperscale facilities.

Hyperscale data centers are experiencing rapid growth, with Amazon, Microsoft, and Google collectively owning more than half of them. According to the latest estimates, Virginia hosts the highest electricity demand associated with data centers in the U.S., serving as the primary hub for both colocation and hyperscale data centers, followed by California and Texas. Figure 1 shows the estimated distribution of data centers by type in the U.S.

Large/AI Data Center Power Demand Breakdown

- Servers and IT equipment can drive 40% of power demand
- Cooling systems often drive another 40% of energy demand
- Storage, lighting and other infrastructure: Internal power conditioning systems represent 8-10% of data center’s energy use, while network and communications equipment and storage systems comprise another 10%, and lighting usually takes just 1-2%

Figure D6: Distribution of Servers by Data Center Type



Data Center Power Use

Demand Drivers

The key drivers of data center energy use are servers/IT equipment, and cooling systems. Other infrastructure elements such as storage systems, network devices, lighting, power distribution units, and UPS represent smaller sources for electricity demand.

The energy used for **cooling** can represent a significant portion of a data center's total power consumption, sometimes nearly equaling the power utilized by the computing equipment. These systems are essential to manage the heat generated by the servers and other hardware.

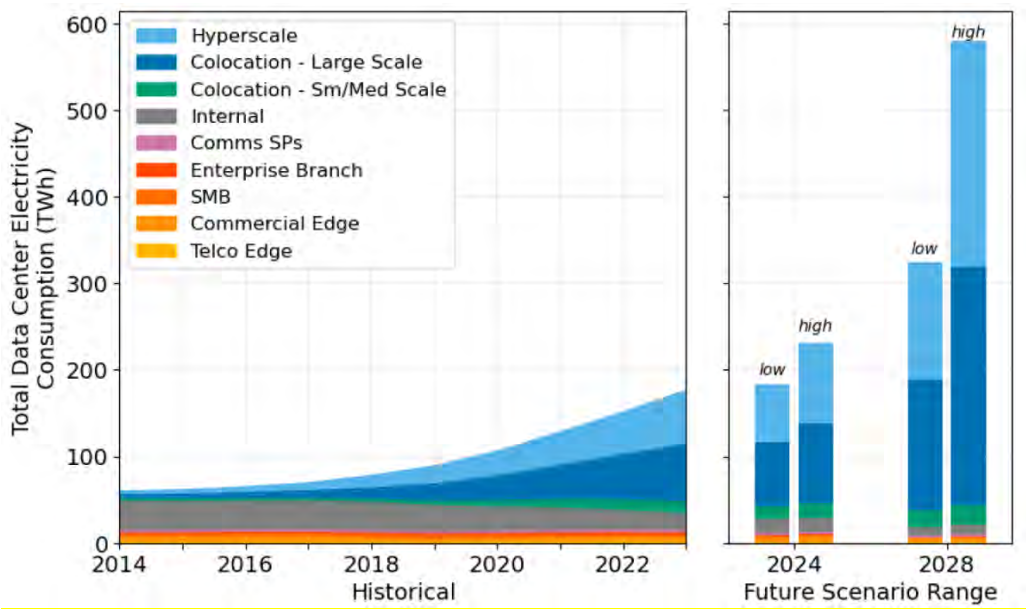
The power consumption of **servers** varies based on their workload, with higher processing power demand leading to increased energy usage. The increasing power density of processing chips results in higher energy demand and heat per square foot compared to other data center designs. AI and hyperscale data centers are experiencing server rack power requirements exceeding 30 kW today, which is expected to continue rising. Rack power is the amount of power used per rack and illustrates the density of computing resources in a data center. Liquid cooling solutions are generally cost-effective or necessary at rack power densities greater than 20-40kW.

Hyperscalers are the most energy intensive data centers, with servers operating on average 50% of the time. When used for AI training, server utilization can reach 80%. Colocation and other small/medium size data centers typically see 15-30% average server operating times. Figure shows the total annual electricity use by data center space type and by component, highlighting the demand from servers/IT equipment. In 2023, hyperscale and colocation data centers accounted for almost 80% of server energy use. The total range of energy use growth for 2024 and 2028 will be highly dependent on the quantity and operation of AI servers.

Reducing the IT power requirements through energy-efficiency improvements cascades through the data center and results in a multiplier effect through savings on infrastructure power: every unit of IT power saved reduces infrastructure power to energize and cool the IT equipment. Many energy efficiency opportunities involving IT equipment such as servers, network, and storage remain untapped. Data center owners and operators can take advantage of not only higher efficiency IT equipment, but also data center management strategies such as utilization, [consolidation](#), and [virtualization](#) to prevent excessive IT energy consumption.

Encouraging data centers to identify savings opportunities through IT equipment upgrades is a relatively straightforward method to help reduce energy demand. LBNL has compiled a comprehensive list of energy efficiency actions data centers can take to improve energy management across IT equipment, cooling & air management, monitoring & controls, environmental conditions, and power (UPS, lighting).

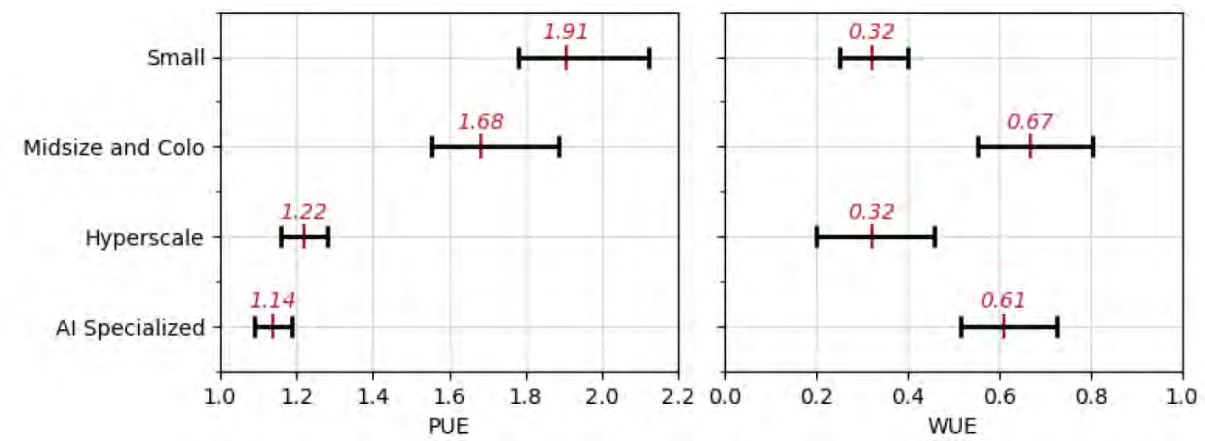
Figure D7: Total Data Center Electricity Use 2014 - 2023, Projected 2024 and 2028 by Space Type and by Equipment Type



Measuring Data Center Efficiency

The range of calculated PUE and Water Usage Effectiveness (WUE) metrics across data center types considering their location and cooling system type is shown in Figure . The average PUE was 1.4⁴⁸ in 2023. The closer the PUE value is to 1.0, the more efficient the data center is in utilizing its power solely for IT equipment, without wasting much on other infrastructures. The LBNL report estimates the average PUE will decline to 1.15 – 1.35 by 2028, driven by the shift to more efficient hyperscale and colocation facilities, combined with the increase in liquid-cooled (efficient) AI servers. However, this shift will also increase the average WUE, growing from 0.36 L/kWh today to 0.45 – 0.48 by 2028.

Figure D8: PUE and WUE by Data Center Type, 2023

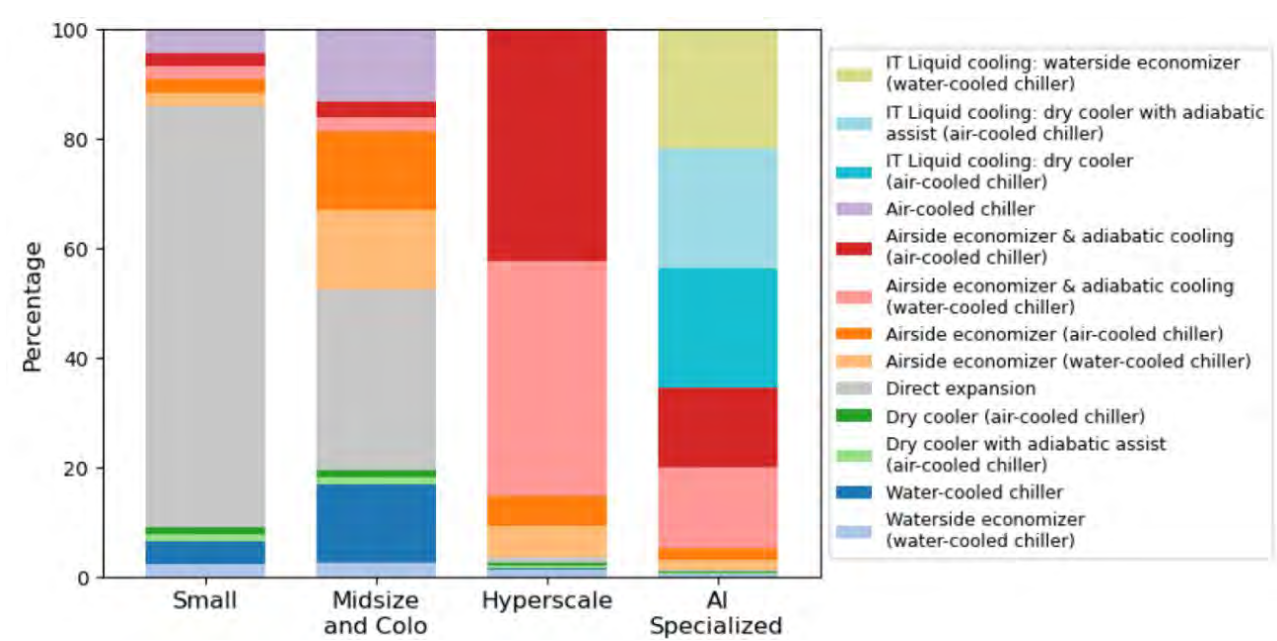


⁴⁸ PUE is calculated as a ratio between total facility energy and the IT equipment energy.

Data Center Cooling Technologies

LBNL estimated the nationwide distribution of cooling systems by data center space type (Figure D9), which illustrates the use of liquid/water cooling technology in medium/large data centers, and almost exclusively for hyperscale and AI data centers. Data centers typically cool computing equipment by blowing cold air over the components using a water-cooled fan coil or by directly cooling the computing equipment with cool water.

Figure D9: Data center cooling systems distributed by space category, 2023



Data Center Cooling & Air Management

Efficient and well-planned air management strategies are crucial for enhancing energy efficiency. Typically, air distribution involves mixing cooled air with air that has been heated by IT equipment. This can pose challenges in directing cool air precisely where it is needed, resulting in an inefficient cooling system. Effective management of cold and hot air streams is essential not only for optimizing the cooling infrastructure but also for maintaining the IT equipment's thermal environment. Improved air management can significantly reduce energy consumption and operational costs, as cooling demands constitute one of the largest energy expenditures in data centers.

Compared to air cooling, liquid cooling delivers up to 40% in energy savings, leading to lower PUE values. For many small and medium-sized data centers, with server loads under approximately 10-15 kW power density per rack, air cooling remains a viable option. However, as power densities increase, air cooling presents certain drawbacks, including elevated cooling costs, risks of performance throttling due to thermal issues, and limited scalability. Although liquid cooling solutions generally incur higher initial costs compared to air-cooled IT equipment within standard racks, these costs may be substantially offset by the enhanced energy efficiency and potential capital savings associated with liquid cooling near the heat source. Liquid cooling also provides opportunities for utilizing waste heat to warm adjacent offices or contribute to district heating systems.

Currently, liquid-cooled rack designs are bespoke and used in standalone data centers. LBNL has identified a goal of a liquid cooled rack specification that could accommodate multiple vendors and provide a reusable infrastructure for multiple refresh cycles with a variety of liquid cooled servers/suppliers. Note: Immersion cooling (submerging IT equipment in non-conducting fluid) is still being explored but typically voids IT hardware warranties at this time.

Data Center Solutioning for Localities

Statewide projections indicate that the data center industry will continue to expand in the coming years. Although publicly available energy reports do not currently isolate data centers as a distinct consumer category, their specific contribution to the region's GHG emissions is expected to be significant given their high energy demand and anticipated growth. Localities within the Richmond MSA vary in their approaches and comfort levels regarding data center development. As localities consider policies and management strategies for this sector, the following information is intended to support informed decision-making and encourage collaboration with data center owners and developers to reduce associated emissions.

GHG Considerations

The following sections list considerations for improving energy efficiency and reducing emissions from onsite back up power for data centers of any size or type. Localities can encourage action by data center developers or owners through the permitting process or requirements related to reporting or meeting efficiency standards. The key drivers of data center energy use are servers/IT equipment and cooling systems.

Consideration 1: IT Equipment Efficiency

- Maximize energy efficiency of IT equipment by adopting procurement policies that ensure ENERGY STAR data center products are used and replace older equipment as it is replaced.
 - ENERGY STAR servers use 30% less energy than regular servers on average when power management is enabled while typically providing better performance per watt, leading to fewer servers being needed.
 - [ENERGY STAR certifications available: computer servers, storage, switches/routers and uninterruptible power supplies](#). Many of these products can also be found on the Electronic Product Environmental Assessment Tool ([EPEAT](#)) [registry](#) which covers additional environmental and sustainability product criteria beyond energy use.
 - Metrics used for these efforts are based in part on efficiency measurements using the Standard Performance Evaluation Corporation's (SPEC) [Server Efficiency Rating Tool \(SERT\)](#) for computer servers and the Storage Networking Industry Association's (SNIA) [Emerald tool](#) for storage products.
 - Sample procurement language can be found [here](#).
- Increase utilization levels in IT hardware when possible. Sometimes, data centers allow servers to run at low capacity or to idle. This is inefficient because those low-capacity servers still require cooling and consume energy.
 - Consolidate workloads onto fewer servers.
 - Use virtualization or cloud management tools to balance loads efficiently.
 - Decommission or power down idle equipment.
 - Increase the percentage of computing power actually being used.
- Educate customers (e.g., data center operators, facilities, IT departments) on best practices for [servers/IT equipment](#). While hyperscale operators will likely already be following best practices, other types, especially smaller or older data centers, operators may not be aware of all their options, or current best practices.
- Data center waste should be recycled to the maximum extent possible. Operators should leverage free IT equipment return and/or recycling programs offered by major IT vendors (HPE, Dell, Oracle, IBM, Cisco, etc.), or contract with reputable e-cycling companies.

Servers and IT equipment on average drive [about 70%](#) of data center power demand, with that share increasing in newer hyperscale and colocation data centers. Encouraging data centers to identify savings opportunities through IT equipment upgrades is a relatively straightforward method to help reduce energy demand.

Reducing the IT power requirements results in a multiplier effect through savings on infrastructure power: every unit of IT power saved reduces infrastructure power to energize and cool the IT equipment. Data center owners and operators can take advantage of not only higher efficiency IT equipment, but also data center management strategies such as utilization, consolidation, and computer server workload virtualization to prevent excessive IT energy consumption.

Consideration 2: Building-level (Mechanical and Electrical)

- Servers require cooling to maximize efficiency and ensure reliability. Data centers are cooled either by air or water circulation. Encourage implementing best practices for [cooling & air management](#), including:
 - Free air cooling through air economizers. Direct free air cooling uses outside air to directly cool equipment. This is very efficient but requires careful air quality and temperature management. Indirect free air cooling uses outside air to cool water or other fluids, which are fed into various forms of heat exchangers in the data center. This requires protecting equipment from outside environmental factors.
 - [In-row](#), overhead, or rear door refrigerant-based heat exchangers are typically more energy efficient than traditional air cooling and can be implemented cost-effectively in traditional enterprise and colocation data center facilities.
 - [Hot aisle/cold aisle arrangements](#) should always be implemented when cooling with any air-based approach. Hot aisle and cold aisle containment separates the hot air released from servers from the cool air used to cool the data center.
- Encourage onsite energy efficiency improvements, including:
 - Raising the chilled water temperature.
 - Evaluating chillers for replacement.
 - Using monitoring systems for real-time management and efficiency (including Data Center Infrastructure Management (DCIM) software) and reviewing operation and efficiency on a regular basis.
- Implement best practices for [power infrastructure](#) and uninterruptible power supplies ([UPS](#)).
 - Data centers that intend to use liquid-cooling could be located at sites with access to recycled wastewater. Using non-potable water for data center cooling processes or using closed-loop cooling systems will limit the impact on local drinking water supplies.⁴⁹

Servers and computer chips generate heat, resulting in significant cooling needs for the building and equipment. Cooling systems often drive 40% of data center energy demand. At the building level, data center cooling systems can be either air-cooled or water-cooled. Evaporative cooling systems use water evaporation to cool air, and while very energy efficient, consume significant amounts of water. Considerations for cooling systems include cost and complexity to implement, load availability, space configurations, future energy needs, and energy efficiency.

Consideration 3: Onsite Energy

- Encourage onsite solar. Smaller data center types may be able to rely on solar as a primary energy source. Onsite solar is unlikely to be able to provide a significant portion of the energy consumed by a very large type of data center. Even if onsite solar does not directly serve the data center itself, it still contributes clean energy generation to the overall grid.
 - Powering a 100 MW hyperscale data center would require nearly 1,500 acres of solar -- roughly 1,100 football fields -- and that power would need to be generated 24/7 (which solar alone cannot provide).
 - However, on-site solar could be included as part of the permitting process to provide community benefits to help meet local goals for clean energy development.

⁴⁹ [What Is Closed-Loop Cooling, and When Should Data Centers Use It? https://www.datacenterknowledge.com/cooling/what-is-closed-loop-cooling-and-when-should-data-centers-use-it-](https://www.datacenterknowledge.com/cooling/what-is-closed-loop-cooling-and-when-should-data-centers-use-it-)

- Encourage options to reduce emissions from backup power and increase efficiency.
 - Replace diesel generators with natural gas generators, which have lower GHG intensity and other air quality benefits.
 - Large battery storage systems to provide on-site backup power are not currently cost-effective at the scale required for hyperscale data centers, but in the future technological advancements could make them more attractive options.
 - Deploying CHP systems can increase the energy efficiency and reliability of data centers by providing a reliable power supply and efficiently utilizing waste heat, either in combination with absorption chillers to provide additional cooling and/or to supplement district heating efforts. They can even be used as a primary energy generation source, turning a utility feed into a backup power option and removing the need for diesel generators and storage.
 - CHP plants can also be paired with fuel cells to realize even greater efficiencies and can use hydrogen blends and/or pure hydrogen in place of natural gas if available. CHP and fuel cells can both play a primary role in microgrid deployments as they can produce constant power which can allow electric grid connections to become secondary or backup electricity options and potentially open grid demand response or load sharing opportunities.
- Collaborate with utilities to encourage participation in demand response programs.
 - Data center load is typically not flexible enough to participate, but they could host grid-scale batteries onsite to provide grid services. Options like on-site CHP plants mentioned above or future development of small modular nuclear reactors may allow for new forms of interactivity between data centers and the electric grid.
- Conduct feasibility studies for district energy.
 - District energy systems carry hot water, steam, and/or water through a network of insulated pipes to provide energy for nearby buildings. Through district energy systems, waste heat from data centers could help provide a base heat resource for nearby buildings and facilities.
 - A district heating system could be considered in planning for new data center campuses, where centralized data center exhaust heat, potentially combined with other local large heat loads to increase the quality of heat, may be able to provide heating resources to local non-data center structures connected to the system, most likely through liquid heat exchangers.

Power Usage Effectiveness (PUE):

A metric used to evaluate the efficiency of energy usage that can be measured by *Total Facility Energy (kWh) / IT Equipment Energy (kWh)*

Water Usage Effectiveness (WUE):

A metric used to evaluate the efficiency of water usage that can be measured by *Total Site Water Usage (liters) / IT Equipment Energy (kWh)*

The closer the PUE value is to 1.0, the more efficient the data center is in utilizing its power solely for IT equipment. WUE value of 0 indicates no water usage. It is important to note that additional IT equipment energy use lowers PUE, so adding more IT capacity in a data center, all else equal, can lower PUE scores while increasing energy use.

Data centers in the PJM region are increasingly sourcing clean energy through **offsite procurement and co-located clean energy development** to meet sustainability goals and reduce GHG emissions. Using this report's activities-based GHG accounting approach, emissions are attributed to the electricity consumed by data centers – making it critical that clean energy is located within the same grid region (like PJM) to impact regional emission factors. Offsite renewables within PJM can reduce grid-average emissions over time, while co-located generation can directly power data centers with clean electricity. PJM, under Federal Energy Regulatory Commission (FERC) oversight, is addressing challenges including a growing interconnection backlog that delays clean energy projects. Solutions being explored include reforming the interconnection process, modernizing transmission planning, and considering nuclear restarts or siting clean energy near high-demand areas. Local governments can participate in PJM stakeholder processes to monitor interconnection issues and support policies that accelerate deployment of clean energy projects needed to meet rising data center demand while reducing regional emissions.

In 2024, Microsoft and Constellation Energy announced a 20-year PPA to re-start Three Mile Island nuclear power plant in Pennsylvania. The PPA will help offset Microsoft's electricity use across its PJM-region data centers. The re-start is pending approvals from the U.S. Nuclear Regulatory Commission and an interconnection agreement from PJM and could provide a model for similar projects.

Consideration 4: Data Tracking and Reporting

- Encourage data center operators to implement metering/monitoring systems to track and report water and energy consumption and benchmark their performance. Key metrics to do so are PUE and WUE, in addition to total consumption of electricity (MWh) and water (gallons).
- Encourage data centers to achieve ENERGY STAR certification and track certifications over time.
- Encourage existing data centers to conduct comprehensive energy assessments to identify key areas of energy use.

Encourage data centers to report the amount of renewable energy directly tied into operations, either through on-site installations or off-site power purchase agreements within the same service territory.

Consideration 5: Engagement and Advocacy

- Implement new policies in localities where applicable:
 - Establish policy guidance and use-specific zoning and permitting standards/ordinances for new data centers and utility substations to address concerns related to grid capacity, land use, compatibility, noise, aesthetics, infrastructure, natural and environmental resources, and to encourage community benefits.
- Require reporting of PUE, where able and set maximum PUE design targets for new data center builds and retrofit/operating targets for existing data centers.
 - Educate locality staff, providing background materials on data centers to support discussion related to planning and zoning changes.

- Coordinate between localities and work with elected officials at the state and federal level on policies and regulations that support decision making, data transparency, and address energy demand concerns. Possibilities may include:
 - Adding select data center items to legislative agendas
 - Supporting bills that improve data reporting and tracking of energy and water use
 - Providing testimony and comments at the SCC proceedings related to impacts on ratepayers data center energy demand
 - Identifying opportunities to participate in PJM or Federal Energy Regulatory Commission (FERC) stakeholder discussions, particularly related to accurate forecasting of data center load and potential ratepayer impacts
 - Supporting local jurisdictions with data driven decision-making (e.g., including data center estimates in future GHG inventories).

Key Implementation Agencies and Partners

Regulating Agencies

- FERC: Regulates electricity and transmission of electricity in interstate commerce, the development of reliability standards and national energy infrastructure, including natural gas pipelines and more.
- Virginia SCC: The regulatory body that acts as a State Public Utility Commission and regulates utility rates.
- State Air Emission Regulators: VDEQ plays a key role in issuing water permits, requiring certifications, and conducting environment impact assessments for data centers, as well as issuing air quality permits for fossil fuel-powered backup generators.

Implementing Agencies

- Federal government agencies: Several federal agencies play a role in developing best practices for and certifying data centers. EPA's ENERGY STAR program certifies data centers that meet high standards for energy efficiency and provides resources on efficient equipment. DOE works with national laboratories, including Lawrence Berkeley National Laboratory and the National Renewable Energy Laboratory, to conduct research on data center energy use and identify solutions and best practices.
- PJM, the regional transmission organization: PJM develops load forecasts for the region and is actively working to adapt to expected data center growth by accelerating interconnection processes, planning for new transmission infrastructure, and addressing the unique challenges posed by co-located data center generation.
- Local government: Localities play an important role in facilitating regional coordination, leading community engagement and outreach, and compiling GHG inventory data. Local planning and zoning departments play a key role in managing and regulating data center development, including updating policies and standards for data center uses.
- Data center developers, owners, and operators: Data center owners and operators make key facility development, operation, and maintenance decisions, and are responsible for ensuring facility reliability and security. This group ultimately decides how their data centers are designed, if they include any of the above efficiency improvements, and what data is collected and/or reported.

- Other partners: Certification programs (e.g., LEED), industry groups (e.g., Data Center Coalition), and others will be key partners to enable the implementation of the measure.
- Electric, water, and gas utilities: Utilities are responsible for supplying the energy and water that data centers use for their operations.

Authority to Implement

Data center owners, operators, and developers have the authority to implement all actions related to data center operations and development. Virginia law does not currently allow local governments to establish Building Energy Performance Standards or related energy tracking policies unless there is a state policy in place. Localities in Virginia could encourage the use of energy efficiency and data tracking by expediting permit approvals for data centers whose designs and commitments meet certain requirements, absent legislative action at the state level requiring reporting on energy usage from data centers. Localities may be able to collect some of this data through permitting processes.

Funding Sources

Example potential funding sources include:

- DOE GRIP Program grants
- DOE Accelerating Speed to Power Funding
- Cooling Operations Optimized for Leaps in Energy, Reliability, and Carbon Hyper efficiency for Information Processing Systems (COOLERCHIPS) Funding

Sample Metrics for Tracking Progress

Localities interested in tracking metrics on data center sustainability efforts can consider the following. Some of these metrics require cooperation from data centers to provide the data, unless and until state regulations require their disclosure.

- PUE
- Water Use Efficiency (WUE)
- Percent of data centers using free air cooling when applicable
- Percent of data center electricity demand offset by clean energy procurements
- Capacity (kW) of onsite solar hosted by data centers
- Number of data centers achieving various energy efficiency certifications (e.g., ENERGY STAR)
- Electricity GHG emission estimates for data centers as a separate consumer class, inclusive of any registered carbon offsets. This data could be incorporated into local and regional greenhouse gas inventories in the future.

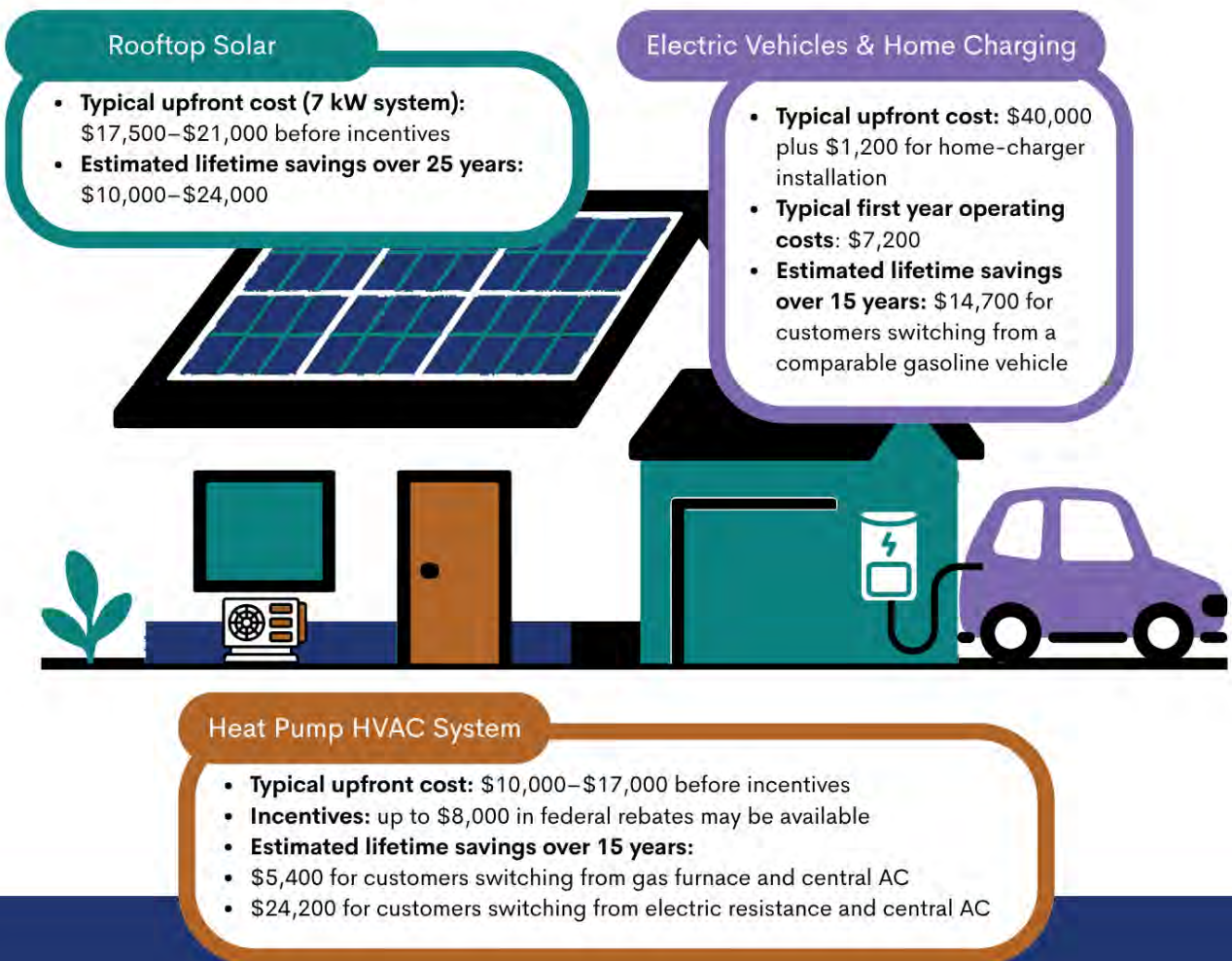
Appendix E: Consumer Costs for Home Upgrades and EVs in Virginia

CONSUMER COSTS

for Home Upgrades & EVs in Virginia

Installing rooftop solar, efficient electric home heating and cooling systems, and switching to an electric vehicle are key actions residents and businesses can implement from the plan that would help significantly reduce emissions across the state. These actions also support lower energy bills, can provide energy resilience and independence, and improve indoor and outdoor air quality. Rooftop solar, heat pumps, and EVs are increasingly cost-competitive and can provide meaningful long-term savings, particularly when paired with available federal, state, and utility incentives.

The graphic below presents typical costs and savings from these upgrades to help residents make informed decisions. Actual costs and savings will vary based on a range of factors, including equipment type, household energy use, energy bill rates, home characteristics, driving patterns, and incentive eligibility.



Example Actions for Community Members

Rooftop Solar

- For a typical single-family home in Virginia, installing a 7 kW rooftop solar system costs between \$17,500–\$21,000 before incentives. While this estimate assumes no federal tax credit, some homeowners may qualify for local government or utility programs that can help reduce upfront costs.
- Once installed, rooftop solar can significantly reduce monthly electricity bills. A 7 kW system can generate most or all of a typical home's annual electricity needs, depending on household energy use, roof orientation, and shading. Many Virginia households experience a simple payback period of approximately 10–15 years, with continued energy bill savings over the remaining life of the system.
- Over a 25-year system lifetime, total savings from reduced electricity costs can range from \$10,000–\$24,000, depending on system performance, retail electricity rates, and household usage. Actual costs and savings will vary based on roof conditions, system size, equipment selected, electricity use, and available incentives, but rooftop solar remains a strong long-term investment for many Virginia households.

Heat Pump HVAC

- For a typical single-family home in Virginia, installing a standard ducted air-source heat pump costs between \$10,000–\$17,000. Once the federal Home Energy Rebate Program (HEAR) becomes available, eligible households can receive up to \$8,000 in rebates to help offset upfront costs. Additional incentives may also be available through local governments and utility programs. Virginia residents can visit energy.virginia.gov for more information on available resources and incentives.
- Heat pumps are significantly more efficient than gas furnaces and electric-resistance heating and can reduce heating and cooling bills over time. In Virginia, households switching from electric-resistance heat with central air conditioning (AC) are expected to save around \$1,200 per year on heating and cooling costs. Even without incentives, these bill savings help offset installation expenses, with a typical payback period of 5–10 years for households transitioning from electric-resistance systems.
- Over a 15-year system life, the total cost of purchasing and operating a heat pump is estimated at \$19,500–\$25,500. With an \$8,000 HEAR incentive, households switching to heat pumps can achieve substantial lifetime savings — up to \$5,400 for gas-heated homes and \$24,200 for homes using electric-resistance heating.
- Actual installation costs will vary depending on the type of equipment installed, the condition of the home and existing ductwork, and whether electrical upgrades are needed. Energy costs and savings will also depend on energy use patterns, and utility rates.

EV & Charger

- Over a 15-year vehicle life and 180,000 miles, the total lifetime cost of owning and operating an EV is estimated at \$70,000 (including purchase, home charger, fuel, and maintenance), compared with roughly \$84,700 for a comparable gasoline vehicle. On average, households that switch to an EV can save around \$14,700 over the vehicle's lifetime, with higher savings for drivers with greater annual mileage or access to low-cost home charging.
- A new passenger EV generally costs about \$40,000, with an additional \$1,200 for home-charger equipment and installation. By comparison, a similar gasoline vehicle typically costs around \$23,500. While the upfront cost of an EV may be higher, EVs generally have substantially lower fuel and maintenance costs. Based on current Virginia gasoline and electricity prices, EV charging costs average \$0.04 per mile, compared with

\$0.15 per mile for gasoline vehicles (assuming \$3.00/gallon and 21 mpg). These savings help offset the higher upfront price, with a typical payback period of approximately 5–10 years, depending on annual mileage, electricity rates, charging access, and available incentives.

Data Sources and Assumptions

Rooftop Solar

- Residential rooftop solar system sized at 7 kW
- Installed cost between \$2.5-\$3 per watt
- No tax credits or incentives applied
- 25-year system lifetime
- 15%-20% capacity factor
- Average 2024 residential electricity price in Virginia (EIA); growth rates based on trends from AEO 2025

Heat Pump HVAC

Upfront Costs

- Heat pump upfront costs (NESCAUM): \$10,361-\$14,070
- Gas furnace upfront cost (NESCAUM/RMI): \$3,300-\$6,400
- Electric resistance furnace upfront cost (RMI): \$4,600
- Central AC upfront cost (NESCAUM/RMI): \$3,300-\$6,000

Operating Costs

- Average 2024 residential electricity price in Virginia (EIA); growth rates based on trends from AEO 2025
- Average 2024 residential natural gas price in Virginia (EIA); growth rates based on trends from AEO 2025

EV and Charging

Vehicle and Charger Characteristics

- New BEV purchase price: \$40,000
- Comparable gasoline vehicle purchase price: \$23,500
- Vehicle lifespan: 15 years
- Annual mileage: 12,000 miles
- Total lifetime mileage: 180,000 miles
- Level 2 home charger equipment + installation: \$1,200

Fuel/Energy Use

- Electricity cost: EV charging assumed at \$0.13/kWh (consistent with recent Virginia residential retail rates)
- EV efficiency: 0.3 kWh per mile (~3.3 mi/kWh)
- EV fuel cost: \$0.04 per mile
- Gasoline price: \$3.00 per gallon
- Gasoline vehicle fuel economy: 21 miles per gallon
- Gasoline fuel cost: \$0.15 per mile

Maintenance Costs

- EV maintenance cost: \$0.12 per mile
- Gasoline vehicle maintenance cost: \$0.19 per mile