NOACA

Northeast Ohio Areawide Coordinating Agency

CITY OF CLEVELAND
Mayor Justin M. Bibb

MAYOR'S OFFICE OF SUSTAINABILITY

CLEVELAND-ELYRIA METROPOLITAN STATISTICAL AREA COMPREHENSIVE CLIMATE ACTION PLAN

TECHNICAL APPENDIX

NOVEMBER 2025

PREPARED FOR:
Climate Pollution Reduction Grant Program
U.S. Environmental Protection Agency

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1. Appendix A - Wedge Analysis

Explanation of Tabs

- Wedge: This tab contains the wedge graph, visually depicting incremental emission reductions over the timeline analyzed.
- Table: This tab provides a structured summary of emission reduction data organized by sector, year, and implementation scenario, enabling clear comparison against the BAU scenario.
- Values: This tab exclusively houses numeric values for simplicity in presentation and ease of calculation. It forms the basis for the "Table" tab but is not a direct replication of the "Measures" tab. Notably, in cases where emission reduction potentials are set to zero, this decision reflects an intentional suppression of measures whose combined effect would otherwise exceed projected emissions for the relevant year. Measures demonstrating relatively minor reduction potentials have thus been reduced to zero, while those with significant potential have been retained to ensure total reductions do not surpass BAU scenario emissions.
- Values Reorganized: This tab presents a restructured version of the original Values tab, with emission reduction measures categorized to support the construction of the wedge diagram.
- Measures: This tab originates from the "Current Measures" sheet within the **GHG Reduction Measures spreadsheet**[1]. It includes specific emission reduction measures, their associated emission categories, and anticipated GHG emission reductions for target years 2030 and 2050. Calculations to estimate emissions reductions are primarily conducted here, except where previously determined calculations from the "Calculations" tab or other referenced documentation are utilized. Detailed calculation methodologies are discussed in subsequent sections.
- 2022Inventory: This tab contains baseline data drawn directly from the **Cleveland-Elyria MSA BAU (Business-As-Usual) Scenario file**[2], serving as the foundational reference scenario for the analysis.

Methodological Assumptions

A key methodological assumption underlying this analysis is that reductions in GHG emissions will occur linearly across two distinct stages: the first stage from the current year (2026) to 2030, and the second stage from 2031 to 2050. Under this approach, annual emission reductions within each stage are uniformly distributed. Emission reduction calculations follow this general formula:

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[1] GHG Reduction Measures, GHG Reduction Measures

[2] Updated Cleveland-Elyria MSA BAU Scenario (1), Updated Cleveland-Elyria MSA BAU Scenario (1).xlsx

Annual Emission Reduction = Baseline Emission * (Progress within Stage (year) / Total Years in Stage * Reduction Percentage or Specified Numeric Target

Examples

- Percentage-Based Reduction: For the measure "Community enrollment in renewable energy CCA," the projected reduction for 2030 is stated as "100% of residential electricity emissions" To compute the emission reduction for the year 2026 (the first year in a five-year stage), the calculation is as follows:

2775682 (2022 Residential Electricity Emissions) * 1/5 (First year fraction) * 100% = 555136

- Numeric-Target Reduction: For the measure "BEV/FCEV adoption of light-duty vehicles," where reductions are provided as absolute numeric targets rather than percentages, the 2026 calculation is:

  494123 (Projected Emission Reduction in 2030) * 1/5 (First year fraction) = 98825

List of Measures Using Similar Approach

The following measures utilize the same stage-based calculation methodology described above:

- 3 C1-1 Community enrollment in renewable energy CCA
- 3 C2-1 Intelligent grid management systems (R)
- 3 C2-2 Grid-scale power systems modernization (R)
- 3 C3-1 Convert lighting to energy efficient light-emitting diode (LED) light bulbs (R)
- 3 C1-3 Physical PPA (Commercial)
- 3 C2-1 Intelligent grid management systems (C)
- 3 C2-2 Grid-scale power systems modernization (C)
- 3 C3-1 Convert lighting to energy efficient light-emitting diode (LED) light bulbs (C)
- 3 C1-3 Physical PPA (Industrial)
- 5 C1-4 Energy Efficient Equipment
- 5 C1-1 Energy audits
- 3 C2-1 intelligent grid management systems (I)
- 3 C2-2 Grid-scale power systems modernization (I)
- 3 C3-1 Convert lighting to energy efficient light-emitting diode (LED) light bulbs (I)
- 5 C3-3 Electrify machine drives in synergy with grid decarbonization (Electricity)
- 5 C2-2 Use lower GWP gases for anesthetics (Electricity)
- 5 C1-2 Waste heat recovery and utilization systems (Electricity)
- 5 C1-5 Automation (Electricity)
- 5 C3-1 Electrification of industrial process heat in synergy with grid development
- 5 C3-3 Electrify machine drives in synergy with grid decarbonization (Non Electricity)
- 5 C2-2 Use lower GWP gases for anesthetics (Non Electricity)
- 5 C1-2 Waste heat recovery and utilization systems (Non Electricity)
- 5 C1-5 Automation (Non Electricity)

- 5 C3-2 Replace BF-BOF system at Cleveland Works with a green steel alternative
- 5 C4-1 Carbon capture at Cleveland Works w/ geologic sequestration
- 6 C1-8 Advance the use of sustainable aviation fuel at regional airports
- 6 C1-9 Advance the use of sustainable liquid and gaseous fuels at regional maritime ports
- 6 C1-1/5/6 Expand BEV charging and FCEV fueling infrastructure
- 6 C1-2/7 BEV adoption in government fleets
- 6 C1-3 BEV adoption of light-duty passenger vehicles by households
- Added BEV/FCEV adoption of medium and heavy-duty vehicles by fleets
- 6 C2-2 Expand networks of protected bike lanes, off-street trails, and lane conversions
- 6 C2-3 Increase density and mix of uses around transit stations and BRT stops
- 5 C3-2 Replace BF-BOF system at Cleveland Works with a green steel alternative
- 5 C4-1 Carbon capture at Cleveland Works w/ geologic sequestration
- 5 C4-2 Cement making carbon capture
- 7 C1-1 Install gas capture systems for landfill gas
- 7 C1-2 Restaurant and grocery food waste reduction/composting program
- 7 C1-3 Add compost bins to public facilities, parks, and sports stadiums to divert organic waste from land fills
- 7 C1-4 Support composting and food waste reduction with organic waste diversion from landfills
- 7 C2-1 Post incineration scrubbers installed at wastewater treatment facilities with fluidized bed incinerators
- 7 C3-1 use climate friendly refrigerants
- 7 C3-2 End of equipment life facilities, dropoff/collection programs to ensure proper containment of refrigerants
- 8 C1-2 Expand Wetland Restoration Programs
- 8 C2-1 Reforest agriculture lands no longer in use

Methodology for Addressing Redundancy

As previously demonstrated, some measures are represented by multiple entries within this analysis. This redundancy is intentional, as certain measures have cross-sectoral impacts, spanning the residential, commercial, and industrial domains. For instance, Intelligent Grid Management Systems are projected to reduce electricity-related emissions by 2% by 2030, an effect that is realized across all three sectors.

To prevent both double counting and overestimation, these measures are evaluated independently within each sector. Emissions data are further disaggregated into electricity-related and non-electricity-related categories. Accordingly, annotations are provided after each measure to denote the relevant sector(s), Residential (R), Commercial (C), and Industrial (I), as well as the distinction between Electricity and Non-Electricity emissions.

The following is a list of these cross-sectoral measures, along with their corresponding sectoral and emission-type annotations.

- 3 C2-1 Intelligent grid management systems (R)
- 3 C2-2 Grid-scale power systems modernization (R)
- 3 C3-1 Convert lighting to energy efficient light-emitting diode (LED) light bulbs (R)
- 3 C1-3 Physical PPA (C)
- 3 C2-1 Intelligent grid management systems (C)
- 3 C2-2 Grid-scale power systems modernization (C)
- 3 C3-1 Convert lighting to energy efficient light-emitting diode (LED) light bulbs (C)
- 3 C1-3 Physical PPA (I)
- 3 C2-1 Intelligent grid management systems (I)
- 3 C2-2 Grid-scale power systems modernization (I)
- 3 C3-1 Convert lighting to energy efficient light-emitting diode (LED) light bulbs (I)
- 5 C3-3 Electrify machine drives in synergy with grid decarbonization (Electricity)
- 5 C2-2 Use lower GWP gases for anesthetics (Electricity)
- 5 C1-2 Waste heat recovery and utilization systems (Electricity)
- 5 C1-5 Automation (Electricity)
- 5 C3-3 Electrify machine drives in synergy with grid decarbonization (Non Electricity)
- 5 C2-2 Use lower GWP gases for anesthetics (Non Electricity)
- 5 C1-2 Waste heat recovery and utilization systems (Non Electricity)
- 5 C1-5 Automation (Non Electricity)

Measures with Distinctive Methodologies

- 3 C4-9 District thermal energy system, 3 C4-1 Utility-scaled solar (in-region), 3 C4-9 Geothermal electricity generation, and 3 C4-10 Offshore wind: One-third of the reduction potential attributed to these measures has been allocated to the residential sector to address non-electric emissions. The remaining reduction potential is assigned to non-electric emissions in the commercial sector.
- 5 C3-2 Replace BF-BOF system at Cleveland Works with a green steel alternative & 5 C4-1 Carbon capture at Cleveland Works w/ geologic sequestration: Cleveland Cliffs operates independently from the broader industrial sector; thus, its emission reduction measures are not shared with other industrial sources. Consequently, the reductions for the remainder of the industrial sector are calculated as the difference between the overall sectoral emissions and those attributable to Cleveland Cliffs. The projection for Cleveland Cliffs is a 90% reduction in stationary combustion emissions by 2040, followed by the adoption of green steel technologies to achieve net zero. Remaining emissions, categorized as process and fugitive, are assumed to follow a similar reduction trajectory. Carmeuse Lime, another significant source of process and fugitive emissions, follows the same methodological approach, but its implementation timeline extends from 2031 to 2050, as opposed to the two distinct periods of 2026–2030 and 2031–2050.
- 7 C1-2 Restaurant and grocery food waste reduction/composting program, 7 C1-3 Add compost bins to public facilities, parks, and sports stadiums to divert organic waste from landfills, and 7 C1-4 Support composting and food waste reduction with organic waste

diversion from landfills: The projected emissions reductions from these combined waste management measures are represented by a single numerical value and are modeled using a linear assumption. As such, annual reductions form an arithmetic progression throughout the projection period.

- 7 C3-1 use climate friendly refrigerants & 7 C3-2 end of equipment life facilities, dropoff/collection programs to ensure proper containment of refrigerants: Both measures target emission reductions in the HFC sector and are highly overlapping in scope. Therefore, only the maximum reduction potential of either measure is considered in projection calculations to avoid double counting.
- 5 C4-3 Regional Direct Air Capture, 8 C1-1 Habitat Restoration, 8 C3-1 Tree carbon-capture, 8 C3-3 Expand agriculture practices, and 8 C3-5 Land bank set-asides for carbon storage: These carbon sequestration measures each have a fixed annual reduction value, which remains constant throughout the implementation stages.

Directly Sourced Data

In certain cases, the figures presented are directly sourced from existing calculations. The table below details each measure along with its corresponding source, cited after each entry.

3 C4-3	Residential rooftop solar	Calculations tab under GHG Reduction Measures1[3]
4 C1-1	Increasing Retrofit Envelope Efficiency	4 C1-1 Retrofit_Annualized tab under GHG Reduction Measures_Comm+Resid4[4]
4 C1-2	Building System Electrification (Deep Retrofit)	4 C1-2 Electrification Annualized tab under GHG Reduction Measures_Comm+Resid
4 C2-1	Implement the latest state adopted building standards & codes (R)	4 C2-1 Code Implementation tab under GHG Reduction Measures_Comm+Resid
4 C4-2	Grid-Coordinated Demand Response & Load Shaping (R)	4 C4-2 Active Energy Adjustment for Grid Support (Demand Response) under GHG Reduction Measures_Comm+Resid
3 C4-9	District thermal energy system	Calculations tab under GHG Reduction Measures
3 C4-4	Commercial-scale rooftop & parking lot solar	Calculations tab under GHG Reduction Measures
3 C4-1	Utility-scaled solar (in-region)	Calculations tab under GHG Reduction Measures
3 C2-3	Community-serving microgrid and minigrid systems	Calculations tab under GHG Reduction Measures

[3] GHG Reduction Measures,GHG Reduction Measures
[4] GHG Reduction Measures_Comm+Resid, GHG Reduction Measures_Comm+Resid.xlsx

3 C2-4	District or utility-scale battery storage - short duration (<4 hrs)	Calculations tab under GHG Reduction Measures
3 C4-6	District or utility-scale battery storage - Long duration (>10 hrs)	Calculations tab under GHG Reduction Measures
3 C4-9	Geothermal electricity generation	Calculations tab under GHG Reduction Measures
3 C4-10	Offshore wind	Calculations tab under GHG Reduction Measures
3 C4-8	New Nuclear at Perry	Calculations tab under GHG Reduction Measures

2. Appendix A – Clean Electricity

Residential Rooftop Solar Recommendations:

Starting with the Greenlink report from 2021, which had suggested an adoption rate of 52 kw/yr for the city of Cleveland for rooftop residential solar, and considering this resource, Standard Solar Panel Sizes And Wattages (100W-500W Dimensions), we've arrived at some estimates for rooftop solar.

If one estimates 17.25 watts per square foot, and a house with 200 sq ft of available roof space, you come up with 3.45kw installed. One would need only ~15 houses a year of rooftop solar added to meet the Greenlink ACES scenario for the City of Cleveland. (Greenlink report is specific to the City of Cleveland).

This page is also useful to come up with daily / monthly and annual calculations, How Much Power Does A 5kW Solar System Produce Per Day, Month, Year? In addition to PVWatts site.

The 52kw number is puzzling - unless for a low adoption scenario. In reading further in the Greenlink report, in the MCE (most cost effective) scenario (page 37) 65% of residential solar potential is met - that seems higher than 52kw/yr.

An important challenge with the scenarios in the Greenlink report is that they did not **have** to reach net zero by 2050.

Therefore 2 scenarios are proposed, given different community typologies:

- 50kw installed / per year / per 1000 stand-alone houses (or 14 houses per 1000 per year). That implies that after 25 years, ~350 homes have installed solar, covering ~1/3 of their annual electricity needs (more with a battery and a home energy management system), out of each 1000 stand-alone homes. (Established cities, legacy cities, 1st ring suburbs)
- 100kw installed / per year / per 1000 stand-alone houses (or 28 houses per 1000). That implies that after 25 years, ~700 homes have installed solar out of each 1000 stand-alone homes. (outer ring suburban/ rural).

With single-family residence counts as follows:

- Cuyahoga County: 414,806
- Geauga County 43,444
- Lake County 77,532
- Lorain County 114,052
- Medina County 72,227
- Non-Cuyahoga County total: 307,255 - **using this as a proxy** for outer ring suburban and rural

- MSA total: 722,061

Please see the calculations sheet on the GHG Reduction Measures table.

Based on this approach, 14,392 houses per year would add a simple rooftop solar array, or nearly 58 houses a day per workday for the year! Nearly 50 MW (49.6) of generation would be installed each year.

For a point of comparison, California lists 1,561,807 residential solar projects[5]. With nearly all of those built in 2008 and later, the average of over 86,767 residences adding solar a year speaks to the size of the industry. Of course, capacity to install solar power has grown and scaled; California was already adding over 50MW of installed residential capacity per year in 2009 but added 1.9 GW of rooftop solar in 2023.

Commercial Rooftop / Parking Solar Recommendations:

If one continues to use 17.25 watts per square foot of solar panel, and a building with 1000 sq ft of available roof space, you come up with 17.25kw installed. So, it would only take ~8 buildings/schools a year of rooftop solar added to meet 150kw of solar installed, as estimated by Greenlink. This page is also useful to come up with daily / monthly and annual calculations.

A proposed scenario of: 150kw installed / per year / per 300 stand-alone commercial / businesses/ schools / mercantile establishments. That implies that after 25 years, ~200 out of the 300 buildings have installed solar.

Using the "Commercial + Education" Building Occupancy classification, we have counts as follows:

- Cuyahoga County: 17,053
- Geauga County 2,138
- Lake County 4,536
- Lorain County 8,470
- Medina County 4,216
- MSA total: 36,413

Based on the counts above, and assuming that commercial properties are more alike from one community to the next than residential units, 8 buildings adding solar per year per 300 buildings translates to 970 buildings per year, with approximately 16.7 MW of solar added each year.

A key challenge facing the energy sector is **how to deal with peak loads**. Per the NERC 2024 Long-Term Reliability Assessment, peak summer periods generally only last for a few hours; however, winter peak loads can persist for 48 hours or longer. The extended duration or winter

[5] https://www.californiadgstats.ca.gov/charts/

peak events “has significant implications for the reliability contribution of energy-limited and non-dispatchable resources.” (NERC, 2024, P 17)

Additionally, NERC notes that for the PJM area, “on-peak reserve margins fall below the Reference Margin Levels (RML) (the levels required by jurisdictional resource adequacy requirements) beginning in 2034. (NERC 2024, P 8)

Long Duration Energy Storage Systems:

With few long-duration energy storage systems (over 10 hours storage) in place, there is a dearth of information as to the emissions reduction potential of such systems. The following 4 articles suggest a framework within which we might estimate such reductions. Collectively, they note that emissions reductions are greatest when paired with abundant renewable energy, when charged and discharged through optimized control management systems by a district or utility-scale operator, and at peak demand when replacing electricity that would otherwise come from the most polluting generation sources.

1. Benchmarking and contribution analysis of carbon emission reduction for renewable power systems considering multi-factor coupling - ScienceDirect
2. Quantifying the carbon footprint of energy storage applications with an energy system simulation framework — Energy System Network - ScienceDirect
3. The carbon footprint of island grids with lithium-ion battery systems: An analysis based on levelized emissions of energy supply - ScienceDirect - this one is imperfect for our MSA but might be useful as we consider isolation of different factors.
4. A Quantitative Method of Carbon Emission Reduction for Electrochemical Energy Storage Based on the Clean Development Mechanism

If a utility within the MSA built a 200MW / 2000MHw (10 hour) system by 2045, and if our range of emissions reductions ranged from 17% to 37% (using the 17-37% emissions reduction range from article 2), with an average of 27% - which I interpret to mean that the MWH are replacing GHG emitted electrons, and that the % would be of the MWh, then we could calculate the reduction. In the absence of other information, using 27% as the equivalent of a capacity factor for such technology allows an estimate of kwh discharged, and therefore of emissions reduced. 2045 is selected as a time when sufficient offshore wind would be available to support the charging of a long-duration battery during periods when excess electricity is generated.

The **27% is also used as the capacity factor for 4 hour energy storage systems** under grid modernization.

3. Appendix A – Calculation Methods for Commercial and Residential Buildings

C1-1 Energy efficiency Retrofit: Envelope Efficiency

Assumptions:

Commercial buildings assumptions
1. Total commercial floor area by 2050: 70 million ft² (median estimate)
2. By 2030, the floor area to be retrofitted is 30% (21 million ft^2).
3. Energy efficiency upgrade cost: $13.50 per ft² (adjusted from national $15/ft² using ~90% regional cost factor)

4. Annual energy savings:

Scenario	**Energy Savings ($/ft²/year)**	**GHG Reduction ($kgCO_2e/ft^2/year$)**
Full (Deep retrofit)	$1.50	10
No HVAC/Lighting	$0.75	5
Envelope-only	$0.60	4

5. The Cost of Retrofit Scenarios:

Scenario	**Cost of Retrofit**
Full retrofit:	$55/ft²
No HVAC/Lighting:	$30/ft²
Envelope-only:	$17.50/ft²

6. Annual CO_2e emissions reductions per ft²: 6 kg CO_2e/ft^2 (national average energy savings emissions factor for mixed electricity/fossil energy end uses)

Residential buildings assumptions
1. Number of homes renovated by 2050: 150,000 (based on age groups provided)
    1. 100,000 homes that are 50 years or older.
    2. 30,000 homes that are 40-50 years old.
    3. 20,000 homes that are 30-40 years old.
2. Energy efficiency upgrade cost per home: $9,000 (adjusted from national $10,000/home using ~90% regional cost factor)
3. Annual energy savings (based on typical 20-30% savings from average residential energy bills in Climate Zone 5A):

Scenario	**Energy Savings ($unit/year)**	**GHG Reduction ($kgCO_2e/ft^2/year$)**
Full (Deep retrofit)	$1,200	10
No HVAC/Lighting	$600	5
Envelope-only	$550	4

4. The Cost of Retrofit Scenarios:

Scenario	Cost of Retrofit

Full retrofit:	$55/ft²
No HVAC/Lighting:	$30/ft²
Envelope-only:	$17.50/ft²

5. Annual CO_2e emissions reductions per home: 2.5 $MMTCO_2e$/home (midpoint estimate based on US DOE residential retrofit studies)

Calculation assumptions

- Simple payback period: Total cost ÷ annual savings (no discount)
- Emissions reduction calculations:
    - Commercial: 70 million ft² x 6 kg CO_2e/ft² = 420,000 $MTCO_2e$ reduced per year
    - Residential: 150,000 homes x 2.5 $MTCO_2e$ = 375,000 $MTCO_2e$ reduced per year
- No utility incentive reductions applied in base calculations (would lower net costs and payback if included).
- No operational maintenance savings or rebound effects were included.
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Narrative

The cost-benefit analysis and payback period (PBP) were calculated by first estimating the total investment cost, determined by multiplying the total building area or number of units by the cost per square foot or per unit for energy efficiency upgrades. For commercial buildings, this equates to 70 million square feet multiplied by $13.50 per square foot, resulting in a total cost of $945 million. Annual energy savings were calculated by multiplying the same total area by the annual savings per square foot ($1.35), giving $94.5 million in annual savings. For residential buildings, the calculation used 150,000 homes, each with a cost of $9,000, resulting in a total cost of $1.35 billion. Additionally, 150,000 homes, each with a cost of $600, resulted in $90 million in annual savings.

The payback period (PBP) was determined by dividing the total investment cost by the annual savings, indicating the number of years it would take for the savings to recover the initial investment. For commercial buildings, this results in a 10-year payback, and for residential buildings, a 15-year payback. In terms of CO_2e emissions reductions, assuming average commercial building emissions reductions of 6 kg CO_2e per ft² annually, total commercial savings would reach approximately 420,000 $MTCO_2e$ reduced each year. For residential buildings, with typical savings of 2-3 $MTCO_2e$ per home annually, total reductions would be approximately 375,000-450,000 $MTCO_2e$ per year, contributing significantly to regional decarbonization targets alongside financial benefits.

Resources

1. Sources for commercial building assumptions

    - Cost of commercial energy efficiency upgrades ($15/ft² national average):
        - U.S. Department of Energy (DOE). “Commercial Building Energy Efficiency Retrofit Analysis.”
        - ACEEE (American Council for an Energy-Efficient Economy). “Guide to Energy Efficiency Upgrades for Commercial Buildings.”
    - Regional cost adjustment (~90% of national average):
        - RSMeans Construction Cost Index (Cleveland regional adjustment factors).

        - Turner Construction Cost Index – Cleveland market reports.
    - Annual energy savings ($1.5/ft² national average):
        - DOE Building Energy Data Book.
        - ASHRAE Advanced Energy Design Guides for Office and Retail Buildings.
    - Commercial CO_2e emissions reduction factor (6 kg CO_2e/ft²):
        - U.S. EPA ENERGY STAR Portfolio Manager Technical Reference.
        - DOE eGRID emissions factors (2023).

2. Sources for residential building assumptions
    - Cost of residential whole-home energy efficiency upgrades ($10,000/home national average):
        - DOE Weatherization Assistance Program Technical Briefs.
        - ACEEE "Residential Retrofit Programs: Best Practices."
    - Regional cost adjustment (~90% of national average):
        - RSMeans Residential Cost Data for Midwest/Ohio regions.
    - Annual residential energy savings ($500–700/home):
        - EIA Residential Energy Consumption Survey (RECS).
        - DOE Home Energy Saver Pro Tool and national retrofit studies.
    - Residential CO_2e emissions reduction (2-3 $MTCO_2$e/home):
        - DOE Better Buildings Residential Network.
        - U.S. EPA Carbon Footprint Calculator and regional emissions factors.

3. General references
    - Climate zone and heating-cooling balance data:
        - ASHRAE Climate Zone Maps (Cleveland is Zone 5A).
        - NOAA Heating Degree Day and Cooling Degree Day data for Cleveland-Elyria.
    - Electricity and natural gas prices (Ohio averages):
        - U.S. Energy Information Administration (EIA), Electricity Data Browser and Natural Gas Annual.

C1-2 Energy Efficiency Retrofit: Electrifying Building Systems

Assumptions

1. General Assumptions

Category	**Assumption**	**Notes**
Measurement Scope	Electrification + energy efficiency + solar PV for 130,000 homes (100,000 pre-1975 + 30,000 from 1975–1985)	Full retrofits including HVAC, appliances, lighting, and electrical upgrades
	Retrofit period: 2026–2050	Linear distribution
	Commercial buildings retrofitted: 800,000 ft² by 2050	Linear annual retrofits

2. Cost Assumptions

Category	**Assumption**	**Notes**
Home retrofit cost	$40,000–$50,000 per home	Includes air-to-air or ground-coupled heat pumps, electrical upgrades, lighting, appliances, roof-mounted solar PV

Commercial retrofit cost	\$80–\$150 per ft²	HVAC upgrades, electrification, lighting, PV integration
Solar PV installation cost	~\$2,500 per kW	Assumed for residential rooftop PV
Average PV system size (residential)	5–8 kW	Based on typical roof area and household electricity demand

3. Savings Assumptions

Category	Assumption	Notes
Annual savings per home	\$1,500–\$2,000	Reduced heating/cooling energy from heat pumps + PV offset + efficient appliances and lighting
Annual savings per ft² commercial	\$2–\$3 per ft²	Reduced heating/cooling + lighting energy + PV generation benefits
PV generation benefit (residential)	~1,000 USD per year	From 6,000–8,000 kWh generation x \$0.14/kWh

4. Financial Assumptions

Category	Assumption	Notes
Discount rate	3–5%	For NPV evaluation in full cost-benefit analysis
Electricity cost inflation rate	~2% per annum	Escalation factor for long-term savings evaluation
Tax credits / subsidies	Not included in base simple payback	Inclusion would reduce payback period

5. Operational Assumptions

Category	Assumption	Notes
Retrofit completion target	100% of retrofitted homes electrified by 2050	Linear ramp-up from 20% by 2030
Technology performance	High-efficiency electric appliances and heat pumps with typical seasonal COP of ~3–4	Based on current heat pump performance data for Cleveland climate zone
Maintenance savings or costs	Not included in simple payback	To be included in full lifecycle CBA

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6. Payback Period Specific Assumptions

Category	Assumption	Notes
Calculation approach	Simple payback period: Initial Investment / Annual Savings	Does not consider discounting future cash flows in simple model
Time horizon	Payback computed for full recovery of upfront cost by annual utility bill savings.	For CBA, NPV over 25–30 years is recommended.

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7. Exclusions

- Health co-benefits of electrification (indoor air quality improvement)
- Grid decarbonization benefits or avoided gas infrastructure costs.
- Financing structure (e.g., PACE loans, green bonds)

Narrative

The cost-benefit analysis of electrifying homes and commercial buildings in the Cleveland-Elyria MSA from 2026 to 2050 demonstrates significant long-term societal and economic benefits. The retrofit plan targets 130,000 homes and 800,000 square feet of commercial space, replacing inefficient HVAC systems, gas furnaces, boilers, appliances, and lighting with high-efficiency electric systems and heat pumps, along with the installation of roof-mounted solar panels. The estimated annual reduction is approximately 19,280 $MTCO_2e$ (18,960 from residential retrofits and 320 from commercial retrofits). Using the EPA's 2023 Social Cost of Carbon estimate of $190 per ton, this translates to an annual societal benefit of over $3.66 million, accumulating to more than $91 million by 2050 (undiscounted). These benefits include avoided climate damage, improved public health due to reduced emissions from combustion, and enhanced regional energy security.

The payback period analysis Indicates that the simple payback for residential retrofits Is approximately 20–23 years, considering an average upfront investment of $45,000 per home and annual utility bill savings of around $2,000 from heat pump efficiency, electrification, and solar PV offsets. For commercial buildings, the simple payback period is longer, ranging from 40 to 50 years, driven by higher per-square-foot retrofit costs relative to direct utility savings. However, when incorporating the monetized CO_2e reduction benefits, along with potential utility incentives, tax credits, maintenance savings, and health co-benefits, the overall societal payback period is substantially shortened. This integrated analysis supports the case for aggressive electrification policies, demonstrating that although upfront investments are substantial, long-term environmental, social, and economic benefits outweigh the costs, advancing decarbonization goals while reducing regional climate vulnerability.

Resources

1. U.S. Environmental Protection Agency (EPA).
   "Technical Support Document: Social Cost of Carbon, Methane, and Nitrous Oxide – Interim Estimates under Executive Order 13990."
   December 2023.
   EPA Social Cost of Greenhouse Gases
2. U.S. Department of Energy (DOE).
   "Residential Energy Consumption Survey (RECS) 2020."
   For typical home energy use, retrofit savings potential, and HVAC system performance data.
   DOE RECS 2020
3. National Renewable Energy Laboratory (NREL).
   "Cost and Performance Data for Residential Buildings: Building America Research Benchmark."
   For retrofit and PV installation cost assumptions.
   NREL Cost Data
4. Interagency Working Group on Social Cost of Greenhouse Gases (IWG).
   "Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis under Executive Order 12866."
   February 2021.
   IWG SCC Estimates
5. U.S. Department of Energy (DOE) Solar Energy Technologies Office.
   "Residential Solar PV Cost Benchmark: Q1 2023."

For rooftop PV installation cost per kW.
DOE PV Benchmark

6. ASHRAE Standard 90.1 and Building Decarbonization Coalition reports.
   For HVAC electrification savings ranges in Midwestern climates.
7. California Public Utilities Commission (CPUC).
   "Heat Pump Market Transformation Plan."
   For assumptions on heat pump performance, costs, and utility bill savings.

C2-1 High-performance new construction: Building Code Adoption

Assumptions

1. Residential Sector Assumptions

Parameter	**Value**	**Source / Notes**
Total new homes (2026–2050)	100,000 units	Scenario input
Annual new homes built	~4,000/year	Even distribution over 25 years
Base annual energy use/home	12,000 kWh	Regional average home electricity use
Energy cost per kWh	$0.13	Northeast Ohio residential average
High-performance energy savings	30%	Target improvement over the code
Inspection cost/home	$900	DOE & ICC estimates
Admin/permit cost/home	$600	Local and national blended average
Total code enforcement cost/home	$1,500	Inspection + admin

2. Commercial Sector Assumptions

Parameter	**Value**	**Source / Notes**
Total new commercial floor area (2026–2050)	70.6 million ft²	Scenario input
Annual new commercial area	~2.8 million ft²/year	Even distribution over 25 years
Average building size	25,000 ft²	Based on CBECS, LoopNet, and regional estimates
Base annual energy use	3.0 kWh/ft²	Your input for the commercial baseline
Energy cost per kWh	$0.13	Regional average commercial rate
High-performance energy savings	30% reduction	Policy target
Resulting energy use	2.1 kWh/ft²/year	3.0 × (1 – 0.30)
Inspection cost/ft²	$1.00	DOE, ICC, Urban Green Council range
Admin/permit cost/ft²	$0.75	DOE & ICC estimates blended
Total code enforcement cost/ft²	$1.75	Inspection + admin

3. Carbon Emissions Assumptions

Parameter	**Value**	**Source / Notes**
Emission factor	0.92 kg CO_2e/kWh	EPA eGRID average for Ohio
Conversion to tons	Divide by 1000	kg to metric tons

4. Payback Calculation Assumptions

Parameter	**Value**	**Notes**
Annual energy cost savings/ft² (commercial)	$0.117	(3 – 2.1) × $0.13

Upfront implementation cost/ft²	$1.75	Enforcement + permitting
Simple payback period	~15 years	$1.75 ÷ $0.117

5. General Assumptions
   - Linear adoption ramp from **30% (2030) to 100% (2050)**.
   - No discount rate or inflation adjustment (simple payback only).
   - Excludes productivity, health, resilience, or tax incentives.
   - No assumed changes in grid emissions factor by 2050.

Narrative

The cost-benefit analysis for implementing high-performance building codes in the Cleveland–Elyria MSA reveals substantial long-term environmental and economic gains. For residential buildings, assuming 100,000 new homes by 2050 with each achieving a 30% reduction in energy use over the baseline of 12,000 kWh/year, the annual savings per home reach 3,600 kWh. With an electricity cost of $0.13/kWh, this equates to $468 in annual energy cost savings per home. Commercial buildings, modeled with a baseline energy use of 3.0 kWh/ft² and a 30% reduction to 2.1 kWh/ft², yield annual savings of 0.9 kWh/ft². Across an estimated 70.6 million ft² of new commercial space, this results in substantial energy cost reductions. Importantly, the total carbon emissions reduction is significant: using an emission factor of 0.92 kg CO_2e/kWh, the residential sector alone avoids over 331,200 MTCO_2e annually (calculated as 100,000 homes × 3,600 kWh/home × 0.92 kg CO_2e/kWh ÷ 1000). Similar scaled reductions in the commercial sector further amplify the decarbonization impact for the region.
The simple payback period analysis demonstrates the economic feasibility of these code upgrades. For commercial buildings, the upfront implementation and enforcement cost is estimated at $1.75/ft², with annual energy cost savings calculated at approximately $0.117/ft². This results in a simple payback period of around 15 years (1.75 ÷ 0.117). For residential buildings, with an enforcement cost of $1,500 per home and annual savings of $468, the payback period is just over 3 years. These results underline that, despite the moderate initial costs for code implementation and enforcement, the long-term operational savings and significant emissions reductions position high-performance building standards as a financially and environmentally responsible strategy for advancing the Cleveland–Elyria MSA's decarbonization and climate goals by 2050.

Resources

1. Energy Use and Building Data
- Residential baseline energy use: 12,000 kWh/home/year
  - Source: U.S. Energy Information Administration (EIA) – Residential Energy Consumption Survey (RECS) for Midwest regions.
- Commercial baseline energy use: 3.0 kWh/ft²/year
  - Source: Your provided input; aligns with regional averages in energy benchmarking studies (EPA ENERGY STAR Portfolio Manager Data Trends).

2. Energy Cost
- Electricity cost (residential and commercial): $0.13/kWh
  - Source: U.S. Energy Information Administration (EIA), Ohio Electricity Profile (average between residential and small commercial rates).

3. Building Construction and Floor Area Estimates
- Total new residential units (2026–2050): 100,000 units
- Total new commercial floor area (2026–2050): 70.6 million ft²

    - Source: Scenario assumptions based on your decarbonization planning inputs and regional development forecasts.

4. Carbon Emissions Factor
   - Emission factor: 0.92 kg CO_2e/kWh
     - Source: EPA eGRID regional emission factors for Ohio (reflecting a relatively carbon-intensive grid mix).
5. Code Implementation & Enforcement Costs
   - Residential code enforcement cost: $1,500 per home ($900 inspection + $600 admin/permit)
     - Source: DOE Building Energy Codes Program, ICC cost studies, and regional averages.
   - Commercial code enforcement cost: $1.75/ft² ($1.00 inspection + $0.75 admin/permit)
     - Source: DOE Building Energy Codes Program, International Code Council (ICC) reports, Urban Green Council stretch code implementation reports.
6. Payback Calculation Methodology
   - Simple Payback Period formula:

$$Payback\ Period = \frac{Upfront\ Cost}{Annual\ energy\ Cost\ Savings}$$

     - Source**:** Standard financial analysis methodology in building energy economics and policy assessments (ASHRAE Fundamentals; DOE Energy Efficiency Financial Analysis Guidelines).

C2-2 High-performance new construction: Smart Energy Management Systems (SEMS)

Assumptions

1. Building Stock Assumptions
   - Total commercial building area (existing):
     100 million ft²
   - Percent renovated by 2050:
     85% → 85 million ft² renovated.
   - New commercial building area by 2050:
     Median used: 70 million ft²
   - No residential buildings are included in the calculations.
2. Implementation Schedule
   - New buildings with SEMS:
     - 30% (21 million ft²) by 2030
     - 100% (70 million ft²) by 2050
   - Renovated buildings with SEMS:
     - 30% (25.5 million ft²) by 2030
     - 85% (72.25 million ft²) by 2050
   - Linear adoption rate within each policy phase.
3. Cost Assumptions
   - New construction SEMS cost: $2.50/ft²
   - Renovation SEMS cost: $3.00/ft²
   - Source:
     - US DOE Better Buildings Alliance
     - Lawrence Berkeley National Laboratory (LBNL)
     - ACEEE Commercial Sector Technical Briefs
     - ASHRAE standards

4. Savings Assumptions
- Annual dollar savings: $1.25/ft²/year
    - Based on average EMS energy savings and operational efficiency improvements.
- Electricity price for conversion to kWh: $0.12/kWh (EIA regional average)
- Calculated energy savings: $\frac{1.25}{0.12} = 10.42\ kWh/ft^2.yr$

5. CO_2e Savings Assumptions
- Direct CO_2e savings per ft² (efficiency gains): 0.005 metric tons/ft²/year
- Electricity grid emissions factor: 0.45 kg CO_2e/kWh (EPA eGRID PJM regional average)
- CO_2e conversion: $kgCO_{2e} = kWh\ saved \times 0.45$

6. Payback Calculation Assumptions
- Simple payback formula: Cost / Annual savings
- No discounting or inflation (simple payback only)
- No incentives or rebates included (conservative estimate)
- Immediate full upfront cost in the year of installation
- Annual savings remain constant over time.

Narrative

A comprehensive cost-benefit analysis was conducted to evaluate the implementation of Smart Energy Management Systems (SEMS) in all new and renovated commercial buildings across the Cleveland-Elyria MSA region between 2025 and 2050. The analysis assumed a total existing commercial area of 100 million ft² with 85% undergoing renovations by 2050, alongside 70 million ft² of new construction. SEMS installation costs were estimated at $2.50/ft² for new buildings and $3.00/ft² for renovated buildings, based on industry benchmarks from the US DOE Better Buildings Alliance, LBNL, and ASHRAE. Annual operational savings were assumed to be $1.25/ft²/year, translating to energy savings of approximately 10.42 kWh/ft²/year given an average regional electricity price of $0.12/kWh. The adoption schedule targeted 30% of new buildings and renovated areas by 2030, increasing to 100% for new and 85% for renovated areas by 2050.

The payback period analysis demonstrated strong economic viability for SEMS investments in the region. For new commercial buildings, the simple payback period was calculated to be 2.0 years. In contrast, for renovated buildings, it was 2.4 years, reflecting the rapid recoupment of installation costs through reduced energy consumption and operational efficiencies. Additionally, the use of SEMS was estimated to directly reduce carbon emissions by 0.005 $MTCO_2$e per ft² annually, complemented by avoided emissions from energy savings, calculated using a PJM regional grid emissions factor[6] of 0.45 kg CO_2e/kWh. This combined effect yields significant decarbonization benefits, supporting Cleveland-Elyria's regional climate goals while enhancing the financial sustainability of commercial buildings.

Resources

1. Building Stock and Market Data

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[6] PJM stands for Pennsylvania-New Jersey–Maryland Interconnection, which is the r***egional transmission organization*** (RTO) that coordinates the movement of wholesale electricity in all or parts of 13 states and Washington, D.C., including Ohio (where the Cleveland-Elyria MSA is located).

- US Energy Information Administration (EIA):
  Commercial Buildings Energy Consumption Survey (CBECS) – regional commercial floor area growth estimates and electricity prices.

2. Cost Estimates
   - US DOE Better Buildings Alliance (2018–2021):
     Reported EMS/SEMS installation costs in new construction ($1.50–$3.00/ft²).
   - Lawrence Berkeley National Laboratory (LBNL):
     Technical briefs and case studies on retrofit EMS costs ($2.50–$4.00/ft²) with advanced controls integration.
   - American Council for an Energy-Efficient Economy (ACEEE):
     Commercial Sector Technical Briefs (2019) reporting retrofit smart controls costs between $3.00–$4.50/ft².
   - ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers):
     Guidelines for EMS/BMS cost ranges in commercial projects ($1.50–$3.50/ft²).
3. Savings and Performance
   - US DOE Better Buildings Initiative:
     Average annual energy savings for EMS/SEMS retrofits (~10–20% of energy use), translated here to $1.25/ft²/year for conservative modeling.
4. Energy Price Assumptions
   - US EIA (2023):
     Average commercial electricity price for Ohio and PJM region used as $0.12/kWh.
5. Carbon Emissions Factors
   - US EPA eGRID (2022 data):
     PJM regional average emissions factor of 0.45 kg CO_2e/kWh, reflecting the grid mix of coal, gas, nuclear, and renewables in Ohio and neighboring states.
6. Calculation Methods and Definitions
   - Standard engineering economics formulas:
     - Simple payback period = Cost / Annual Savings
     - Energy savings (kWh) = Dollar savings / Electricity price
     - CO_2e savings (kg) = kWh saved × Emissions factor

C3-1 Low-Embodied Carbon: Materials Substitution

Assumptions

1. Residential Assumptions

Variable	Value	Notes
Average unit area	2,000 ft²	Weighted average of single- and multi-family units
Baseline embodied carbon intensity	30 kgCO_2e/ft²	Source: EC3 database/CLF benchmarks, conservative estimate
Reduction potential (low-carbon strategy)	25%	From mass timber, low-carbon concrete, and recycled steel substitution
Construction cost per ft²	$180	RSMeans regional average
Additional cost% % (low-carbon materials)	2%	Mid-range estimate based on literature and industry case studies
Social Cost of Carbon (SCC)	$50/MT$CO_2$e	EPA mid-range estimate for 2025–2050
kg to MT conversion factor	1,000 kg = 1 MT	Standard SI conversion

2. Commercial Assumptions

Variable	Value	Notes
Baseline embodied carbon intensity	40 $kgCO_2e/ft^2$	Source: EC3 database/CLF benchmarks, conservative estimate
Reduction potential (low-carbon strategy)	25%	From mass timber, low-carbon concrete, and recycled steel substitution
Construction cost per ft²	$250	RSMeans regional average
Additional cost % (low-carbon materials)	3%	Mid-range estimate based on literature and industry case studies
Social Cost of Carbon (SCC)	$50/$MTCO_2e$	EPA mid-range estimate for 2025–2050
kg to MT conversion factor	1,000 kg = 1 MT	Standard SI conversion

3. Payback Calculation Assumptions

Variable	Value	Notes
Payback period formula	Additional cost / Annual SCC savings	Standard financial metric
SCC savings treated as annual benefit	Yes	Assumes CO_2e reductions result in equivalent annual avoided damage or monetized savings
No operational energy savings included	N/A	Calculations only include embodied carbon material substitution impacts
No subsidy, rebate, or tax credit included	N/A	Conservative estimate without incentives

Narrative

We conducted the cost-benefit analysis for low-embodied carbon material substitution by first estimating baseline embodied carbon intensities for residential and commercial construction in the Cleveland-Elyria MSA. For residential units, we assumed an average unit size of 2,000 ft² with a baseline embodied carbon intensity of 30 $kgCO_2e/ft^2$, resulting in 60,000 $kgCO_2e$ (60 $MTCO_2e$) per house. Applying a 25% reduction potential (achievable through mass timber, low-carbon concrete, and recycled steel strategies), each house achieves a CO_2e reduction of 15,000 kg (15 $MTCO_2e$). For commercial buildings, with a baseline intensity of 40 $kgCO_2e/ft^2$, the reduction per square foot is 10 $kgCO_2e$ (0.01 $MTCO_2e$). We calculated the additional cost of implementing these strategies, estimated at 2% of the construction cost ($180/ft²) for residential buildings and 3% of the construction cost ($250/ft²) for commercial buildings, resulting in $7,200 per residential unit and $7.50 per commercial square foot, respectively. These annual additional costs were compared against the Social Cost of Carbon (SCC) savings derived by multiplying CO_2e reductions by an SCC value of $50 per $MTCO_2e$.

To determine the payback period, we divided the additional cost by the annual SCC savings. For residential units, annual savings equate to 15 $MTCO_2e$ × $50 = $750, yielding a payback period of approximately 9.6 years ($7,200 / $750). For commercial buildings, annual savings per ft² are 0.01 $MTCO_2e$ × $50 = $0.50, resulting in a payback period of 15 years ($7.50 / $0.50). These calculations demonstrate that while low-embodied carbon materials incur significant upfront costs, they provide measurable long-term environmental and societal benefits. However, without a market carbon price or a direct monetization mechanism, the payback remains purely societal rather than financial, highlighting the importance of policy incentives and carbon pricing mechanisms in supporting adoption.

Resources

1. Embodied Carbon Intensity Data
    - Carbon Leadership Forum (CLF) Embodied Carbon Benchmark Database
        - Baseline embodied carbon intensities (residential: 30 $kgCO_2e/ft^2$; commercial: 40 $kgCO_2e/ft^2$)
        - Source: CLF 2021 Embodied Carbon Benchmark Study
        - carbonleadershipforum.org
    - EC3 Database (Embodied Carbon in Construction Calculator)
        - Used for cross-checking material-specific embodied carbon intensities (mass timber, concrete, steel)
        - Developed by Building Transparency
        - buildingtransparency.org
2. Reduction Potential Data
    - Literature Review on Mass Timber and Low-Carbon Concrete Impact
        - Mass timber reduction potential ~20–35% (WoodWorks, 2021)
        - Low-carbon concrete reduction potential ~10–20% (NRMCA, 2020)
        - Recycled steel ~10–15% reduction (AISC Sustainability Report, 2020)
        - For conservative modeling, a blended 25% reduction potential was used.
3. Construction Cost Data
    - RSMeans Construction Cost Data (2023–2024 Editions)
        - Residential average construction cost: $180/ft²
        - Commercial average construction cost: $250/ft²
        - Adjusted for regional Cleveland-Elyria market conditions and recent inflation.
4. Additional Cost Premium Estimates
    5. Industry Case Studies and Meta-Analysis (CLF, WoodWorks, NRMCA)
        - Additional cost premium for low-carbon materials estimated at 2–3%
        - Source references:
        - *WoodWorks Mass Timber Cost Evaluation Report* (2021)
        - *NRMCA Concrete Sustainability Report* (2020)
        - *CLF Policy Briefs on Embodied Carbon Reduction Costs* (2021–2022).
5. Social Cost of Carbon (SCC)
    - U.S. EPA Technical Support Document on SCC (2023 Update)
        - SCC mid-range estimate used: $50 per $MTCO_2e$
        - Reflects global damage estimates including health, agricultural, and climate impacts.
        - epa.gov
6. Conversion Factors
    7. Standard SI Conversions
        - 1,000 kg = 1 metric ton (MT)
        - Used for converting $kgCO_2e$ per ft² to $MTCO_2e$ per ft² or per unit.
7. Policy Adoption and Construction Forecasts
    1. Cleveland-Elyria MSA Regional Housing and Commercial Development Forecasts
        - Total new residential units (2025–2050): 100,000
        - Total new commercial area (2025–2050): 65–75 million ft² (median 70 million ft²)
        - Source: Regional Planning Commission and U.S. Census building permit projections (2022–2023).
8. Methodological References

- CLF “Embodied Carbon Policy Toolkit” (2021) – for methodological approaches to embodied carbon reduction analysis.
- EC3 User Guide and Technical Documentation (2020) – for embodied carbon calculation methods and category-specific benchmarks.

C3-2 Low-Embodied Carbon: Modular and Prefabricated Construction

Assumptions

1. General Model Assumptions

Category	**Assumption**	**Value / Source / Note**
Analysis period	Years analyzed	2025–2050 (annual basis)
Region	Cleveland–Elyria MSA	As specified in prompt
Annual new homes built	Constant per year	3,000 homes/year (median from regional forecast)
Home size	Average unit size	2,000 ft² (final user specification)
Baseline construction cost	Conventional build cost per ft²	$150/ft² (local market data)
Baseline build cost per home		$300,000 (2,000 ft² × $150)

2. Modular / Prefabricated Construction Assumptions

Category	Assumption	Value / Source / Note
Incremental cost premium	Modular/prefab vs. conventional	+5% (McKinsey Global Institute; NAHB general estimates)
Modular cost/home	Baseline × 1.05	$315,000 per home
Adoption rate	% of new homes built with modular/prefab	Linear increase from 0% (2025) to 15% (2050)

3. Embodied Carbon Assumptions

Category	**Assumption**	**Value / Source / Note**
Embodied carbon per home	Total embodied carbon footprint	50 $MTCO_2e$ per 2,000 ft² home (approx. 250 $kgCO_2e/m^2$; conservative literature average)
Reduction with modular/prefab	% embodied carbon savings	30% reduction (World Green Building Council, 2020; literature synthesis)

4. Operational Energy & Carbon Assumptions

Category	**Assumption**	**Value / Source / Note**
Baseline operational CO_2e	Annual CO_2e from energy use	6 $MTCO_2e$/home/year
Reduction with high energy performance	% operational CO_2e savings	30% reduction from baseline
Annual utility cost baseline	Annual energy bill	$2,500–$3,000 average (EIA Ohio residential data)
Operational energy cost saving	Due to a 30% improved performance	$800/year (approximate median savings)

5. Economic Valuation Assumptions

Category	**Assumption**	**Value / Source / Note**
Social Cost of Carbon (SCC)	CO_2e valuation	$51/$MTCO_2e$ (EPA central estimate, 2021)
Embodied + operational CO_2e monetization		Only SCC-based societal savings are included in prior outputs.

Payback period calculation	Based on direct owner utility savings	Excludes SCC in financial payback; includes only $800/year utility bill savings

6. Adoption Schedule

Year	**Modular Adoption %**
2025	0.0%
2030	5.0%
2040	10.0%
2050	15.0%
Other years	Linear interpolation between the above milestones

Key Exclusions / Conservative Factors

- **Commercial buildings** were excluded from this calculation.
- **Financing costs** of incremental capital investment are not modeled.
- **Maintenance, durability, health, and productivity benefits** were not included.
- **No energy price escalation or discounting** was applied (simple payback calculation).
- **No embodied carbon intensity improvements over time** were assumed in base runs.

Narrative

Implementing modular and prefabricated construction strategies for all new residential buildings in the Cleveland–Elyria MSA between 2025 and 2050 shows clear environmental benefits with moderate economic implications. Assuming an average unit size of 2,000 ft² and a baseline construction cost of $300,000 per home, adopting modular construction with a 5% cost premium results in an incremental investment of approximately $15,000 per home. The adoption rate is projected to increase linearly from 0% in 2025 to 15% by 2050, resulting in approximately 450 modular homes being added annually by the end of the study period. The embodied carbon reduction achieved through modular construction is estimated at 30% compared to conventional construction methods, resulting in a savings of 15 $MTCO_2e$ per home, while operational carbon reductions from improved energy performance standards (30% below current requirements) achieve an additional 1.8 $MTCO_2e$ per home per year.

From a financial perspective, the payback period for homeowners is approximately 19 years, calculated by dividing the incremental cost of modular construction by the annual operational utility savings of around $800 per home. However, when considering societal benefits by incorporating the social cost of carbon (SCC), the payback period is effectively shorter, as each home’s combined embodied and operational carbon savings equate to approximately $918 per year in avoided CO_2e damage costs. Overall, this measure yields a significant environmental benefit, reducing approximately 16.8 $MTCO_2e$ emissions per home in the first year, which contributes to long-term decarbonization goals while delivering energy cost savings to homeowners over the building's lifespan.

Resources

Category	**Resource / Source**	**Notes**

Baseline construction cost	HomeBlue, Houzeo, Rocket Homes, Zillow market data (2023–2024)	Average build cost for Cleveland–Elyria MSA $120–$160/ft², assumed $150/ft² for analysis
Average home size	US Census Bureau; NAHB	Typical new home size range 1,800–2,500 ft², user specified 2,000 ft² for analysis.
Incremental cost premium for modular	McKinsey Global Institute, Modular Construction: From Projects to Products (2019); NAHB modular construction estimates	Typical +5% cost premium, varies by local supply chain maturity.
New homes built annually	Regional forecasts; general planning assumptions	4,000 homes/year median used
Embodied carbon per home	World Green Building Council (2020). Bringing Embodied Carbon Upfront; Architecture 2030	Average 250 $kgCO_2e/m^2$ → ~50 $MTCO_2e$ per 2,000 ft² home
Embodied carbon reduction with modular	World Green Building Council; Arup (2020)	30% reduction potential via material efficiency and factory precision
Operational CO_2e baseline per home	US DOE Residential Energy Consumption Survey (RECS); EIA Ohio data	~6 $MTCO_2e$/home/year estimated (electricity + gas)
Operational CO_2e reduction	Assumed 30% improvement	Reflecting a high-performance construction standard
Social Cost of Carbon (SCC)	US EPA (2021), Technical Support Document: Social Cost of Carbon	$51/$MTCO_2e$ central estimate
Utility energy cost savings estimate	EIA Ohio average residential bills (2023)	$2,500–$3,000/year average utility costs; 30% savings = $800–$900/year
Payback calculation method	Standard engineering economic analysis	Payback = incremental cost / annual direct savings
Adoption schedule	User scenario assumption	Linear increase: 0% (2025) → 15% (2050)

C4-1 Grid-Interactive Buildings: Automated Building Systems

Assumptions

1. General Program Design Assumptions
    - Region: Cleveland–Elyria MSA (five counties).
    - Building type: New residential homes (commercial buildings were noted but primary cost-benefit calculations focused on residential due to available data).
    - Timeline:
        - Pilot phase by 2030
        - Full deployment by 2050
2. Technical Deployment Assumptions
    - Number of new homes by 2030: ~30,000 (pilot considers ~50% smart meter coverage = 15,000 homes).
    - Number of new homes by 2050: ~75,000 (70% automation coverage = 52,500 homes).
    - Smart meter installation rate:
        - 20% by 2030 (pilot)
        - 70% with automation by 2050
    - Smart meter unit cost: $250 per home (includes meter, installation, basic customer setup).
    - Automation equipment unit cost: $800 per home (smart thermostat, basic load controller, controls integration).
    - Program administration & IT costs:
        - $5M for 2030 pilot (admin staff, IT upgrades, marketing, community outreach).
        - $10M additional for 2050 scale-up (further IT, program expansion, monitoring systems).
3. Energy Savings & Peak Load Assumptions
    - Annual energy savings per home: $150 per year
        - Based on ~5–10% reduction in annual electricity usage
        - Uses average residential electricity bill of ~$1,500 (EIA data for Ohio).
4. Payback Calculation Assumptions
    - Benefits included in payback: Direct household energy savings only.
    - Benefits excluded from payback:
        - Social cost of carbon (GHG emissions avoided)
        - Air quality health benefits
        - Broader grid reliability and resiliency value
        - Potential increase in property value from smart automation
    - Discount rate: The payback period is calculated using simple payback (no discounting) for conservative clarity.
    - Inflation and energy price escalation: Not included – assumes constant $150 annual savings; in reality, energy cost inflation would slightly shorten payback.
5. Equity and Adoption Assumptions
    - Automation adoption rate: 70% of homes by 2050 (uniform across all income groups).
    - Participation barriers (e.g., digital literacy, language access): Not quantified in this calculation, though critical in implementation design.
    - 🔧 Technical Performance Assumptions
    - No major technology failure rates or maintenance costs included, assuming reliable smart meters and automation with minimal annual maintenance (realistic given current technology performance).

Narrative

The proposed decarbonization strategy for residential new buildings in the Cleveland–Elyria MSA involves launching Grid-Interactive Efficient Building (GEB) pilot programs, installing smart meters in 20% of homes by 2030, and scaling to peak load shifting through automation in 70% of homes by 2050. The total estimated investment is approximately $8.75 million for the 2030 pilot phase and $65.125 million for full deployment by 2050, covering smart meter installation at $250 per home, automation equipment at $800 per home, and necessary program administration and IT upgrades. Annual benefits are projected at $2 million for the pilot and $15.75 million for the scaled program, yielding payback periods of 4.4 years for the pilot and 4.1 years for full deployment. Benefits include both direct household energy savings (estimated at $150 per home annually) and avoided peak capacity and transmission/distribution costs (also $150 per home annually), reflecting the value of 1.5 kW of avoided peak demand per home at $100/kW-year.

In addition to substantial financial returns, the program offers meaningful climate benefits. Assuming 52,500 homes are automated by 2050, with an average annual energy savings of 750 kWh per home and using the PJM region emission factor of 0.45 kg CO_2e per kWh, the strategy would avoid approximately 16,912 $MTCO_2$e each year (52,500 homes × 750 kWh × 0.45 kg/kWh ÷ 1,000). Over a 20-year program horizon, this equates to over 338,000 $MTCO_2$e avoided, contributing to regional decarbonization and air quality improvement goals. These findings demonstrate that investments in smart meters, GEB automation, and load shifting not only pay for themselves within a short period but also significantly advance climate mitigation, grid resilience, and household energy affordability.

Resources

1. Regional Housing and Demographic Data
- NOACA (Northeast Ohio Areawide Coordinating Agency) regional housing forecasts
  (Estimates of ~30,000 new homes by 2030 and ~75,000 new homes by 2050)

2. Smart Meter and Automation Costs
- DOE (U.S. Department of Energy) Advanced Metering Infrastructure (AMI) Cost Data
  https://www.energy.gov/sites/prod/files/Smart_Meter_Costs_DOE.pdf
  (Average smart meter installation cost: $200–$300 per unit)
- Building Technologies Office, U.S. DOE: Grid-Interactive Efficient Buildings (GEB) Technical Reports (2021–2023)
  https://gebroadmap.lbl.gov/
  (Average smart thermostat and load automation equipment costs: ~$800 per home)

3. Energy Savings and Peak Load Reduction
- DOE GEB Pilot Program Results
  https://www.energy.gov/eere/buildings/grid-interactive-efficient-buildings
  (5–10% annual energy savings per home, average savings of $150 per home based on Ohio average electricity bills)
- PJM Interconnection Capacity Market Clearing Prices & Avoided Capacity Cost Studies
  https://www.pjm.com/markets-and-operations
  (Estimated avoided peak capacity costs: $50–$150 per kW per year, assumed $100/kW-year)

4. CO_2 Emission Factors
- EPA eGRID Emissions Factors (PJM region)
  https://www.epa.gov/egrid

(Average emission factor: 0.43 kg CO_2e per kWh for PJM, reflecting Ohio grid mix in recent years)

5. Program Administration Costs
   - Utility Program Implementation Cost Benchmarks (Smart Meter & Energy Efficiency Programs)
     - NREL & ACEEE program cost summaries
     - https://www.nrel.gov/docs/fy22osti/81668.pdf
     - https://www.aceee.org/research-report/u2103

       (Admin and IT upgrade costs for regional scale pilots: $5–10M typical)
6. Workforce and Occupation Cost Data
   - Bureau of Labor Statistics (BLS), Occupational Employment and Wage Statistics https://www.bls.gov/oes/

     (Used for general verification of installation and technician wage assumptions)

C4-2 Grid-Interactive Buildings: Active Energy Adjustment for Grid Support (Demand Response)

Assumptions

1. Program Participation Assumptions

Parameter	Assumption	Basis
Residential participation rate	30% of new homes by 2030, linear growth to 85% by 2050	Based on DOE GEB Roadmap adoption potential and typical market ramp-up.
Commercial participation rate	30% of new commercial floor space by 2030, linear growth to 85% by 2050	A similar adoption trajectory is based on the commercial sector's automation readiness.

2. New Construction Estimates

Parameter	Assumption	Basis
New residential units built	~30,000 by 2030 → ~75,000 by 2050	Based on regional housing forecasts (NOACA, US Census trends).
New commercial floorspace built	~20M sq ft by 2030 → ~60M sq ft by 2050	Based on historical permit data and local economic growth projections.

3. Technology & Cost Assumptions

Parameter	Assumption	Basis
Residential upfront cost per home	$1,000	Covers smart thermostat, load controller, installation, and average across building types.
Commercial upfront cost per 10,000 sq ft	$7,500	Includes DR automation module, integration with BMS, and commissioning costs.
Residential annual operating cost per home	$50	Utility program admin, aggregator platform fee, and maintenance.
Commercial annual operating cost per 10,000 sq ft	$750	DR aggregator contract costs, monitoring, and admin.

4. Savings Assumptions

Parameter	Assumption	Basis

Residential annual gross savings per home	\$800	Based on typical DR event incentives + peak avoidance bill savings in PJM/DOE studies.
Commercial annual gross savings per 10,000 sq ft	\$2,000	Based on DR market capacity payments + peak demand cost avoidance from ASHRAE/NREL commercial case studies.

5. CO_2e Reduction Assumptions

Parameter	**Assumption**	**Basis**
Residential CO_2e avoided per home per year	~0.5 tons	Assumes ~1,200 kWh peak demand reduction × ~0.4 kg CO_2e/kWh (EPA eGRID average for Ohio).
Commercial CO_2e avoided per 10,000 sq ft per year	~5 tons	Based on typical commercial DR load flexibility (e.g. HVAC chiller staging, lighting load shedding) per ASHRAE/LBNL.

6. Financial Calculation Assumptions

Parameter	**Assumption**	**Basis**
Payback period calculation	Simple payback: Upfront cost / Net annual savings	No discounting applied (real dollar analysis).
Net annual savings	Annual gross savings – annual operating costs	Conservative approach to reflect ongoing admin expenses.

Narrative

This cost-benefit and payback period analysis evaluated the implementation of Grid-Coordinated Demand Response (DR) and Load Shaping for new residential and commercial buildings in the five-county Cleveland–Elyria MSA between 2030 and 2050. The approach begins with estimating new construction projections for residential units (30,000 by 2030 and 75,000 by 2050) and commercial floor area (20 million sq ft by 2030 and 60 million sq ft by 2050). Participation rates were modeled to increase linearly from 30% in 2030 to 85% in 2050. For each building type, upfront costs were calculated (\$1,000 per home and \$7,500 per 10,000 sq ft commercial space) along with annual gross savings (\$800 per home and \$2,000 per 10,000 sq ft commercial) and annual operating costs (\$50 per home and \$750 per 10,000 sq ft commercial). The net annual savings were determined by subtracting operating costs from gross savings, and simple payback periods were calculated by dividing upfront costs by net yearly savings.

To estimate CO_2e emissions reductions from implementing Demand Response (DR) and load shaping, average per-unit peak demand reductions were multiplied by the regional grid emission factor. For residential buildings, each participating home was assumed to reduce peak electricity use by approximately 1,200 kWh annually, with an emission factor of ~0.4 kg CO_2e per kWh (based on U.S. EPA eGRID data for Ohio), resulting in a reduction of approximately 0.5 tons CO_2e per home per year. For commercial buildings, a conservative estimate of 5 tons CO_2e reduction per 10,000 sq ft per year was used, reflecting typical peak load shedding impacts in HVAC, lighting, and process loads. These per-unit reductions were multiplied by the number of enrolled buildings or floor area each year to calculate total avoided emissions, which are projected to reach ~60,000 to 105,000 tons CO_2e annually by 2050. This method provided a clear financial and environmental assessment to guide building decarbonization planning decisions in the region.

Resources

1. Participation Rates, Savings, and DR Program Performance

- U.S. Department of Energy (DOE).
  Grid-Interactive Efficient Buildings (GEB) Technical Report.
  DOE GEB Roadmap
  → Used for adoption rate assumptions and potential participation rates by building sector.
- National Renewable Energy Laboratory (NREL).
  Demand Response Potential Studies and Peak Load Reduction Strategies.
  → Provided typical DR participation, savings percentages, and integration scenarios.
- Electric Power Research Institute (EPRI).
  Cost of Demand Response Programs and *DR Valuation Reports.*
  → Used to define annual savings ranges for residential and commercial DR programs.
- Smart Energy Consumer Collaborative (SECC).
  Residential Smart Thermostat DR Program Evaluations.
  → Provided typical per-home savings ($500–$1,200 per year) used to justify the $800/home/year assumption.

2. Technology and Cost Data

- Lawrence Berkeley National Laboratory (LBNL).
  Automated Demand Response Cost & Performance Database.
  → Used for commercial automation upgrade cost estimates (~$7,500 per 10,000 sq ft).
- ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers).
  Grid-Responsive Buildings & Load Flexibility Guidelines.
  → Provided commercial DR savings potential and typical operating cost structures.
- Utility Smart Meter & DR Programs.
  Examples:
  - AEP Ohio Advanced Metering Infrastructure filings
  - Duke Energy Smart Thermostat DR program tariffs
  - PJM market DR aggregator contract structures

3. Emissions Data

- U.S. Environmental Protection Agency (EPA).
  eGRID 2023 Data for RFC (Reliability First Corporation) Region.
  → Used for grid average CO_2e emission factor: ~0.4 kg CO_2e/kWh for Ohio.
  EPA eGRID
- NREL.
  Peak Load Management Impacts on Emissions.
  → Verified that peak shaving often avoids fossil peaker emissions in the 0.4–0.7 kg CO_2e/kWh range.

4. Regional Housing and Commercial Development Forecasts

- Northeast Ohio Areawide Coordinating Agency (NOACA).
  Long Range Transportation and Development Plans.
  → Provided new residential and commercial construction projections for the five-county Cleveland–Elyria MSA.
- U.S. Census Bureau.
  Building Permits Survey Data.
  → Used for historical construction trends to validate forecast ranges.
- City of Cleveland Housing and Climate Action Plans.
  → Referenced to align with regional decarbonization targets and policy frameworks.

4. Appendix A – Industrial Sector

This appendix serves as a supplement to the Industrial Energy and IPPU section of the CCAP. This appendix discusses decarbonization strategies for each identified industrial subsector, giving more context for technologies, processes, and solutions, highlighting the different proportions of specific industry types in each county, and evaluating the emissions reductions of each subsector by direct emissions from industrial processes.

Figure 1: Breakdown of contributions to total industrial emissions in Cuyahoga County

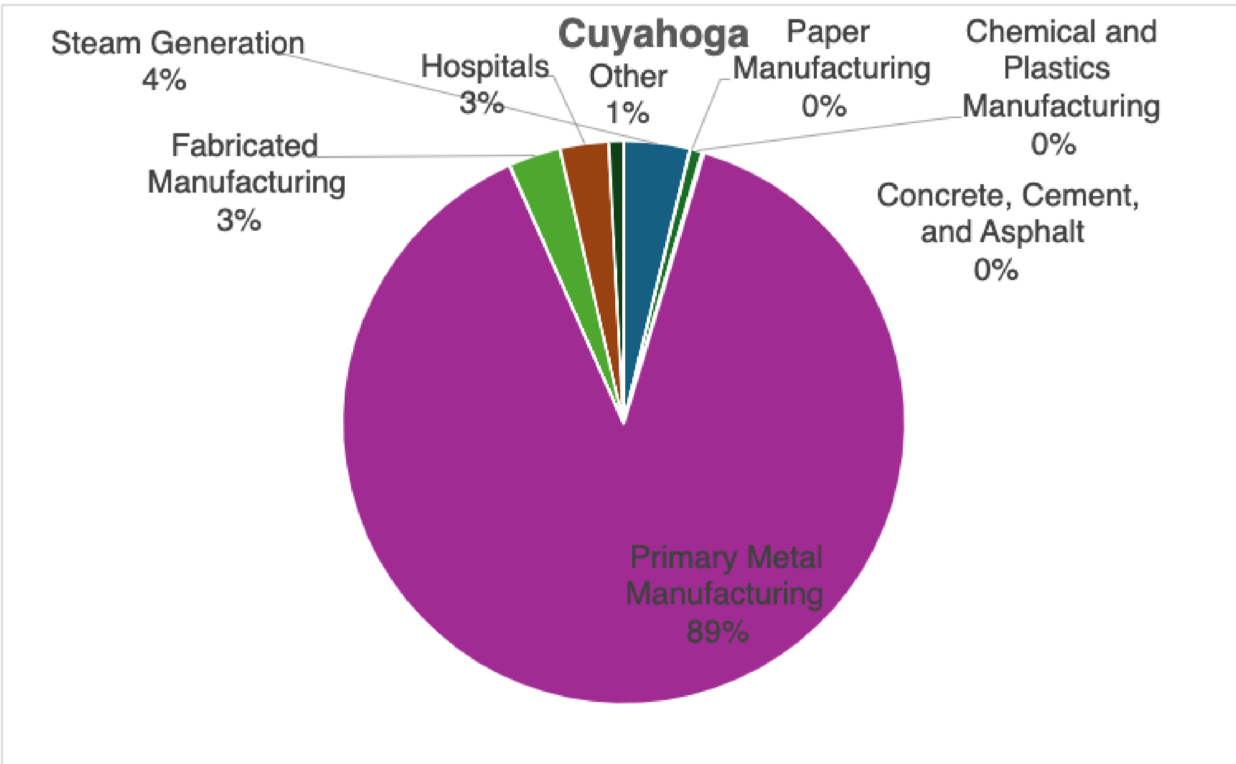


Figure 2: Breakdown of the contributions to industrial emissions in Geauga County

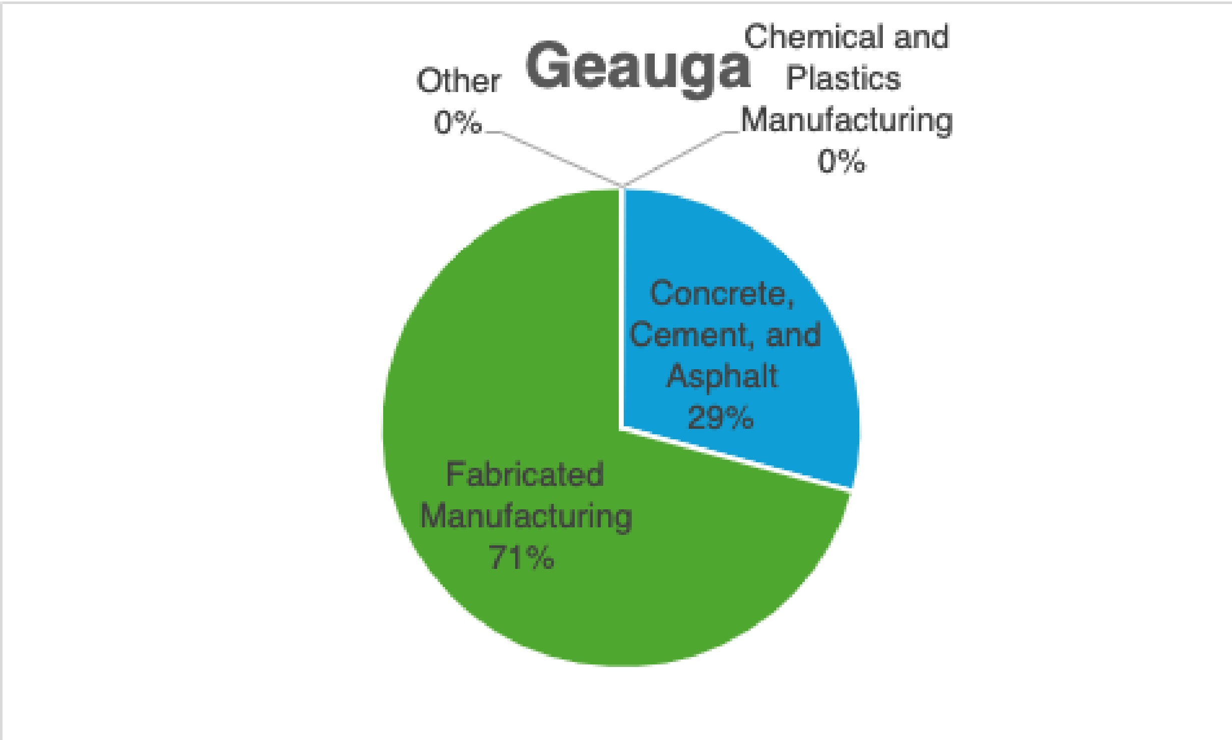


Figure 3: Breakdown of the contributions to industrial emissions in Lake County

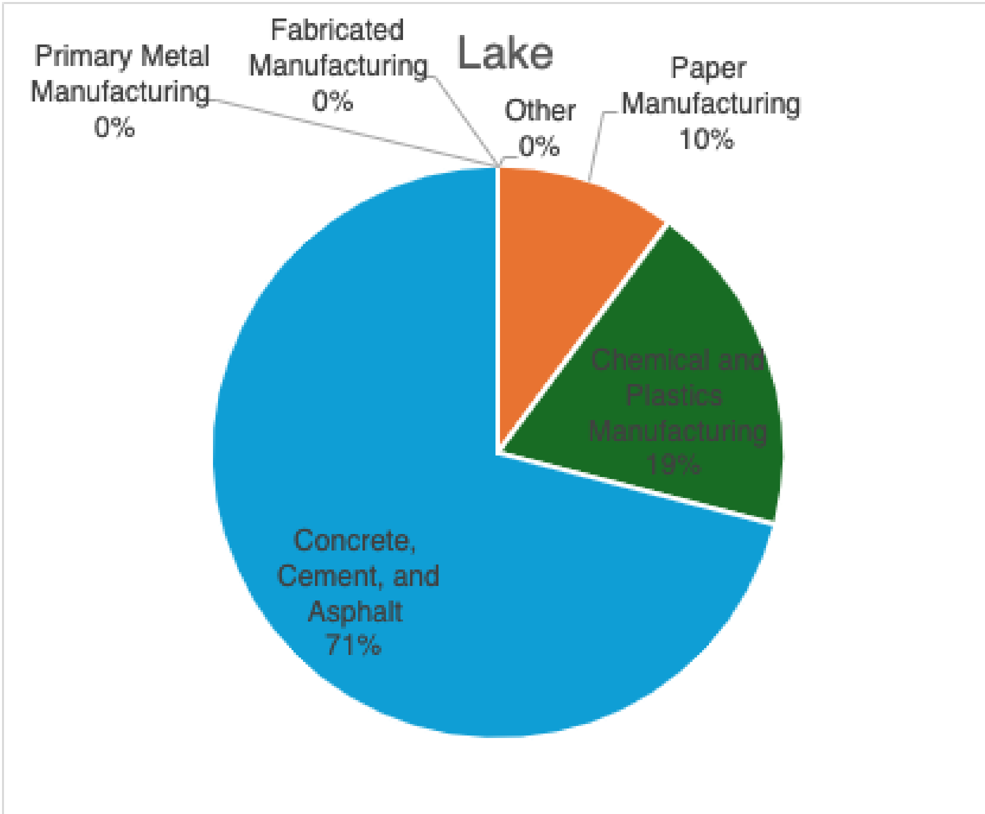


Figure 4: Breakdown of the contributions to industrial emissions in Lorain County.

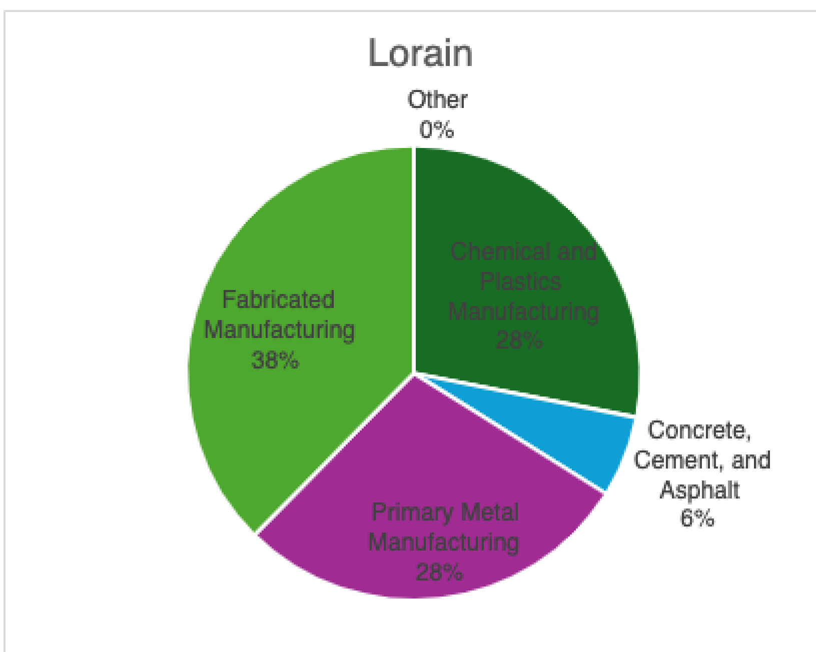
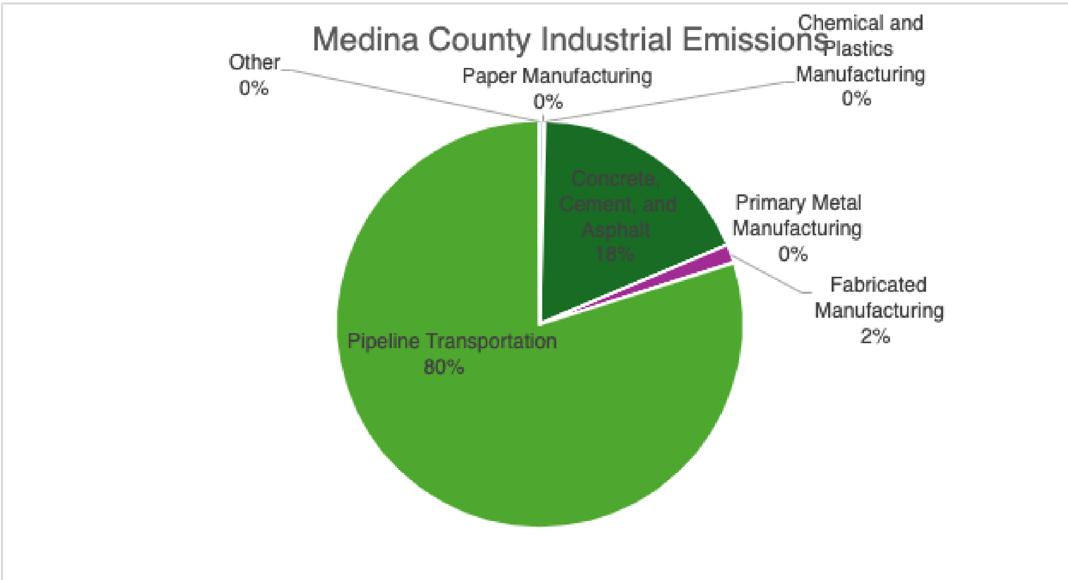


Figure 5: Breakdown of the contributions to industrial emissions in Medina County



We developed a classification system for the sources of direct emissions in the context of industrial processes. These sources are onsite energy generation, onsite transportation, heating and cooling for processes, chemical reactions, machine drives, and other. Onsite energy generation refers to emissions from onsite generators that provide power, fuel used for facility HVAC systems, and any other non-renewable electricity generation. Onsite transportation includes diesel powered machinery, trucks, and propane powered forklifts. Heating and cooling is often the largest source of industrial emissions, as it includes the combustion of fossil fuels for heating, incinerating, melting, and drying. Chemical reactions describe the emissions from chemical processes themselves in material processing. These emissions are often unavoidable since they are necessary to the process. These will be discussed further in their relative subsectors. Machine drive describes the emissions from the fuel that is consumed in running fans, pumps, compressors, or other machine-driven systems.

All Industry Solutions

Some solutions are relevant across all industries. Industrial buildings are excellent opportunities for energy savings and siting rooftop solar panels. There are also opportunities for industries to work together to coordinate recycling or communally invest in more expensive infrastructure such as carbon capture pipelines.

2025 – 2030

Energy Efficiency

All industries should conduct an energy audit to identify specific places where they could save energy in equipment updates or processes. The US Department of Energy (U.S. DOE) has funded Industrial Assessment Centers (IACs) that conduct free energy audits for small to medium sized manufacturers.[7] ENERGY STAR has free industrial energy management resources that encourage optimization of energy performance.[8]

Discussed in more detail in the Residential and Commercial Buildings sector, new buildings should be designed to conserve as much energy as possible and existing buildings should be retrofitted to adopt LED lighting, optimum insulation, automatic lighting and shading for maximizing building efficiency. These changes save money and reduce emissions from energy usage by 20-30%.[9]

Installing energy monitoring systems in industrial buildings or along key processes give real-time updates of energy usage and identify energy waste and process inefficiencies, leading to energy savings of 5-10%.[10]

Process and Material Efficiency

To reduce transportation emissions, industries should look for opportunities to source materials locally and shorten supply chains. This would also minimize supply chain disruptions and could reduce transport emissions by 15-25%.[11]

Instead of designing items for single use in cradle-to-grave frameworks, all industries should consider potential secondary use for their products, designing them in a cradle-to-cradle framework, whether by identifying opportunities to recycle materials within their own industry or by establishing partnerships with other industries.[12]

Renewable Energy

Increasing the amount of onsite energy production at industrial facilities would reduce electricity costs, improve electricity resiliency, and can reduce the grid impact of electrifying industries. Placing onsite solar on rooftops or in other locations would vastly reduce industrial grid dependence. Some industries have more opportunities for siting solar. Warehouses[13], landfills[14], and wastewater treatment centers are all excellent opportunities for large solar projects.[15]

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[7] Industrial Assessment Centers
[8] Industrial Energy Management | ENERGY STAR
[9] Industrial building efficiency
[10] Industrial energy monitoring systems
[11] Supply chain emissions reduction
[12] Cradle-to-Cradle in LCA – What is it & How does it work? | Ecochain
[13] Solar warehouses
[14] Solar at landfills
[15] MI WWTF solar selling back to the grid

Pairing rooftop solar with green roofs can make the solar panels more efficient and create a cooling effect on the buildings.[16]

New Industry Support

The changes required to decarbonize industry offer many opportunities for new industries to emerge in this region.

Manufacturers will require electric heating equipment from electric boilers to electric arc furnaces. The region should attract electric heating equipment manufacturers and maintenance companies.

While our region only has one industry, primary metal manufacturing, or steel making, that could readily justify the cost of carbon capture, transport, and sequestration, there are many smaller emitters that could collectively invest in the development of a carbon dioxide (CO_2) pipeline that connects smaller emitters to a utilizer or sequestration site. With CO_2 streams comes opportunities for CO_2 utilization, and encouraging a utilizer to locate to the region to collaborate with CO_2 suppliers will create circular industries in the region and create jobs.

Not all industrial usage of fossil fuels can be electrified because they require a chemical reaction and not just heat. In these cases, hydrogen can be used as an alternative. This region will require green hydrogen production facilities and net zero transportation and distribution of hydrogen to industrial end users.

To replace industrial transport and handling equipment from garbage trucks to forklifts and mining equipment, battery electric and hydrogen fuel cell vehicle manufacturers and distributors should be encouraged to locate in the region. Ohio is already well positioned for this role with a large automotive manufacturing workforce[17] and nearby companies with experience in building hydrogen fuel cell vehicles.[18]

2030 – 2040

Electrification / Alternative fuels

Diesel and propane-powered forklifts, material handling equipment, and fleets should be replaced by battery electric or hydrogen fuel cell alternatives. This would improve facility air quality and remove tailpipe emissions from onsite transportation[19]

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[16] green roofs and solar panels
[17] Automotive & EV in the Northeast Ohio Region
[18] Honda Advances Hydrogen Strategy with Production Launch of Fuel Cell Electric Vehicle in Ohio | Honda Global Corporate Website
[19] “Transforming Warehouses Towards a Sustainable Future.”

2040 – 2050

Carbon Capture Utilization and Sequestration

Some difficult to decarbonize industries may consider CCUS as a solution. CO_2 storage and pipelines will be required to support these industries in permanently sequestering the CO_2. This is discussed in more detail in the Primary Metal Manufacturing subsector.

Direct air capture takes CO_2 from the air, and the technology currently exists but is expensive due to solvent and material costs and significant amounts of renewable energy required to operate. In the future, it may make sense to invest in a regional direct air capture facility to aid in decarbonizing difficult to decarbonize industries and serve as an additional CO_2 source for utilization industries.[20]

Primary Metal Manufacturing: 7.51 MMTCO_2

Primary metal manufacturing includes rolling, drawing, smelting, and refining iron and steel. These are extremely energy-intensive processes that represent the highest source of industrial emissions within the five-county region. Cleveland Works, Cleveland Cliffs' Cleveland steel mill location, produces 28% of the region's industrial emissions alone, and is the focus of this section, but there are primary manufacturing facilities in all of the counties except for Geauga.[21] Fortunately, there are many opportunities for decarbonizing this sector and Cleveland-Cliffs has shown much willingness to invest in low-carbon technologies, even to the point of supporting research and development projects related to hydrogen steel making.[22]

Figure 6 shows the percentages that different processes within the iron and steel industry contribute to the total emissions of the industry.[23] The largest source of emissions from primary metal manufacturing is due to process heating. Process heating is used in the coking process that makes iron ore followed by the deoxidization process that makes iron ore into steel. Currently, Cleveland Works uses a Blast Furnace – Basic Oxygen Furnace (BF-BOF) system to produce its steel. One challenge to decarbonizing Cleveland Works is that the quality of steel must be higher than at many other steel mills because much of Cleveland Works' steel is used in automotive applications. Nevertheless, we believe that there are solutions that would successfully decarbonize this subsector over the next twenty-five years. The next largest source of emissions is onsite energy generation from conventional boilers and combined heat and power generation. Machine drive emissions come from compression of air, powering fans, pumps, and handling and processing materials. Finally, onsite transportation of materials contributes to the direct emissions in the industry.

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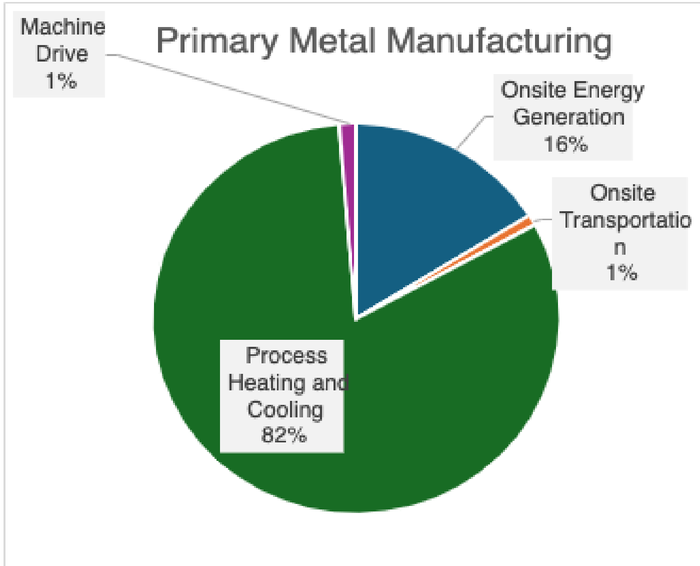
[20] DAC Facility in TX
[21] Based on the 2022 emissions from the EPA GHGRP and NOACA's 2022 Regional Emissions Inventory
[22] Cliffs research project for co-production of hydrogen with University of Wisconsin
[23] https://www.energy.gov/sites/prod/files/2013/11/f4/energy_use_and_loss_and_emissions_iron.pdf

Figure 6: Percent of total emissions based on end use in the iron and steel industry.[24]



2025 – 2030

In the short term, the majority of decarbonization methods would come from energy efficiency and process efficiency strategies and technologies. However, the next five years would need to be a time of strategizing, planning, and potentially obtaining permitting for carbon capture, utilization, and sequestration.

Energy Efficiency

Reducing friction in pumps by changing settings, more frequent maintenance, or replacing old pumps could improve energy efficiency by up to 10%.[25]

Upgrading old equipment with high-efficiency motors with variable speed drivers reduces power demand by up to 20% and allows for customizable speeds that can follow the demand.[26] Paired with smart manufacturing technology that automates the speed of flow based on the requirements at that time would even further reduce power demand from motors.[27]

Adding heat recovery systems to processes such as after compression processes would recover 50-90% of heat. This heat could be fed back into the original heating system, could be used in other processes, or could be used in combined heat and power systems.[28]

Conducting an energy audit with ENERGY STAR or the U.S. DOE's IACs could provide more specific opportunities for energy efficiency for the specific facility, including scalability of equipment to process sizes. Occasionally, facilities are over-engineered for their process.

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[24] DOE Manufacturing Energy Use and GHG analysis
[25] ABB white paper "Energy Efficiency in iron and steel making"
[26] ABB white paper, page #
[27] ABB white paper, page #
[28] ABB white paper, page #

Ensuring that the proper sized motors, pumps, fans, etc. are being used for the process being done could save up to 15% electricity.[29]

Process and Material Efficiency

Increasing the percentage of recycled content in secondary steelmaking can dramatically reduce the emissions of the steelmaking process (0.6 $MTCO_2e$ per ton of steel produced if recycled content increases to 70%)[30] The issue with this is that recycled steel is becoming increasingly rare and that some end uses of steel, such as automotive steel, are incompatible with such high percentages of recycled steel. This is not a solution that would be relevant to Cleveland Works, but other steel manufacturers in the region could adopt this.

Install water recycling systems rather than pump in and out all new water. Cleveland Works began construction on a water recycling system in 2022 with the goal of recycling 95% of its water. Recycling the water reduces energy demand by 10% and reduces the amount of treated oily wastewater being released into the Cuyahoga River.[31]

Thin slab casting of steel involves pouring thinner layers of steel rather than rolling out thicker slabs of steel. This process, while requiring major facility upgrades costing around $50 million,[32] could lead to up to 75% in energy savings.[33]

Renewable Energy

Combined heat and power (CHP) systems can generate enough electricity to exceed an operation's electricity needs. In some cases, CHP systems send electricity back to the grid. At Cleveland Works, they installed a 137 MW CHP generator that produces most of the site's electricity.[34]

Carbon Capture Utilization and Sequestration

Cleveland Works is a good candidate for CCUS due to its high volume of CO_2 released in the BF-BOF process. If this were a strategy Cliffs would like to pursue, the next five years would have to be spent in planning and permitting for building a CO_2 pipeline and sequestering the CO CO_2.

New Industry Support

If CO_2 was captured at Cleveland Works, there is potential opportunity for CO_2 utilization industries to come to the region. There are many demonstration projects that are showing ways to utilize captured CO_2, such as sustainable aviation fuel,[35] sequestering CO_2 in cement,[36] solid

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[29] ABB white paper, page #
[30] "Energy Efficiency and Advanced Technologies in the Iron and Steel Industry"
[31] U.S. Department of Energy Better Buildings Solution Center "Field Validation of Electrocoagulation Treatment for Oily Waste Water at Cleveland-Cliffs Steel Mill in Cleveland, Ohio" 2024
[32] Industrial Assessment Center Database
[33] EEATI&SI paper
[34] Cliffs Sustainability Report 2022
[35] SAF by Twelve
[36] "Carbon sequestration and storage in concrete"

long-term storage fuels,[37] and creating electricity from ions that are produced in absorption of CO2.[38]
Electrifying process heat is crucial for decarbonization as heating is the largest source of industrial emissions.[39] To support the massive number of electric heating units that will be necessary, the region should encourage manufacturers of electric boilers, heat pumps, inductive and resistance heaters, and other heating systems to locate here.

2030 – 2040

To completely decarbonize the region, the Blast-Furnace Basic-Oxygen Furnace at Cleveland Works will eventually need to be replaced. Fortunately, by the end of 2040, there should be some commercially viable options for this process to become electrified.

Electrification

Electric Arc Furnaces (EAF) are already starting to become a viable option for secondary steel making. They can take iron ore and scrap steel and make new steel. Due to the nature of the steel that Cleveland Works produces, however, the EAF could not entirely replace the BF-BOF system that currently exists. Instead, a combination of Hydrogen based Direct Reduction (H2DRI) and EAF could replace the BF-BOF system. This process is currently being used in Sweden with a technology called HYBRIT (Hydrogen Breakthrough Ironmaking Technology), and the steel is being tested by Volvo for automotive purposes.[40] Right now, it does not make commercial sense to entirely switch because making H2DRI is extremely expensive due to the price of hydrogen and the cost of construction. (Cleveland Cliffs is spending $1.3 billion on replacing one of their seven Blast Furnaces with a combined DRI-EAF system at Middletown Works.[41]) This system would lead to massive emissions reductions as the entire coking process would be replaced with hydrogen that would not produce CO_2 and should be commercially viable for replacing both BF-BOFs at Cleveland Works around 2040.

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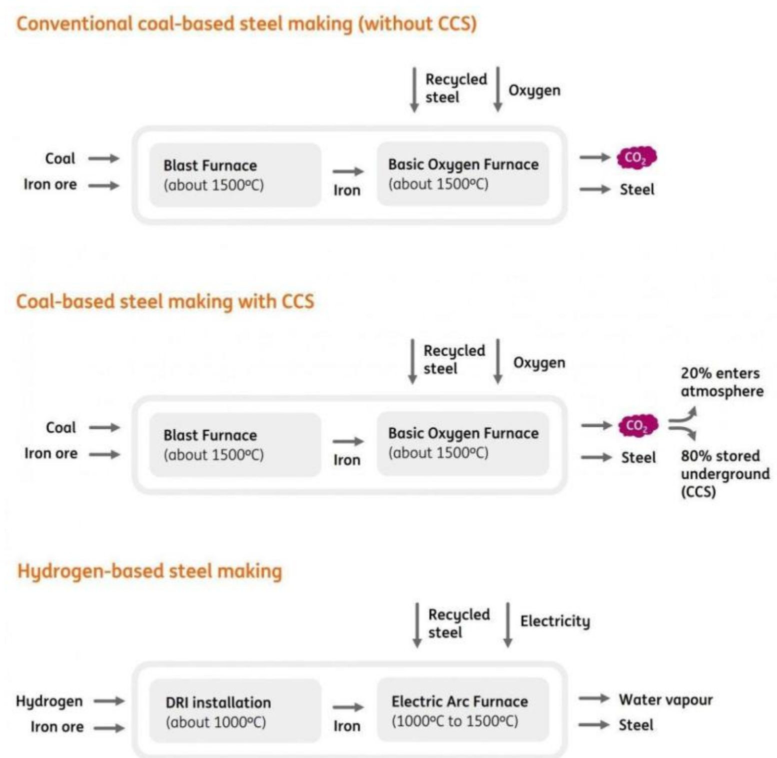
[37] Solid Fuel from electroreduction
[38] Diffusive electricity from ions
[39] Electrification of Industrial Heat
[40] Hybrit
[41] Middletown Works Project

Figure 7: Comparison of the current BF-BOF steel making process to Carbon Capture and a combined Hydrogen DRI and Electric Arc Furnace process[42]



Alternative Fuels

Hydrogen Based Direct Reduced Iron (H2-DRI) would have to be coupled with the electric arc furnace to replace the BF-BOF at Cleveland Works and any other location that makes primary steel.[43] This would be a massive investment, and hydrogen would either need to be produced onsite (50 kg H2 per ton of steel) or transported via truck or pipeline, which would be an even larger investment. However, DRI uses 39% less energy than a Blast Furnace, yielding additional energy savings associated with the switch.[44] This combined solution would depend on a clean electric grid or an ability to produce significant amounts of onsite electricity. One strategy outlined in a recent Industrious Labs study discusses the practical application of H2-DRI steelmaking at Cleveland Works.[45] The Industrious Labs study suggests replacing BF #6 with a H2-DRI by 2030, and replacing BF #5 by 2050.

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[42] "Hydrogen sparks change for the future of green steel production."
[43] H2 DRI
[44] European Parliament Briefing
[45] Cleveland Needs Clean Steel, July 2025 https://industriouslabs.org/archive/cleveland-needs-clean-steel

Carbon Capture, Utilization, and Sequestration

One pathway to decarbonizing the region's industrial sector involves capturing CO_2 at the point of emission, transporting it to a regional storage site, and injecting it deep underground for permanent sequestration. This approach to carbon management could prove economically viable for one of the region's most challenging industries to decarbonize: iron and steelmaking.[46] Establishing a mutually agreeable Community Benefits Agreement (CBA) between developers and the community could address public concerns regarding safety and transparency while mitigating costly project risks by fostering public support through a formalized process.

CCS Potential at Cleveland Works

The Cleveland Works integrated steelmaking facility operated by Cleveland-Cliffs is one of the most productive steelmaking facilities in the world. It is also one of the largest sources of GHG emissions in the Cleveland-Elyria MSA. In 2022, while one of the blast furnaces at Cleveland Works was offline for a part of the year, the facility reported direct emissions of 2.9 $MMTCO_2$.[47] This represented around 10% of the region's GHG emissions for that year.[48]

However, these emissions are not easily abated. Iron and steel manufacturing requires large amounts of heat energy, which cannot be easily or cost-effectively generated using electricity for many processes.[49] The industry in general is susceptible to high revenue volatility.[50] As an energy-intensive industry, iron and steel manufacturing is also particularly sensitive to fluctuations in the cost of energy inputs, such as natural gas.[51] These factors together contribute

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[46] *Carbon management* is an umbrella term that encompasses carbon capture, carbon transportation (via pipelines, trucks, trains, barges, or ships), the conversion of CO_2 into value-added products such as fuels and chemicals, and geologic storage of CO_2 in underground rock formations. For more on carbon management, see U.S. Department of Energy, "Carbon Management Strategy."
[47] U.S. Environmental Protection Agency, "Greenhouse Gas Reporting Program. 2023 Data Summary Spreadsheets."
[48] Total gross CO_2-equivalent emissions for NOACA's 5-county region were estimated at 30,151,210 metric tons for 2022. For a disaggregation of these regional emissions by sector and county, see City of Cleveland, Mayor's Office of Sustainability, "2022 Regional Greenhouse Gas Emissions Inventory: Cleveland-Elyria MSA."
[49] Kim et al., "Decarbonizing the Iron and Steel Industry."
[50] Khaustovich, "Iron & Steel Manufacturing in the US."
[51] Cleveland-Cliffs, for example, consumes 5 to 6 million Btu's (MMBtu) of natural gas per net ton of raw steel that it produces across its operations. The Cleveland Works facility, with a production capacity of 3.4 million tons of raw steel annually, would consume around 14 million Btu of natural gas annually at a capacity utilization of 75%, which is near the industry average over the last year. This translates to an increase in annual energy costs of around $14 million per $1/MMBtu increase in the price of natural gas just for the Cleveland Works facility. Natural gas prices for the first 12 weeks of 2025 were about $1.90/MMBtu higher on average than during the same period in 2024. For further information on Cleveland-Cliffs' natural gas consumption per ton of output, the price of natural gas, current capacity utilization in the iron & steel sector, and the production capacity at Cleveland Works, see Cleveland-Cliffs, "FY 2024 Form 10-K Annual Report."; American Iron and Steel Institute, "Industry Data: Weekly Raw Steel Production"; U.S. Energy Information Administration, "Henry Hub Natural Gas Spot Price."

to the industry's tight profit margins, making it challenging in general to attract investment for long-term capital upgrades.[52]

Cleveland-Cliffs has nonetheless continued to pursue solutions to decarbonize its operations. These include a successful trial using hydrogen as a reductant in place of carbon-intensive coke, as well as an initial engineering design for a scalable carbon capture system for blast furnace gas, both at its integrated steelmaking facility in Northwest Indiana.[53] The company expects its future emissions reductions to be driven by, among other strategies, the ongoing implementation of direct iron reduction—using hydrogen where possible—while continuing to evaluate carbon capture and utilization.[54]

Cost of CCS at Cleveland Works and GHG Reduction Potential

While implementing CC at an integrated steel facility is challenging due to the necessity of using multiple capture points, the Study Team analyzed the breakeven cost of capturing CO_2 emitted at Cleveland Works and transporting it via pipeline to a site within 100 miles for permanent geological sequestration.[55] This total cost was calculated on a dollar-per-metric-ton basis to facilitate comparison with the federal tax credit available for geological carbon sequestration. Known as the 45Q credit—named after its location in the U.S. Tax Code—this credit provides up to $85 per $MTCO_2e$ sequestered for projects starting construction before the end of 2032.[56] The 45Q credit enjoys broad, bipartisan support and is unlikely to have provisions rolled back that were enhanced under the Inflation Reduction Act.[57]

CCS has been projected as a lower cost decarbonization pathway for iron and steelmaking than other options in the near- to mid-term, particularly for the production of automotive-grade steel. Figure 8 illustrates the current and projected future cost per MT to produce steel in the U.S. for net-zero pathways, as well as for more carbon-intensive incumbent technologies, based on BloombergNEF's levelized cost models for materials.[58] The cost of recycled steel is included for reference. Cleveland-Cliffs specializes in supplying high-quality steel for the automotive sector.[59] While there are instances of automotive steel being produced entirely from scrap, significant advancements in both the quantity and quality of steel scraps are still needed before this secondary steel can be adopted in automotive manufacturing more broadly.[60]

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[52] For U.S. companies, the steel industry's net margin was less than the total market's for 7 out of 10 years from 2015 through 2024. See Damodaran, "Operating and Net Margins by Industry"; Kim et al., "Decarbonizing the Iron and Steel Industry."

[53] Dmitrovich, "Cleveland-Cliffs Holds Groundbreaking Hydrogen Trial at the Indiana Harbor."; Henry et al., "Decarbonization of the Iron and Steel Sector: Challenges and Opportunities."

[54] Cleveland-Cliffs, "FY 2024 Form 10-K Annual Report."

[55] RMI Opportunities for Decarbonizing Great Lakes Steel Operations; The *breakeven cost* represents what the selling price of CO_2 would have to be for a project to recover all costs associated with capture, transportation, and storage.

[56] The maximal amount of $85 per MT is for facilities that meet prevailing wage and apprenticeship requirements. See Congress.gov, "The Section 45Q Tax Credit for Carbon Sequestration."

[57] Siegel and Bikales, "House Republican Support Grows for Keeping Clean Energy Tax Breaks."

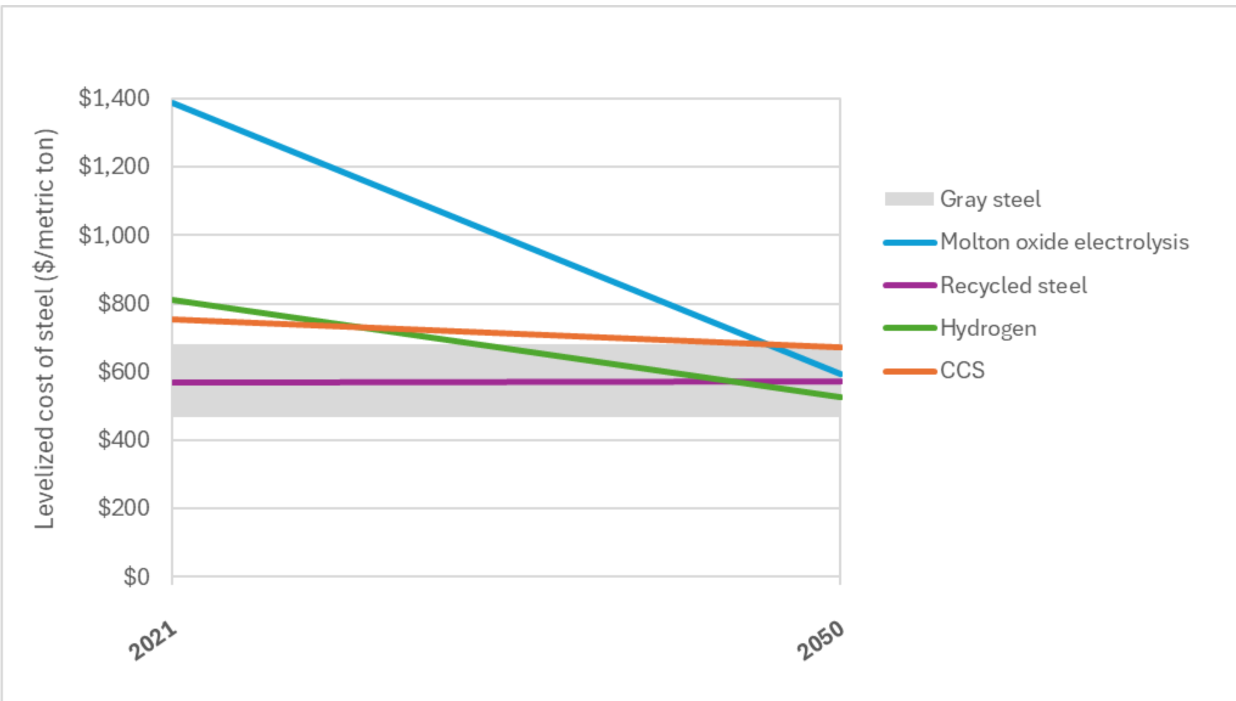
[58] Attwood, "Green Steel Demand Is Rising Faster Than Production Can Ramp Up."; Ampofo, "Steel Decarbonization: The Scale of the Challenge."

[59] Cleveland-Cliffs, "FY 2024 Form 10-K Annual Report."

[60] World Economic Forum, "Closing the Loop on Automotive Steel: A Police Agenda."

The Bloomberg analysis—which does not incorporate the effects of tax credits such as 45Q—shows the cost of steel production with CCS being less than the cost of hydrogen-based production until about 2030. One important caveat to consider in the cost projection for hydrogen is that Bloomberg assumed a delivered green hydrogen cost of $1 per kilogram for this pathway.[61] The current unsubsidized cost of green hydrogen production is more than $4 per kg, which does not include the cost of transportation or storage.[62] Such an increase in the total cost of delivered hydrogen likely pushes the crossover point where hydrogen-based steelmaking falls below a CCS pathway past 2030. Indeed, an analysis by the Boston Consulting Group conducted after passage of the Inflation Reduction Act (IRA) found that after incorporating the effects of the IRA's expanded tax credits, steel production with CCS would cost an estimated $55 per ton less than a green hydrogen-based pathway by 2030.[63]

Figure 8. Average levelized cost of net-zero steel production in 2021 and 2050. Adapted from BloombergNEF.



Cost of Capture

The cost of retrofitting Cleveland Works with a carbon capture system was modeled using a reference case developed by the National Energy Technology Laboratory (NETL).[64] Under this reference case, NETL estimated the capital expenditures and ongoing operating expenses to

[61] BloombergNEF, "Scaling Up Hydrogen: The Case for Low-Carbon Steel."
[62] Lazard, "Levelized Cost of Energy+."
[63] Boston Consulting Group and Breakthrough Energy, "Impact of IRA, IIJA, CHIPS, and Energy Act of 2020 on Clean Technologies."
[64] Hughes et al., "Cost of Capturing CO_2 from Industrial Sources."

retrofit a BF-BOF integrated steel mill to capture 90% of the CO_2 from flue gas and exhaust gas streams. In particular, NETL modeled the cost to capture CO_2 from coke oven gas, the blast furnace stove, and the power plant stack, as these are the point sources with the highest CO_2 concentrations within a BF-BOF process. At Cleveland Works, these combustion-related emissions represent 80-85% of the facility's annual greenhouse gas (GHG) emissions.[65]

The capital costs for a CCS retrofit were scaled from the reference case to Cleveland Works based on the CO_2 flowrates at each facility.[66] Converting the cost to build and operate carbon capture at Cleveland Works to a dollar-per-metric-ton cost of capture (CoC) basis depends on several operational and financial assumptions. These are listed in Table 1 below.

Table 1: Assumptions Made in Calculating Cost of Capture at Cleveland Works

Parameter	Value	Source
Construction duration	3 years	NETL reference case
Expected life of retrofitted equipment	30 years	NETL reference case
Cost of equity for steel industry	9.17%	Damodaran, NYU Stern School of Business[67]
Electricity price for large industrial customers in the U.S.	\$50/MWh	IEA[68]
Before-tax cost of debt for steel industry	5.78%	Damodaran, NYU[69]
Effective tax rate	25%	Cleveland-Cliffs Form 10-K annual report for FY 2024
Price of natural gas for iron & steel mfg. (NAICS 331110) in the Midwest	\$4.40/MMBtu	EIA Manufacturing Energy Consumption Survey (MECS) [70]
Depreciation	150% declining balance accelerated depreciation	NETL reference case

All dollar values are in 2024 dollars. Energy prices, tax rates, and costs of capital reflect 2024 conditions.

[65] U.S. Environmental Protection Agency, "Greenhouse Gas Reporting Program. 2023 Data Summary Spreadsheets."
[66] Scaled capital costs were converted to 2024 dollars using the Chemical Engineering Plant Cost Index (CEPCI). For a discussion of using CO2 flowrates to scale capital costs for carbon capture, see Hughes et al., "Analysis of Carbon Capture Retrofits for Cement Plants."
[67] Damodaran, "Costs of Capital by Industry Sector."
[68] International Energy Agency, "Electricity 2025."
[69] Damodaran, "Costs of Capital by Industry Sector."
[70] Dollar values from the 2018 MECS survey—the most recently available version as of this writing—were inflated to 2024 dollars using the Consumer Price Index for All Urban Consumers: Utility (Piped) Gas Service in U.S. City Average. See U.S. Energy Information Administration, "Manufacturing Energy Consumption Survey (MECS): 2018 MECS Survey Data."; U.S. Bureau of Labor Statistics, "Consumer Price Index for All Urban Consumers: Utility (Piped) Gas Service in U.S. City Average."

Given this set of fixed assumptions, the Study Team calculated the cost of capturing carbon dioxide per metric ton under different scenarios where the values for additional parameters were allowed to vary.[71] These additional factors include the following:

Engineering, procurement, and construction (EPC) costs include detailed design, contractor permitting, and project management costs. Under NETL's cost estimation methodology, EPC costs are estimated as a percentage of bare erected costs (BEC), which include the cost of equipment and facilities to be installed along with construction labor. NETL's reference case for retrofitting a steel plant with carbon capture includes EPC costs that are 17.5% of BEC. NETL has estimated EPC costs of 10% BEC for more mature technology deployments such as fossil energy plants.[72]

Process contingency represents the uncertainty in cost estimates due to the maturity level of a given technology. Process contingency is also estimated as a percentage of BEC. NETL's reference case for retrofitting a steel plant with carbon capture includes process contingency that is 17% of BEC. There are currently 10 large, commercial-scale CO_2 capture projects in operation throughout the world with an annual capacity of more than 1 $MMTCO_2e$, half of which are in the United States.[73] However, an additional 14 such deployments are under construction globally, 4 of which are in the U.S.[74] As commercialization progresses and more design data becomes available, estimated process contingency falls to no higher than 10% according to cost engineering best practices.[75]

Project contingency is the cost allocated to address general uncertainties in cost estimates and mitigate potential risks during the development of a project.[76] NETL's reference case for retrofitting a steel plant with carbon capture includes project contingency that is 20% of the sum of BEC, EPC costs, and process contingency. As with process contingency, a project contingency rate of 10% is appropriate for commercial-scale technology deployments.[77]

Capacity utilization is the percentage of a steel mill's total potential production capacity that is actually being used to produce steel. The steel industry in the U.S. has a target of at least 80 percent capacity utilization.[78] More recently, the industry has been operating domestically at a capacity utilization of around 75 percent.[79]

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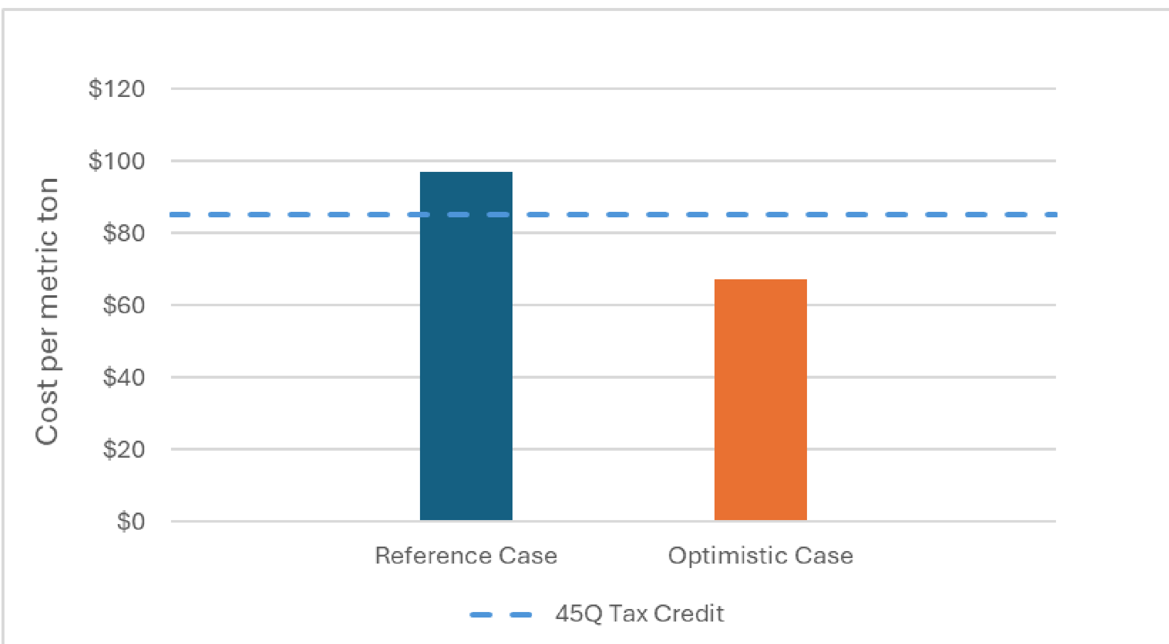
[71] For a more detailed discussion of NETL's methodology for calculating the cost of CO_2 captured from industrial sources, see Hughes et al., "User Guide for the Public Industrial CO_2 Capture Retrofit Database Models.""; Theis, "Quality Guidelines for Energy Systems Studies."
[72] Fout et al., "Cost and Performance Baseline for Fossil Energy Plants Volume 1a."
[73] International Energy Agency, "CCUS Projects Database."
[74] Ibid.
[75] Association for the Advancement of Cost Engineering (AACE) International, "Conducting Technical and Economic Evaluations – as Applied for the Process and Utility Industries TCM Framework: 3.2 – Asset Planning, 3.3 – Investment Decision Making, AACE International Recommended Practice No. 16R-90."
[76] Hughes et al., "Quality Guidelines for Energy System Studies."
[77] Stevens, "Current and Future Technologies for Power Generation with Post-Combustion Carbon Capture."
[78] American Iron and Steel Institute, "Public Policy: Trade."
[79] American Iron and Steel Institute, "Industry Data: Weekly Raw Steel Production."

Share financed with debt is the percentage of a project financed with debt as opposed to equity. The NETL reference case for retrofitting a steel plant with carbon capture assumed a capital structure that included 39% debt. An analysis conducted by the World Economic Forum around the same time as NETL's evaluation indicated an upper limit of 60% debt financing for steel CCS.[80]

For the sake of simplicity, we show below the combined effects of these variable factors on the cost of carbon capture at Cleveland Works under a reference case and an optimistic case. Under the reference case, EPC costs, process and project contingencies, and the share of a carbon capture retrofit financed with debt are the same as the NETL reference case for a steel plant, with capacity utilization at its current domestic level of 75%. Under the optimistic case, EPC costs, process contingency, and project contingency are at a reduced—and more favorable—level of 10%, with capacity utilization and the share of carbon capture financed by debt at higher rates of 80% and 60%, respectively.

Figure 9. Estimated cost of CO_2 capture at Cleveland Works (2024 USD)



Under the reference case, the cost of CO_2 capture at Cleveland Works is estimated at $96.84 per MT.[81] This would yield estimated annual mitigation of 2.42 $MMTCO_2e$.[82] Under the optimistic

[80] World Economic Forum and Oliver Wyman, "Financing the Transition to a Net-Zero Future."
[81] The reference case assumes EPC costs of 17.5%, process contingency of 17%, project contingency of 20%, capacity utilization of 75%, and debt's share for financing a carbon capture retrofit of 39%.
[82] A 2022 response to a US EPA information request for Cleveland Works indicated that the facility operated at 82.7% capacity in 2021 based on its reported steel production for that year and the plant's

case, the cost of CO_2 capture is estimated at $67.30 per MT.[83] This would yield estimated annual CO_2 mitigation of 2.58 $MMTCO_2e$.[84] The cost of capture under the optimistic case—nonetheless plausible with maturing commercialization for carbon capture and the steel industry reaching its target for capacity utilization—would be lower than the $85-per-ton 45Q tax credit for CO_2 captured for geological sequestration. There would thus be remaining value to cover the cost of pipeline transportation and permanent storage.

Geological Sequestration

Even upon reaching commercial scale across the carbon management value chain, the utilization portion of CCUS is projected to account for only 10-15% of captured emissions by 2050 for the use of CO_2 in products that support climate goals, such as sustainable aviation fuel.[85] The remainder of captured emissions will have to be geologically sequestered. For such large volumes of CO_2, pipelines are expected to be the most economical and efficient mode of transport.[86]

The Study Team evaluated the cost of transporting captured CO_2 via pipeline to potential storage sites in the eastern half of Ohio. The analysis focused on saline formations—deep underground structures composed of permeable rock saturated with saltwater—which have the greatest potential storage capacity for CO_2.[87] NETL has developed both a CO_2 Saline Storage Cost Model and a CO_2 Transport Cost Model, which the Study Team used to estimate the cost of CO_2 transportation and storage on a per-metric-ton basis.[88]

Potential Storage Locations and Storage Resource Potential

In addition to having enough capacity to store the volume of CO_2 captured, a suitable storage site must have sufficient permeability. CO_2 is stored underground as a fluid. The more permeable the rock formation in which the CO_2 is stored, the less energy has to be spent overcoming resistance to fluid flow during injection. Differences in permeability across Ohio's

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3.4-million-ton production capacity. This implies that the facility would emit nearly 3.6 $MMTCO_2$ annually at 100% capacity given the 2.96 $MMTCO_2$ from combustion that were reported for the facility for 2021. At 75% capacity utilization and a capture rate of 90%, 2.42 $MMTCO_2$ would be captured. See Cleveland-Cliffs, "Submitting Cleveland Cliffs Cleveland Works ICR Response," June 3, 2022.2; Cleveland-Cliffs, "FY 2024 Form 10-K Annual Report."

[83] The optimistic case assumes EPC costs of 10%, process contingency of 10%, project contingency of 10%, capacity utilization of 80%, and debt's share for financing a carbon capture retrofit of 60%.

[84] *Supra*, fn 33. At 80% capacity utilization and a capture rate of 90%, 2.58 $MMTCO_2$ would be captured.

[85] Under the Net-Zero America Project's *high electrification* and *less-high electrification* scenarios, production of synthetic fuels utilizes approximately 88% and 85% of captured emissions, respectively, by 2050. See Larson et al., "Net-Zero America: Potential Pathways, Infrastructure, and Impacts."

[86] Smith et al., "The Cost of CO_2 Transport and Storage in Global Integrated Assessment Modeling."

[87] Other suitable storage formations include oil and natural gas reservoirs, unmineable coal seams, basalt formations, and organic-rich shales. See National Energy Technology Laboratory, "Carbon Storage FAQs."

[88] Morgan, Guinan, and Sheriff, "FECM/NETL CO_2 Transport Cost Model.""; Shih and Morgan, "FECM/NETL CO_2 Saline Storage Cost Model."

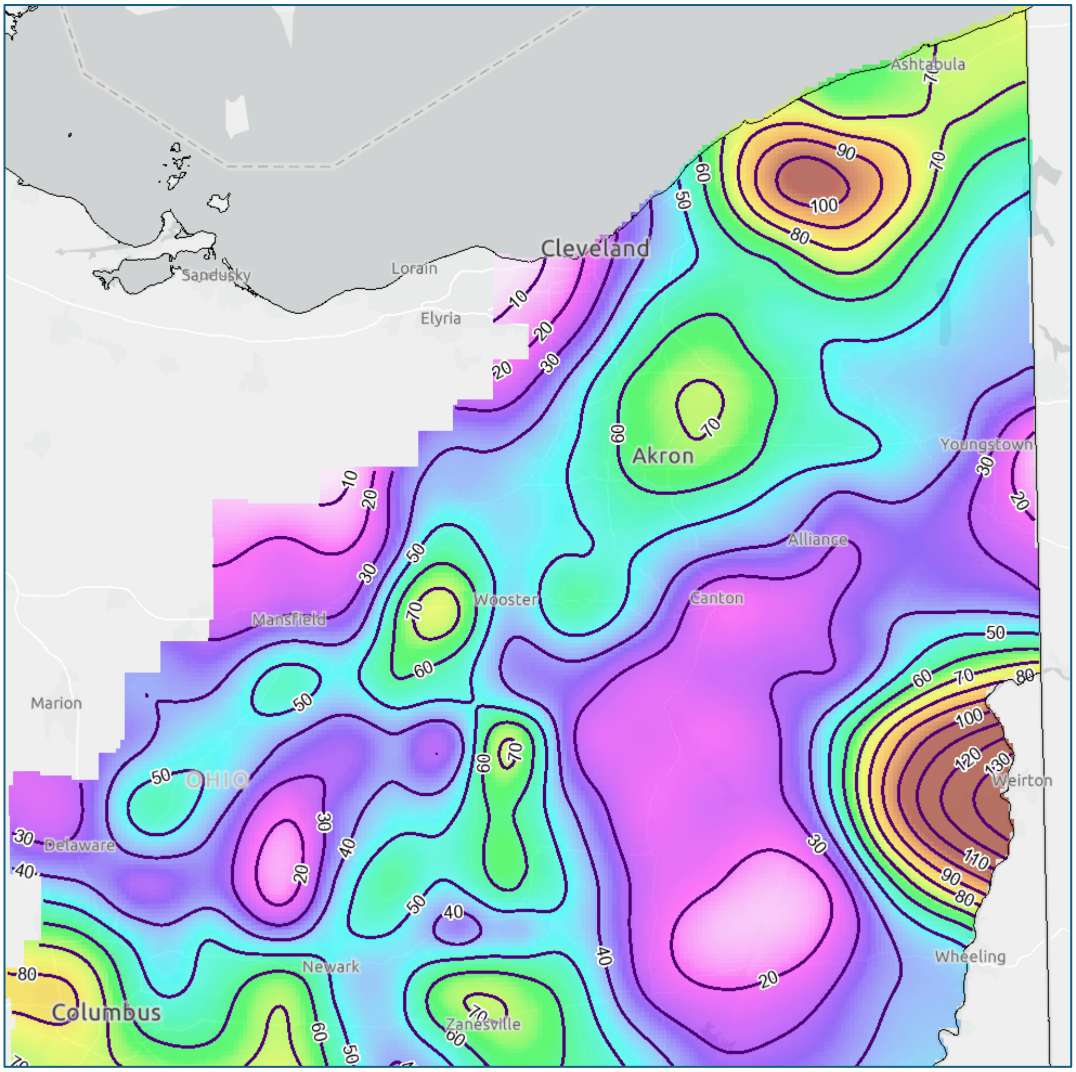
many geological formations explain the wide variance in the cost of storing CO_2 at potential sites. For example, of the nine Ohio formations included in NETL's Saline Storage Cost Model, the two with the highest permeability have an average breakeven price for CO_2 storage of $15-$25 per MT under the model's default financial assumptions, while the two least permeable formations have an average breakeven price per MT of $648-$981 for geological sequestration.[89]

The Upper Copper Ridge formation has the highest estimated permeability among formations in the eastern half of Ohio that are included in the NETL cost model's geologic database. Figure 10 shows the CO_2 storage resource potential of the Upper Copper Ridge formation in the region based on an analysis of borehole samples performed under the Midwest Regional Carbon Initiative (MRCI).[90] The contours shown in Figure 10 illustrate the CO_2 storage potential in terms of thousand metric tons per square kilometer.

[89] *See* the Saline Storage Cost Model's *CO2_S_COM_Results.xlsm* Supplementary Results file. Dollar amounts are in 2024 dollars assuming a 2.3% CAGR between the 2023 and 2028 breakeven prices that are included for each formation in the Supplementary Results file. Permeability is measured according to Darcy's law, describing the flow of a fluid through a porous medium, where a higher value indicates higher permeability.

[90] MRCI is a DOE-sponsored initiative led by Battelle and the Illinois State Geological Survey to accelerate CCUS deployment in the Midwest. For further discussion of the CO_2 storage potential of geological formations in Eastern Ohio, see Fukai, "CO_2 Storage Resource and Reservoir Feasibility Assessment for Deep Saline Cambrian-Ordovician Formations in Eastern Ohio."; Fukai, "CO_2 Storage Resource Assessment of Deep Saline Cambrian-Ordovician Formations in Eastern Ohio."

Figure 10. Prospective CO_2 Storage Potential for the Upper Copper Ridge in Eastern OH



Map (in thousand metric tons per square kilometer)
Source: Midwest Regional Carbon Initiative (MCRI)[91]

At an average depth of 5,157 feet in Eastern Ohio, the Upper Copper Ridge formation has an estimated storage potential of around 100,000 $MTCO_2e$ per square kilometer in parts of Geauga and Lake Counties, and 130,000 $MMTCO_2e$ per square kilometer farther southeast in Jefferson County.[92] These should be considered illustrative screening-level estimates of resource potential. A site-specific characterization study would be needed to determine the suitability and economic viability of the Upper Copper Ridge or other geological formations for long-term CO_2

[91] Midwest Regional Carbon Initiative (MRCI), "MRCI Cambrian-Ordovician Carbon System Map."
[92] These storage densities reflect estimates at the P50 (median) percentile.

storage more locally.[93] CO_2 storage operators are currently undertaking these more detailed assessments of multiple geological formations in and around Jefferson County.[94]

Pipeline Routing

The Study Team mapped hypothetical pipeline routes to the two locations shown in Figure 11 having at least 100,000 MT per square kilometer of CO_2 storage potential.[95] Pipelines were mapped to not only minimize the distance from Cleveland Works to the potential storage sites, but to also minimize their overlap with developed areas where people live and work.[96] The resulting hypothetical routes include 50.8 miles of pipeline to a location centered in northern Geauga County, and 97.4 miles of pipeline to a site centered in eastern Jefferson County, as illustrated below in Figure 11. Based on MRCI's estimates of CO_2 storage resource in the region, around 70.4 $MMTCO_2$ could potentially be stored in northeast Ohio within the Upper Copper Ridge formation, while 94.6 $MMTCO_2$ could potentially be stored within the same geological formation in southeast Ohio in Jefferson County.[97] This could mitigate an estimated 27-37 years' worth of CO_2 emissions captured from Cleveland Works, assuming a 90% CO_2 capture rate and a targeted 80% capacity utilization for the steel industry.

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[93] For more information on the the phased approach to site selection and assessment for CO_2 storage as employed under the U.S. Department of Energy's Carbon Storage Assurance Facility Enterprise (CarboneSAFE) Initiative, see National Energy Technology Laboratory, "CarboSAFE."

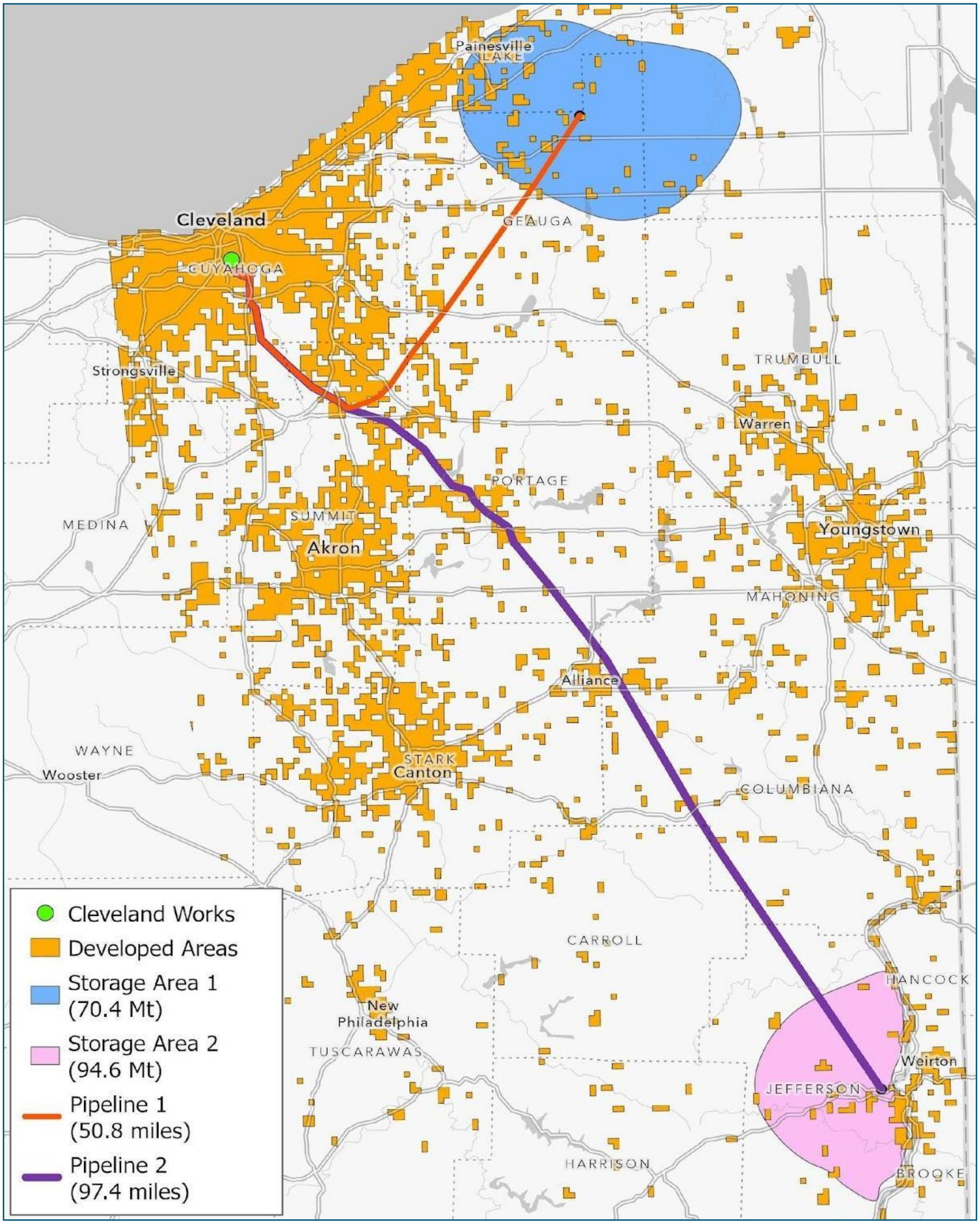
[94] Wernette, "Bipartisan Infrastructure Law (BIL): Tri-State CO_2 Storage Hub."

[95] The storage locations were mapped by the centroid of the contour with the highest projected storage capacity for the Upper Copper Ridge formation.

[96] Developed areas were identified according to the U.S. Geological Survey's (USGS) National Landcover Database. See U.S. Geological Survey, "National Land Cover Database."" Areas mapped in Figure 11 are those with low, medium, and high development intensities. For a description of developed area intensity levels, see Multi-Resolution Land Characteristics Consortium, "National Land Cover Database Class Legend and Description." The *Optimal Corridor Connections* tool was used in the desktop software ArcGIS Pro to map a shortest distance pipeline path that avoided developed areas, with greater weight for avoidance placed on high intensity developed areas.

[97] Storage potential for a location centered in Geauga County is based on the areas of the 80, 90, and 100 thousand metric-ton-per-square-kilometer contours shown in Figure 10. Storage potential for a location centered in Jefferson County is based on the areas of the 110, 120, and 130 thousand metric-ton-per-square-kilometer contours.

Figure 11. Prospective Pipeline Routes for CO_2 Captured at Cleveland Works



Mt = million metric tons

Cost of Pipeline Transportation and Sequestration

Like the cost of capture, the cost-per-metric-ton to build and operate a CO_2 pipeline and storage facility depends on several assumptions. Some of these, which were used in conjunction with NETL's Saline Storage Cost Model and Transport Cost Model for CO_2, are listed below in Table 2.

Table 2. Assumptions Made in Calculating Cost of CO_2 Transportation and Storage

Parameter	Value	Source
Construction duration	3 years	Same as for CO_2 capture under NETL reference case
Length of operations for transportation and storage	30 years	Same as for CO_2 capture under NETL reference case
Cost of equity for transportation and storage	7.85%	Cost of equity for Oil/Gas Distribution Industry; Damodaran, NYU Stern School of Business [98]
Before-tax cost of debt for transportation and storage	5.53%	Cost of debt for Oil/Gas Distribution Industry; Damodaran, NYU Stern School of Business [99]
Effective tax rate	19.72%	Effective tax rate for Oil/Gas Distribution industry; Damodaran, NYU Stern School of Business [100]
Type of instrument used for financial responsibility for corrective action, well plugging, and post-injection site care	Trust Fund	Used for some existing CO_2 storage projects;[101] suitable for multiple phases of project (corrective action, well plugging, and post-injection site care)[102]
Trust Fund discount rate	6.43%	Nominal return for an illustrative portfolio of 50% 10-year Treasury securities, 25% Aaa corporate bonds, and 25% equities (S&P 500) over a 30-year horizon (1995-2024)[103]

[98] Damodaran, "Costs of Capital by Industry Sector." Some companies currently in the midstream segment for oil and gas are also actively exploring transportation and storage for CO_2.
[99] Ibid.
[100] Damodaran, "Effective Tax Rate by Industry."
[101] For examples of CO_2 storage operators using trust funds to meet financial responsibility requirements, see North Dakota Department of Mineral Resources, "Class VI - Geologic Sequestration Wells."
[102] For a description of the suitability of trust funds to meet the *range* of financial responsibility requirements, see U.S. Environmental Protection Agency, "Research and Analysis in Support of UIC Class VI Program Financial Responsibility Requirements and Guidance."
[103] This weighting for an illustrative Trust Fund portfolio for financial responsibility of a CO_2 injection well is presented by NETL in Energy Sector Planning and Analysis (ESPA)Energy Sector Planning and Analysis (ESPA), "Financial Responsibility Pricing Foundations White Paper."

<table>
<tr><td>Electricity cost</td><td>$71.60/MWh</td><td>EIA price of electricity for industrial sector in Ohio[104]</td></tr>
<tr><td>Depreciation for pipeline transportation</td><td rowspan="2">150% declining balance accelerated depreciation</td><td rowspan="4">Default values in NETL cost models; consistent with IRS guidance[105]</td></tr>
<tr><td>Depreciation for storage site characterization and development capital costs</td></tr>
<tr><td>Depreciation for well installation capital costs</td><td>200% declining balance accelerated depreciation</td></tr>
<tr><td>Depreciation for seismic capital costs for long-term well monitoring</td><td>Straight line</td></tr>
<tr><td>Change in elevation from point of capture to CO_2 storage facility</td><td>+600 feet</td><td>Review of elevation contours in the U.S. Geological Survey's National Map[106]</td></tr>
</table>

All dollar values are in 2024 dollars. Tax rates and costs of capital reflect 2024 conditions.

The Study Team calculated the cost of transporting and geologically sequestering CO_2 given the assumptions outlined above. As with carbon capture, the cost of transportation and storage was calculated for both a reference case and an optimistic case. For the reference case, NETL's CO_2 transport and storage cost models were run using default values for the following parameters: project contingency; process contingency; the percent of infrastructure financed with debt; and the timeframe for post-injection site care.[107]

The default values in NETL's cost models, representing the reference case, serve as a baseline reflecting current conditions.[108] For project contingency and process contingency, these default values were 15% and 20%, respectively. Under the reference case, 55% of infrastructure

[104] NETL's cost models use the EIA's industrial price of electricity for electricity to power pumps used for pipeline transportation and injection. For the average price of electricity for the industrial sector in Ohio in 2024, see U.S. Energy Information Administration, "Electricity Data Browser."
[105] For the IRS guidance underpinning the default values for depreciation, see Internal Revenue Service, "Publication 946: How to Depreciate Property."
[106] U.S. Geological Survey, "The National Map: National Boundaries Dataset."
[107] Post-injection site care (PISC) is the period after which CO_2 injection has ceased when well operators must undertake ongoing monitoring of the injection zone and perform any necessary corrective action to ensure the safety of underground sources of drinking water (USDW). PISC can last from 10 to 50 years. Upon completion of this period, when the injected CO_2 has been demonstrated to "no longer pose an endangerment to USDWs," the operator is issued a certificate of project completion and relieved of ongoing monitoring and maintenance requirements. For further discussion on the duration of PISC, including applicable federal regulation, see Great Plains Institute and Environmental Defense Fund, "Approaches to Long-Term Liability of Class VI Injection Wells."; Post-injection Site Care and Site Closure.
[108] For further discussion of baseline results in NETL's CO_2 Saline Storage Cost Model, see Morgan and Grant, "FE/NETL CO_2 Saline Storage Cost Model: Model Description and Baseline Results."

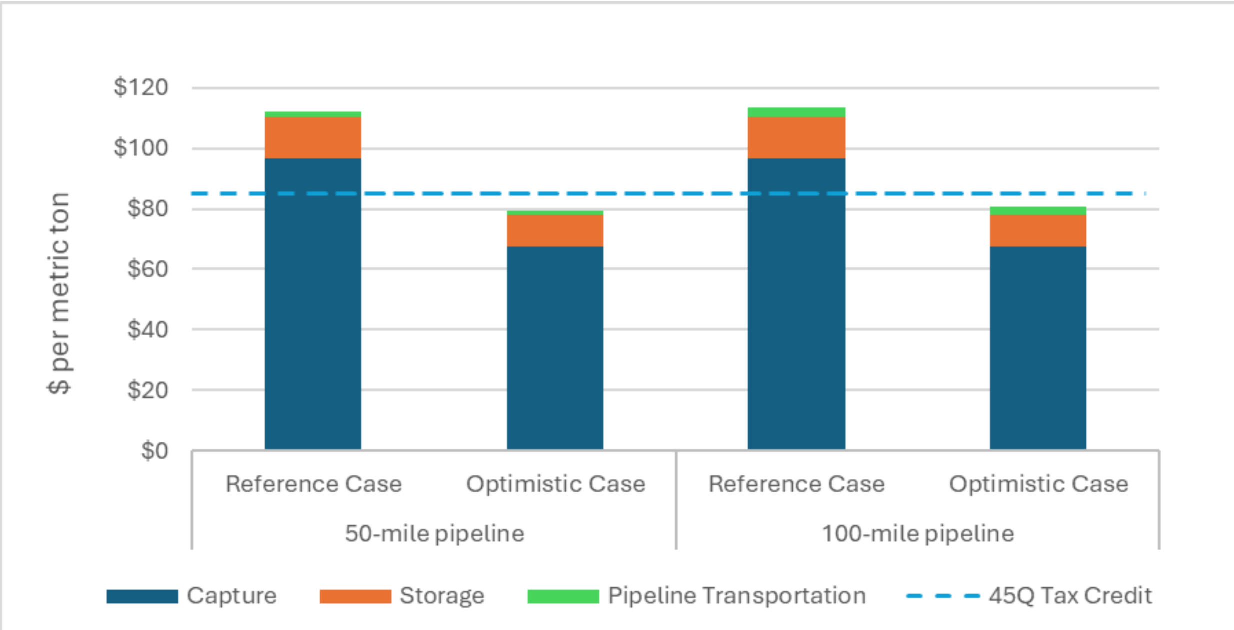
spending would be financed through debt, while the post-injection site care timeframe would be 50 years—the default duration stipulated by federal regulations under the Safe Drinking Water Act. [109] Additionally, capacity utilization was assumed to be 75%, consistent with the rate used for the steel industry in the carbon capture reference case.

For the optimistic case, project and process contingencies were set at 10%, the share of debt finance at 60%, and capacity utilization at 80%, consistent with the values for these parameters for the development of carbon capture under more favorable conditions. The timeframe for post-injection site care was assumed to be 20 years under the optimistic case. Federal regulations allow for an alternative timeframe other than the default length of 50 years for this period when CO_2 injection ceases and operators must continue monitoring the well and address any potential threats to underground sources of drinking water. In Wyoming, one of the first states to be granted authority by US EPA to regulate CO_2 injection wells at the state level, this period is at least 20 years.[110]

Figure 12 shows the resulting cost of transport and storage added to the cost of capture under both the reference and optimistic cases for a 50-mile pipeline and a 100-mile pipeline. Most of this total cost is dedicated to capturing CO2, followed by storage, and then pipeline transportation. Under the reference case, the total cost to capture, transport, and store CO_2 from Cleveland Works would exceed the $85-per-metric-ton 45Q federal tax credit. However, this total cost—inclusive of the required returns to investors and the cost to service debt to finance such a project—is estimated at around $80-per-metric ton in the optimistic case, both with a 50-mile pipeline and a 100-mile pipeline. While this sort of screening-level cost estimate may involve considerable uncertainty, it remains plausible that a CO_2 capture, transport, and storage project in Northeast Ohio could achieve a per-metric-ton cost below the value of the 45Q federal tax credit–leaving sufficient margin for community investment such as CO_2 training for first responders and workforce development for occupations in the low-carbon economy.

[109] Post-injection Site Care and Site Closure.
[110] Lewis and Fornstrom, “Wyoming’s Class VI Regulations: Managing the Risk of CO_2 Storage.”

Figure 12. Estimated cost of capture, transport, and storage of CO_2 from Cleveland Works



Health Co-Benefits of CCS at Cleveland Works

One of the primary additional benefits of strategies such as carbon capture to reduce GHG emissions is the accompanying reduction in co-pollutants. Improvements in air quality resulting from pollutants such as particulate matter (PM) being removed from the atmosphere alongside carbon dioxide can positively impact human health. This benefit can be estimated at the county level using U.S. EPA's Co-Benefits Risk Assessment (COBRA) model.[111] This peer-reviewed screening tool enabled the Study Team to estimate the air quality, human health, and associated economic impacts of carbon capture as an emission reduction strategy specifically for the steel industry.

In the case of fine particulate matter with a diameter of less than 2.5 micrometers—also known as $PM_{2.5}$—the cost to capture the condensable portion of this air pollutant is already reflected in the project cost developed by NETL in the reference case for carbon capture at an integrated steel mill.[112] Based on a review of facility-level data for air pollutant emissions reported to the

[111] U.S. Environmental Protection Agency, "CO-Benefits Risk Assessment Health Impacts Screening and Mapping Tool (COBRA)."

[112] Hughes et al., "Cost of Capturing CO_2 from Industrial Sources"; Great Plains Institute and Carbon Solutions, "Carbon Capture Co-Benefits: Carbon Capture's Role in Removing Pollutants and Reducing Health Impacts." The CANSOLV CO_2 absorption system whose cost was modeled in the NETL study includes a direct contact cooler (DCC) as a pre-scrubber that removes 100% of the *condensable* $PM_{2.5}$ prior to capturing 90 percent of the inlet CO2. $PM_{2.5}$ is typically divided into two types: filterable and condensable particulates. Condensable particulates are initially emitted as vapors or gases that condense into liquid or solid form after cooling. In contrast, filterable particulates are already in a solid or liquid state at the time of emission.

U.S. EPA through its National Emissions Inventory, an estimated 5.14 short tons of condensable $PM_{2.5}$ are emitted per 100,000 $MTCO_2e$ emissions at Cleveland Works.[113] If the facility were retrofitted with carbon capture and operated at 80% of its productive capacity, the estimated annual CO_2 mitigation would be accompanied by the annual abatement of 147.31 short tons of $PM_{2.5}$.[114] Table 3 illustrates the health benefits of this reduction in $PM_{2.5}$ as estimated using U.S. EPA's COBRA tool, both for NOACA's five-county region and for Ohio overall.[115]

Table 3. Estimated Annual Public Health Benefits of $PM_{2.5}$ Reduction

Health Endpoint	Reduction in annual cases/costs for Cleveland-Elyria MSA	Reduction in annual cases/costs for Ohio overall
Mortality	2.2	3.2
Nonfatal heart attacks	0.9	1.3
Asthma onset	2.6	3.9
Asthma symptoms	490	730
Minor restricted activity days	800	1,200
Work loss days	135	200
Total health benefits	**$33,050,000**	**$48,840,000**

Health endpoint values reflect the midpoint of high and low estimates from U.S. EPA's COBRA model. Dollar values are in 2024 dollars.[116]

Community Benefits Agreements for Industrial-Scale CCS

Large infrastructure projects—such as industrial-scale carbon capture involving pipeline transportation and geological sequestration—can raise public concerns regarding safety, landowner protections, and the distribution of financial benefits to the communities most

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113 Criteria air pollutants under the National Emissions Inventory (NEI) are reported in short tons, also known as U.S. tons, while greenhouse gas emissions under the EPA's Greenhouse Gas Reporting Program (GHGRP) are reported in metric tons. For 2020-2022, the three most recent years for which data is available, there were an estimated 163.6 short tons of $PM_{2.5}$ emissions annually at Cleveland Works. During the same period, as reported under the GHGRP program, the facility had 3.18 $MMTCO_2e$ emissions annually on average. For facility-level greenhouse gas and air emissions data, see U.S. Environmental Protection Agency, "Greenhouse Gas Reporting Program. 2023 Data Summary Spreadsheets"; U.S. Environmental Protection Agency, "2020-2022 Air Emissions Modeling Platforms."

114 As previously noted, the Study Team estimated annual CO_2 emissions for Cleveland Works of nearly 3.6 $MMTCO_2$ at 100% capacity utilization. The CO_2 absorption system includes a pre-scrubber that would remove 100% of the condensable $PM_{2.5}$ prior to capturing 90 percent of the inlet CO2. At 80 percent capacity utilization, $PM_{2.5}$ would be removed from approximately 2.9 $MMTCO_2$

115 Health benefits were estimated using the COBRA Web Edition at https://cobra.epa.gov/. The value of future benefits was calculated using COBRA's default discount rate of 2%.

116 Dollar values were adjusted using GDP Implicit Price Deflator. See U.S. Bureau of Economic Analysis, "Gross Domestic Product: Implicit Price Deflator."

affected by the project.[117] If left unaddressed, these concerns may result in delays which, if prolonged for as little as two years, can nearly double overall project costs.[118] One way to address the community's concerns while increasing project certainty for the developer is through a Community Benefits Agreement (CBA) between the two parties.[119]

A CBA is a legally binding contract negotiated between a project developer and a community—often represented by a coalition of local groups—that outlines the specific benefits the community will receive in exchange for their support or lack of opposition to a project. Large-scale energy developments typically require a range of complex permits and land use approvals from various local, state, and federal agencies. The permitting process often includes opportunities for public challenges, which can result in delays or even cancellation of a project. Through a CBA, community representatives agree to support or refrain from opposing a project during these regulatory and permitting stages. A CBA can serve as a collaborative framework for addressing critical project issues, potentially offering increased long-term stability for the development.

What qualifies as a "benefit" in a CBA varies based on the specific needs and priorities of each community. For some, this might include enhancements to local infrastructure—like the development of community centers, green spaces, or services such as childcare and transportation funded by project revenues. Other communities may place greater value on investments in workforce training programs.

Participants in a community benefits agreement should represent a broad spectrum of local priorities, often including labor unions and worker advocacy groups, community organizations and neighborhood associations, environmental advocates, faith-based groups, and other interest-based organizations. However, the specific composition will differ from one community to another. Since one of the key advantages of a CBA is reducing project risk, it is important to involve not only groups that already support the project. Just as important is ensuring that participants are trusted within their communities and genuinely represent their constituents' needs, so the agreement truly addresses the concerns of those most affected by the project.

While the specific benefits outlined in a CBA may differ by community, certain key elements are commonly included:[120]

- Commitment to support or not oppose the project. A central feature of a CBA is the community's pledge to either support or refrain from opposing the project. To ensure clarity and mutual understanding, the agreement should clearly define what constitutes the "project" as well as what is meant by "support" or "non-opposition."

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[117] Chrysostomidis, Perumalpillai, and Wolff, "CCS Stakeholder Issues Review and Analysis"; Bonham and Chrysostomidis, "Local Community Benefit Sharing Mechanisms for CCS Projects."
[118] Chipman, "America's Corn Belt Bristles at $8 Billion Lifeline."
[119] The framework for Community Benefits Agreements found herein is adapted from U.S. Department of Energy guidance on CBAs. See U.S. Department of Energy, "FAQ: Community Benefits Agreements."
[120] For an extended list of best practices for Community Benefits Agreements, see Eisenson and Webb, "Expert Insights on Best Practices for Community Benefits Agreements."

- The CBA is a legally enforceable contract. All parties to the agreement, including community groups and developers, have the right to enforce its terms.
- Steering Committee. Most CBAs involve the creation of a community oversight group, such as a community benefits steering committee, which meets regularly to monitor agreement implementation and manage how community investment funds are allocated. The agreement should clearly define the criteria for committee membership, the length of terms, the selection process, and how appointments are approved.
- Reporting Requirements. The agreement should detail how and when the developer will report on its compliance with CBA terms, including a schedule for demonstrating progress and fulfillment of commitments.
- Specific and measurable terms. CBA commitments should be specific, measurable, and achievable so that agreements have clear outcomes that are easy for all parties and the public to track and examine.
- Commitment to transparency. To foster accountability and public trust, the CBA and related implementation and benefit reports should be made publicly available. Additionally, meetings of the steering committee should be open to the public.

Example of Community Benefits Agreement for CCS

While each CCS project is unique, as would be each Community Benefits Agreement, it is helpful to review existing agreements to better understand the scope of potential benefits available and how community concerns could be addressed under a CBA. In 2024, a first-of-its-kind CBA was signed between a developer and a community coalition concerning a pipeline that will deliver CO_2 captured at an ethanol plant in Nebraska to an underground storage facility in Wyoming.[121] Community concerns centered on landowner protections, public safety, and community investment. To that end, the developer agreed to the following provisions, among others, in exchange for a commitment from the coalition of community groups to not oppose the pipeline project:[122]

- Upfront payments of $500,000 to a community investment fund to support counties along the right-of-way, $100,000 for development of a regional CO_2 emergency alert system, $200,000 for development of a First Responder CO_2 training program, and $400,000 to help emergency response organizations purchase equipment to prepare for, detect, and respond to CO_2 release.
- Ongoing payments of $40,000 per year to replace equipment used by emergency responders to detect and respond to CO2 release, $0.10 per $MTCO_2$ sequestered each year to be contributed to a community investment fund, and a royalty of $0.10 $MTCO_2$ sequestered to landowners along the right-of-way in addition to their easement payment.

[121] Brungard and Fraser, "Community Benefits Snapshot: Tallgras-Bold Alliance CO_2 Pipeline Community Benefits Greement."
[122] For a list of benefits included in the Brungard and Fraser. agreement, see Columbia Law School Sabin Center for Climate Change Law, "Community Benefits Agreements Database."

Regional Cohesion for a Community Benefits Agreement

The City of Cleveland has an extensive history of utilizing CBAs for projects that receive City financial assistance.[123] In the case of a CCS project, a developer may not seek local financial incentives but instead aim to avoid project delays. Nonetheless, the City's experience with CBAs offers a valuable framework for applying such agreements. This framework could be extended to a regional level to reflect the priorities and concerns of all impacted communities. Given the geographic scale of a potential CO_2 pipeline—particularly if the storage facility lies outside the Cleveland-Elyria MSA—NOACA may need to coordinate with other Metropolitan Planning Organizations and Regional Transportation Planning Organizations to convene the diverse cross-section of communities comprising the coalition that would be party to a CBA.

2040 – 2050

By 2050, further alternatives to replacing the BF-BOF system will likely be commercially viable options and for other heating processes in the primary metal manufacturing industry, there will be high temperature electric heating options.

Electrification

Thermal storage, multi-process heat pumps, electric boilers, resistive heating, and inductive heating are all currently available for low to medium temperature processes, but by 2050 they will be commercially viable for higher temperature processes as well.[124]

Replacing the BF-BOF system with molten oxide electrolysis (MOE).[125] Instead of replacing the BF-BOF system with a combined H2DRI-EAF system, Boston Metal developed a molten oxide electrolysis system that uses electricity to directly produce steel from iron ore. This is a single step process with zero CO_2 emissions. The process relies on solely electricity, removing the need for H2 production, transportation, and storage onsite, and can use lower grades of iron ore than DRI can use. Boston Metal is working on a demonstration plant set to open in 2026 to showcase commercial viability of the technology.

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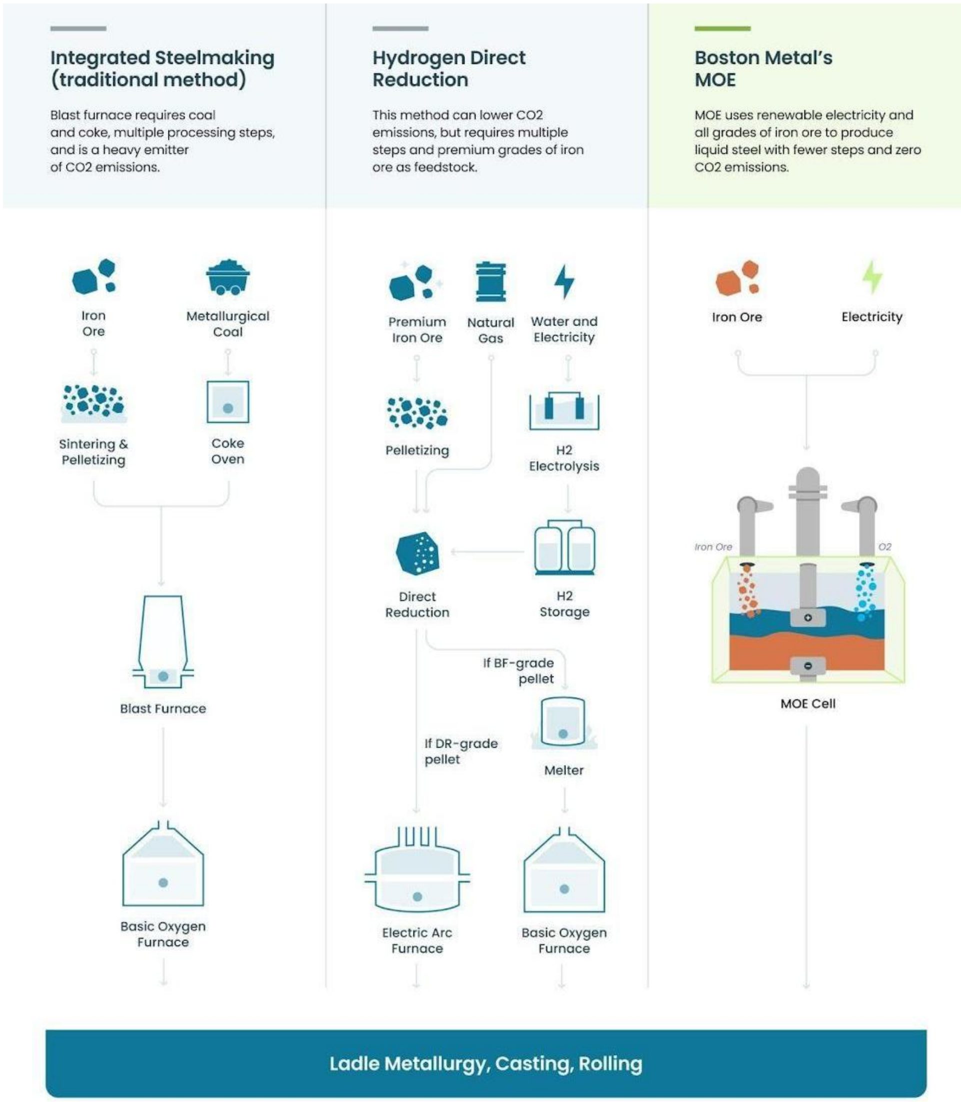
[123] City of Cleveland, Mayor's Office of Equal Opportunity, "Community Benefits Resource Guide."
[124] Electrification of Industrial Heat
[125] Boston Metal Electrolysis System

Figure 13: Schematic from Boston Metal comparing traditional steelmaking to DRI-EAF and its own Molten Oxide Electrolysis process[126]



Carbon Capture Utilization and Sequestration

Phase out capture

Emissions Evaluation

For primary metal manufacturing, 82% of the emissions come from process heating and cooling. By replacing the fossil fuel based furnaces with electric or alternative fuel systems or installing a carbon capture system, 90% - 100% of these process heating emissions can be abated. Onsite energy generation can be replaced with renewable energy alternatives.

126 Boston Metal MOE process

Table 4: Emissions Reductions by CO_2 Source for the Primary Metal Manufacturing Subsector

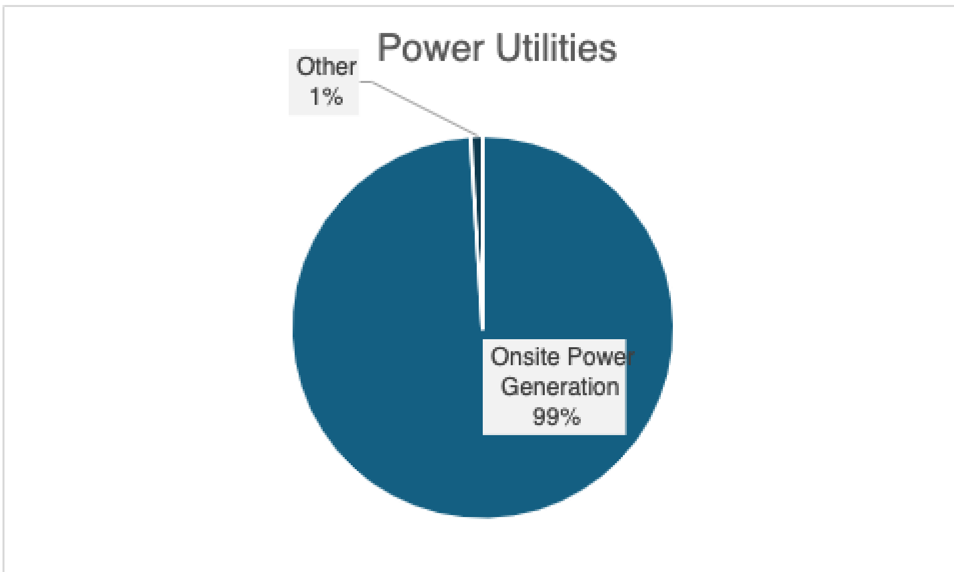
Source of Emissions	Initial Emissions	Reduction Percentage	Final Emissions
Process Heating and Cooling	7.14 $MMTCO_2e$	95%	0.3 $MMTCO_2e$
Onsite Energy Generation	1.21 $MMTCO_2e$	95%	0.06 $MMTCO_2e$
Machine Drive	0.098 $MMTCO_2e$	75%	0.02 $MMTCO_2e$
Onsite Transportation	0.066 $MMTCO_2e$	100%	0 $MMTCO_2e$
Total	**7.52 $MMTCO_2e$**	**99.7%**	**0.02 $MMTCO_2e$**

Overall, using Cleveland Works as an example, it is possible to decarbonize primary steelmaking by 99% by 2050 with a combination of these methods. The most important component is deciding what to do with the process heating component by either introducing carbon capture or replacing furnaces with electric or hydrogen-based alternatives.

Steam Generation: 1.06 MMT CO2e

Utilities are the second largest industrial emitter in the region, making up 20% of total regional industrial emissions. Most of those utility emissions come from fossil fuel electric power plants like West Lorain in Lorain County and facilities that generate steam or chilled water for cooling, like Corix Cleveland Thermal in Cuyahoga County. Decarbonization of fossil fuel electric power is discussed, at length, in the Electricity Sector. Steam providers in the region will either need to capture their CO_2 or switch to a different process for providing heating and cooling. All the counties except Geauga County have power utilities.

Figure 14: The contributions to emissions in the power utilities subsector.



2025 – 2030

There are no immediate solutions for decarbonizing the power utilities.[127] Instead, the next five years should be used for strategic planning of clean electricity development and evaluation of retrofitting existing systems for geothermal or implementing carbon capture.

New Industry Support

One potential option for existing district heating systems would be to retrofit them for distributing geothermal heat rather than steam derived from natural gas. To support such a massive change, investment in geothermal systems design, maintenance, and components could be a good opportunity for new industries in the region.[128]

2030 – 2040

[127] Current power plants can run with 20-30% blended hydrogen
[128] district geothermal

Process and Material Efficiency

Traditional natural gas power plants waste 30-50% of their energy input as heat. Capturing waste heat from both thermal power plants and natural gas electric power plants to use as additional power generation or district heating could improve plant efficiency by 10-20%.[129]

Carbon Capture Utilization and Sequestration

Calpine Texas CCUS Holdings LLC and Electricore Inc. are currently deploying post-combustion carbon capture technology at a natural gas power plant in Deer Park, Texas.[130] This system will capture 95% of total $CO_2$from the flue gas at the power plant. It would cost ~$33 / ton $CO_2$to capture (not including any transportation or sequestration costs). It would also take ~50kWh/ton CO_2 of electricity for capturing the CO2.[131]

2040 – 2050

Renewable Energy

Retrofitting existing district heating for geothermal district heating would remove the reliance on natural gas-powered steam generation. Munich, Germany plans to have transferred their entire district heating system to geothermal by 2040.[132] Heat suppliers that use steam-based systems rather than water-based systems would have to change their network to a water-based network. Ball State University began converting their coal powered, steam-based district heating system to a geothermal, water-based network in 2009. This has led to millions of dollars in annual savings and halved the university's emissions contributions.[133] This is a substantial undertaking, however, requiring the establishment of geothermal resources via borehole drilling, installation of ground-based heat pumps, replacing existing steam lines with insulated hot water lines, and upgrading control systems.[134]

Emissions Evaluation

Table 5: Emissions Reductions by CO_2 Source for the Steam Generation Subsector

Source of Emissions	Initial Emissions	Reduction Percentage	Final Emissions
Onsite Energy Generation	1.05 $MMTCO_2e$	95%	0.05 $MMTCO_2e$
Other	0.01 $MMTCO_2e$	0%	0.01 $MMTCO_2e$

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[129] Waste heat recovery at power plants
[130] NETL deer park energy center natural gas
[131] Cost of capture
[132] Germany Geothermal
[133] https://eri.iu.edu/erit/case-studies/ball-state-university-geothermal.html
[134] https://decarbonization.dartmouth.edu/how-it-works/steam-hot-water-transition; https://www.greeneru.com/articles/converting-buildings-to-accept-high-efficiency-energy-systems

Total	1.06 $MMTCO_2e$	95%	0.06 $MMTCO_2e$

Power utilities can achieve 95% decarbonization by investing in carbon capture. To completely decarbonize, they would have to change their energy source by investing in geothermal, solar, wind, and battery storage.

Cement, Concrete, and Asphalt Manufacturing: 0.55 $MMTCO_2e$

Cement, concrete, and asphalt manufacturing are responsible for 6% of the region's industrial emissions. More specifically, the large industrial emitter in the Cleveland-Elyria MSA that falls into this category is Carmeuse Lime, which specializes in lime product manufacturing, a subset of cement manufacturing. In cement making, limestone is heated and releases CO_2 in a process called calcination before being dried, cooled, and mixed with other materials, ready to be combined with water, sand, or gravel to make concrete. Asphalt is made by heating and mixing sand, gravel, or crushed stone with a petroleum-based binder. Each county has some concrete, cement, or asphalt manufacturing. Emissions in this sector come from high-temperature processing, chemical reactions, grinding and mixing (machine drive), and transportation.[135,136]

Carmeuse Lime located in Grand River, Ohio in Lake county, produces high calcium quicklime, dolomitic quicklime, calciment LKD, high calcium limestone, and magnesium enhanced quicklime.[137] Used in a wide range of applications from wastewater treatment to steelmaking and finally cement making, the demand for lime products is unlikely to decrease any time soon.[138] Most of these products are made by heating combinations of calcium and limestone to high temperatures, a process which inherently emits CO2.[139]

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[135] Pisciotta et al., "Opportunities for Cement Decarbonization."
[136] Barbhuiya et al., "Decarbonising Cement and Concrete Production."
[137] https://www.carmeuse.com/na-en/products-map
[138] Each lime product has specification, uses, and a description of the manufacturing process. https://www.carmeuse.com/na-en/products/lime-products
[139] https://www.carmeuse.com/na-en/products/dolomitic-quicklime

Figure 15: Breakdown of the contributions to emissions in the cement industry[140]

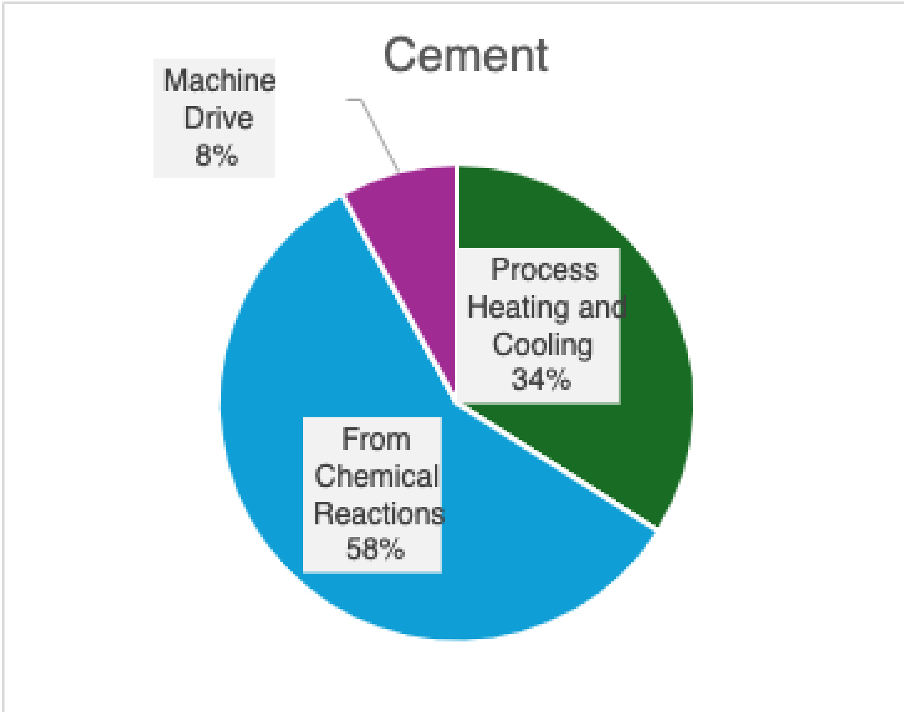
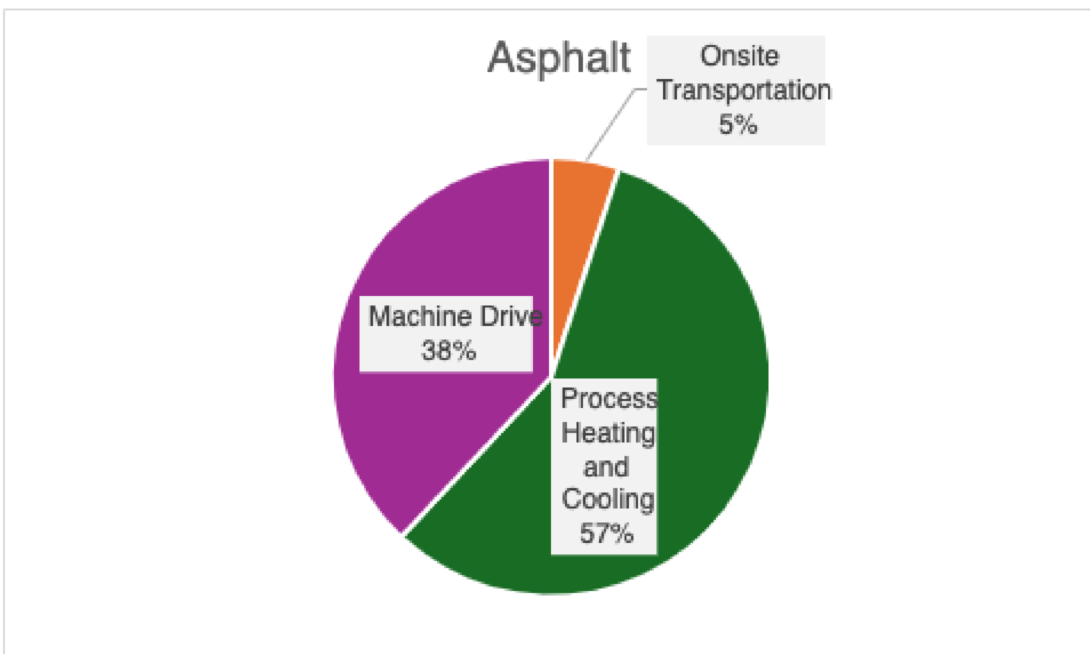


Figure 16: Breakdown of emissions contributions to asphalt making[141]



[140] Dollinger, "Industrial Decarbonization Roadmap."
[141] Schacat, Willis, and Ciavola, "The Carbon Footprint of Asphalt Pavements: A Reference Document for Decarbonization."

2025 – 2030

Energy Efficiency

There are energy savings opportunities in high-efficiency clinker cooling and grinding technologies.[142]

Process and Material Efficiency

Clinker is currently a key component of cement, and is made by heating limestone and other raw materials to high temperatures in a kiln in a process called "calcination." Reducing the clinker content in cement would decrease the amount of energy needed in this heating process. Clinker could be replaced with materials such as fly ash, slag, or calcined clay. This could reduce emissions due to cement manufacturing by the same percentage as clinker reduced.[143]

The calcination process is responsible for much of the emissions in cement making due to combustion of fuel and the chemical reaction of limestone itself releasing CO_2. Precalciner technology improves the thermal efficiency of cement kilns by optimizing fuel combustion and heat transfer. This technology more uniformly heats materials by suspending them in a stream of hot gases. They are also compatible with alternative fuels. Overall, precalciners can reduce emissions from the calcination process by 112.61 kg co2/ ton clinker produced.[144]

In asphalt making, increasing the amount of recycled asphalt pavement in new asphalt production can reduce emissions up to 30%.[145]

Switching the process to a lower temperature process by using Warm Mix Asphalt technologies can reduce emissions by 9-16%.[146]

Electrification

Cement grinding and milling processes currently depend on fossil fuel-based machinery. Electrifying cement grinding and milling would reduce emissions by reducing the reliance on fossil fuels.[147]

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142 "Technology Roadmap - Low-Carbon Transition in the Cement Industry."
143 https://www.scientificamerican.com/article/solving-cements-massive-carbon-problem
144 precalciner co2 reduction
145 Schacat, Willis, and Ciavola, "The Carbon Footprint of Asphalt Pavements: A Reference Document for Decarbonization."
146 Schacat, Willis, and Ciavola.
147 Grinding and milling

2030 – 2040

Process and Material Efficiency

In asphalt making, binder is used to keep the asphalt together and solidify it. Currently, binder is a petroleum derivative, but there is ongoing research on replacing binder with biobased alternatives.[148]

Electrification

Coal and petroleum coke are currently used in cement kilns for the heating process. Electrifying process heating could eliminate emissions from heating.[149]

Alternative Fuels

Another option for removing the reliance on coal and petroleum coke in heating would be to replace coal and petroleum coke in cement kilns with biomass or hydrogen. This could reduce cement emissions by up to 33%.[150]

Carbon Capture Utilization and Sequestration

Even if heating was entirely electrified or transitioned to an alternative fuel, the calcination process itself produces CO2. Adding carbon capture technology to the flue gas system is likely a necessary solution. Once captured, the CO_2 can be used in calcium looping, where the CO_{2c}reacts with Calcium Oxide to form calcium carbonate, which can then be recycled through the calcification process. Captured CO_2 can also be used to cure concrete, making the concrete stronger and sequestering the CO_2.[151] Carbon capture can reduce total emissions of the cement sector by 65%.[152]

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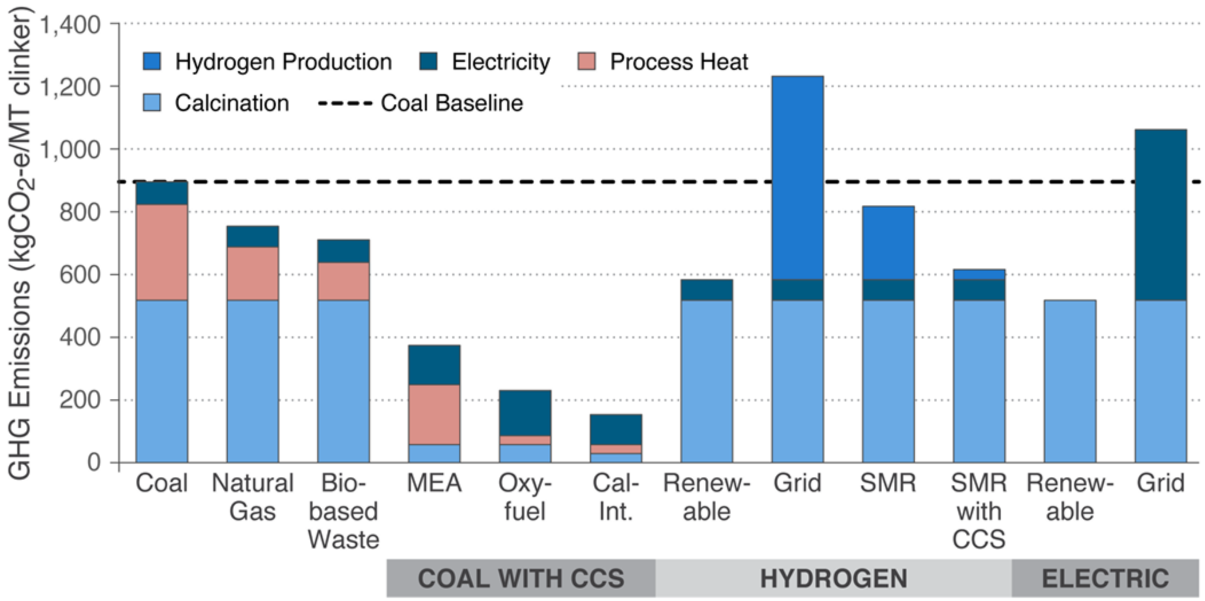
[148] Schacat, Willis, and Ciavola, “The Carbon Footprint of Asphalt Pavements: A Reference Document for Decarbonization.”
[149] Quevedo Parra and Romano, “Decarbonization of Cement Production by Electrification.”
[150] Dollinger, “Industrial Decarbonization Roadmap.”
[151] Barbhuiya et al., “Decarbonising Cement and Concrete Production.”
[152] Dollinger, “Industrial Decarbonization Roadmap.”

Figure 17: GHG Emissions from Cement Production by Process and Fuel Type[153]



2040 – 2050

Electrification

High temperature heating necessary for the calcination process can be electrified with electric furnaces or microwave technology by 2050.[154] This would reduce overall cement manufacturing emissions by up to 44%.[155]

New Industry Support

Development of sustainable pavement and construction materials that do not require binder as in asphalt or clinker as in concrete would be a good opportunity for a new industry in the region.

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[153] Dollinger.

[154] U.S. Department of Energy Advanced Manufacturing Office, Sustainable Manufacturing: Opportunities, Trends, and Technoeconomic Analysis, presented at the Advanced Manufacturing Office FY2020 Program Review Virtual Meeting, 2020, https://energy.gov/sites/prod/files/2020/05/f75/FY20%20AMO%20Peer%20Review%20%20Sustainable%20Manufacturing%20Project%20Slides_Final_0.pptx.

[155] Dollinger, "Industrial Decarbonization Roadmap."

Emissions Evaluation

Table 6: Emissions Reductions by CO_2 Source for the Cement, Concrete, and Asphalt Cement Manufacturing Subsector

Source of Emissions	Initial Emissions	Reduction Percentage	Final Emissions
Chemical Reactions	0.32 $MMTCO_2e$	90%	0.03 $MMTCO_2e$
Process Heating and Cooling	0.19 $MMTCO_2e$	100%	0 $MMTCO_2e$
Machine Drive	0.04 $MMTCO_2e$	100%	0 $MMTCO_2e$
Total	0.55 $MMTCO_2e$	95%	0.03 $MMTCO_2e$

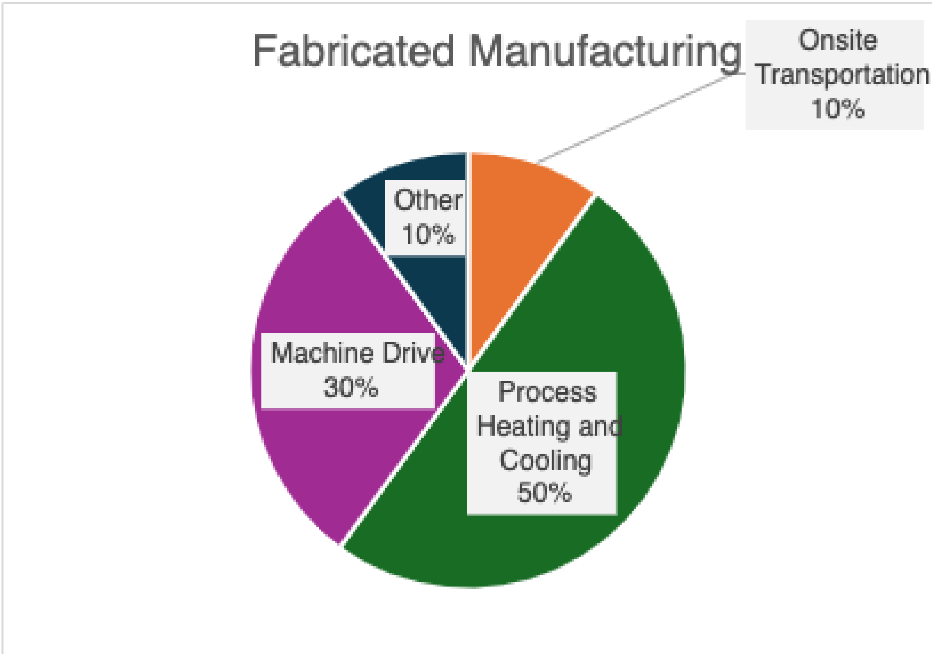
While asphalt manufacturing can be electrified, processed at lower temperatures, and energy intensive materials can be substituted in ways that will decarbonize its manufacturing, due to the chemical calcination process in cement making, it can only fully decarbonize through the implementation of some sort of carbon capture system.

Fabricated Manufacturing: 0.34 MMT CO2e

Fabricated product manufacturing is a broad sector that includes stamping, machining, coating, engraving, plating, polishing, and forging metal into products for the aerospace, automotive, and construction industries. To limit the scope of this work, we have also included machine, transportation, and electric equipment manufacturing in this category as the decarbonization strategies are similar. There are fabricated manufacturing facilities in each of the five counties. The processes involved in fabricated metal manufacturing typically include melting, machining, cutting, welding, pressing, anodizing, and coating. Heating is responsible for 50% of the sector's emissions. Fuel needed in machine drives such as for compression or pumping is the second largest emissions contributor at 30%, and the rest of the emissions come from a combination of onsite transportation, and process gas used in anodizing and coating.[156]

[156] Fabricated metal manufacturing

Figure 18: The contributions to emissions in the fabricated manufacturing subsector.



2025 – 2030

Energy Efficiency

Since process heating is the largest contributor to the emissions, optimizing furnace efficiency by replacing furnaces with high-efficient furnaces or changing settings that already exist on furnaces to reduce operating temperatures to the minimum temperatures necessary can lead to 10-15% energy savings.[157]

Installing automatic shutoffs for when equipment isn't in use reduces the emissions from idle power consumption and can reduce electricity consumption by 5-10%.[158]

Waste heat recovery systems that recover heat from furnaces, machining, and forging processes can be reused for preheating metal or elsewhere throughout the facility. This reduces energy demand by 20-30%.[159]

Insulating heating process lines like gas lines, steam pipes, and molten metal transport systems prevents heat loss and improves heating efficiency, leading to 5-10% reductions in heating energy.[160]

[157] Energy efficient furnaces
[158] Automatic shutoffs
[159] Waste heat recovery
[160] Insulating heating lines

Often, motor speeds are run at the maximum speed regardless of whether that is the most efficient. Optimizing machine drive speeds by introducing variable speed drivers can allow motor speeds to vary in response to demand. This can reduce energy demand by 15-20%.[161]

Process and Material Efficiency

Automation can be used to optimize workflows by improving efficiency, optimizing material usage, and minimizing waste. This can reduce process errors, material waste, and energy consumption, leading to a 5-10% reduction in energy consumption.[162]

Smart sensors offer real-time monitoring of energy consumption, gas leakages, or other inefficiencies at each stage of production. This can lead to 3-7% reduction in energy consumption and can improve safety of equipment and processes.[163]

Lightweighting involves re-designing products to use less material while maintaining their strength. This could involve adding new shapes to improve strength or using different materials in production. Lightweighting can lead to 5-15% reduction in material processing energy consumption like forging.[164]

2030 – 2040

Process and Material Efficiency

Implementing onsite closed-loop recycling systems to reuse metal scraps produced in the manufacturing process can reduce the quantity of raw materials needed and can reduce emissions by 10-15%.[165]

Additive manufacturing may not be suitable for all fabricated metal manufacturing applications, but it is a process that effectively 3D prints metal components, significantly reducing the material waste compared to traditional machining. It can reduce material usage by up to 50%, reducing heating emissions.[166]

Electrification

Replacing gas-powered furnaces and coating curing ovens with electric alternatives such as electric arc furnaces (EAF), induction furnaces, or resistance heating for forging would replace fossil fuel reliance with electricity derived heating that requires less energy per ton of metal produced than gas-powered alternatives. This would reduce the heating energy required by about 40% and cut process heating emissions in half.[167]

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[161] Variable speed drive
[162] Automation of workflows
[163] Real-time monitoring of workflows
[164] lightweighting
[165] Closed-loop recycling
[166] Additive manufacturing
[167] energy efficiency of eaf

Replace hydraulic and pneumatic systems with electric alternatives for compression or pressurizing processes. Electric alternatives consume less energy than traditional systems and could lead to 10% emissions reductions.[168]

Alternative Fuels

Using green h2 for processes where electrification is not feasible, though since fabricated metal is processing existing metal rather than creating new metal, all processes should be able to be electrified. However, some anodizing and coating processes may need high temperature fast drying, which electric systems cannot fully replace. This would be one case where hydrogen-fired drying would be useful.[169] This could eliminate emissions from drying.[170]

Emissions Evaluation

By 2050, the fabricated manufacturing industry could be completely fossil free, using a combination of energy efficiency, process and material efficiency, electrification, and alternative fuels.

Table 7: Emissions Reductions by CO_2 Source for the Fabricated Manufacturing Subsector

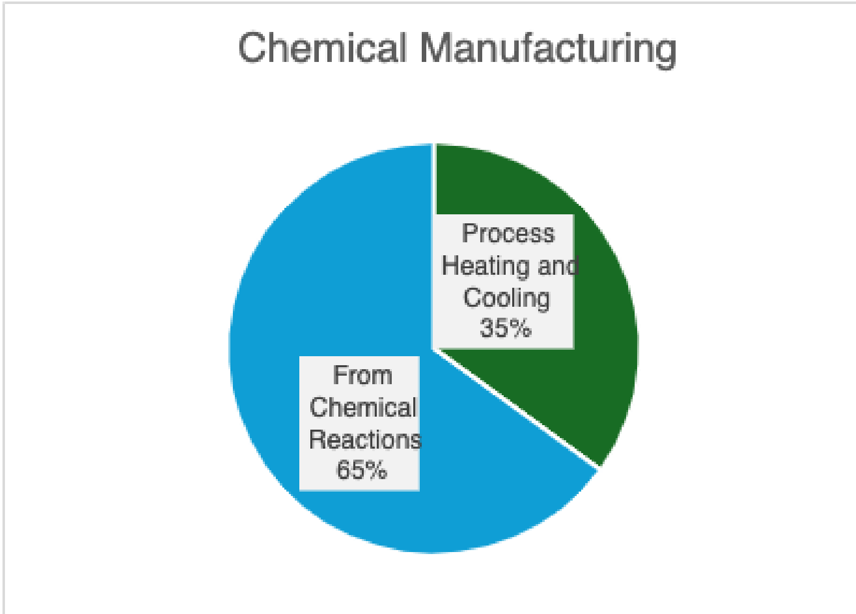
Source of Emissions	Initial Emissions	Reduction Percentage	Final Emissions
Process Heating and Cooling	0.17 $MMTCO_2e$	90%	0.02 $MMTCO_2e$
Machine Drive	0.10 $MMTCO_2e$	100%	0 $MMTCO_2e$
Onsite Transportation	0.03 $MMTCO_2e$	100%	0 $MMTCO_2e$
Other	0.03 $MMTCO_2e$	10%	0.03 $MMTCO_2e$
Total	0.34 $MMTCO_2e$	87%	0.05 $MMTCO_2e$

Chemical Manufacturing: 0.24 $MMTCO_2e$

Chemical manufacturing includes manufacturing of rubber, paint, plastics, petrochemicals, and all other organic or inorganic chemical production. These processes can be energy-intensive due to high temperature, steam, and power requirements as well as chemical reactions that produce CO_2. There are chemical manufacturers located in all five counties.

[168] Electric compression and pressurization
[169] Hydrogen-fired drying
[170] H_2 drying emissions

Figure 19: The contributions to emissions in the chemical manufacturing subsector



2025 – 2030

Energy Efficiency

High efficiency pumps can reduce energy consumption by optimizing fluid flow of chemicals through production lines. These pumps can improve efficiency by 10-20%.[171]

Typically, motors are run at full capacity regardless of whether that level of speed and power is necessary. Variable drive motors can be tailored to run at different speeds and power usages for different cases and demands. They can reduce energy use by 10-20%.[172]

Digital monitoring equipment gives real-time updates on energy consumption and can give insights into where settings could be optimized. This allows for better energy management, consistency in operations, and reduced energy consumption.[173]

CHP systems could be implemented in facilities that need process heating as well as electricity generation onsite. They can capture and utilize waste heat, reduce the need for fuels for heating processes, and improve energy utilization by 20-30%.[174] This would also be a strategy to reduce indirect emissions from electricity usage in powering pumps, motors, and other electric equipment.

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[171] Energy efficient pumps
[172] Variable Drive Motors
[173] Digital monitoring equipment
[174] Combined heat and power

Process and Material Efficiency

Some processes may need a lower volume or temperature of steam as they currently are being supplied. Conducting an energy audit to identify whether there are process changes, opportunities for redesigning processes, or existing equipment settings to reduce steam demand can lower fuel consumption.[175]

Chemical production requires significant amounts of energy whether in making chemicals in bulk or in small batches. By shifting to bulk chemical production rather than small batch, improvements in efficiency can be obtained due to the use of fewer resources per unit of chemical produced.[176]

Electrification

Electric boilers and heat pumps can replace fossil fuel-based heating systems used for low temperature processes (<150 C). This can reduce emissions by 45 -70% depending on the specific process.[177]

Alternative Fuels

Chemical manufacturing uses fossil fuels as a feedstock for chemical reactions. These are cases where electrification cannot replace the chemical reaction taking place. To move away from a dependence on fossil fuels, alternatives such as green H2, biomass, consumer waste, or manufacturing waste can be used as feedstocks.[178]

Carbon Capture Utilization and Sequestration

For industries where CO_2 makes up 10% or more of the exhaust gas, CO_2 could be captured through scrubbers.[179] The CO_2 concentration is crucial for making capture economically feasible, and the higher the concentration, the more economic sense it makes to capture it.[180] Chemical manufacturers in the region do not emit enough to justify transportation and sequestration, but there may be smaller utilization opportunities interested in smaller quantities of CO2, like sequestering it in cement.[181] The CO_2 could also be reused as a feedstock for carbon-based chemical production in a closed-loop manufacturing process.[182]

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[175] Reduce steam demand
[176] Bulk chemical production
[177] Decarbonization of the chemical industry through electrification: Barriers and opportunities
[178] Alternative feedstocks
[179] CO_2 direct exhaust through scrubbing
[180] IEA Cost of Capture
[181] Cement CO_2 sequestration
[182] Circular CO_2 usage as a feedstock

New Industry Support

Chemical production includes the manufacturing of plastics. Encouraging a societal reduction in demand for single use plastics by supporting alternatives could encourage industries to invest in more recyclable alternatives and lead to a reduction in landfill waste.[183]

2030 – 2040

Process and Material Efficiency

Retrofitting natural gas reactors for hydrogen heating can significantly reduce emissions from higher temperature chemical reaction processes, leading to 50-70% emissions reductions.[184] Retrofitting can be less expensive than completely replacing a reactor.[185]

Thinking about decarbonizing the chemicals industry allows for the opportunity to reevaluate and determine whether there are opportunities for redesigning high-temperature processes for lower temperatures. This would reduce operating temperatures and directly reduce emissions by 10-15%.[186]

Alternative Fuels

Combusting hydrogen rather than natural gas in high temperature reactors and furnaces would lead to phasing out of fossil fuels, allowing for combustion with virtually no CO_2 emissions. This may require that the hydrogen being used is green, i.e. made entirely from renewable or nuclear energy, or is otherwise be produced in a manner that does not emit carbon dioxide.[187]

Carbon Capture Utilization and Sequestration

Continue to capture carbon and use it as a feedstock to make a circular process, find a local utilizer of smaller amounts of CO_2, or begin coordinating with other, smaller CO_2 capture facilities to invest in regional CO_2 pipeline and sequestration infrastructure.[188]

2040 – 2050

Electrification

High temperature heating processes like chemical reactors, steam generators, and dryers can be replaced by advanced technologies such as thermal storage, multi-process heat pumps, electric boilers, resistive heating, or inductive heating.[189] Since process heating is responsible for the majority of the emissions in the chemical manufacturing sector, this would reduce the

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[183] Methods for encouraging reduced demand for single use plastics
[184] H2 retrofit
[185] Retrofit vs. replace reactor
[186] Redesigning for lower temperatures
[187] Combusting hydrogen
[188] Circular CO2
[189] direct electrification of process heat

emissions by up to 90 - 100%, depending on the process, and as long as the grid was completely decarbonized.[190]

Emissions Evaluation

By 2050, chemical manufacturing could reduce its emissions by 70 – 90% through a combination of energy efficiency, electrification, alternative fuels, and CCUS, with most of the reductions from electrification of process heating.

Table 8: Emissions Reductions by CO_2 Source for the Chemical Manufacturing Subsector

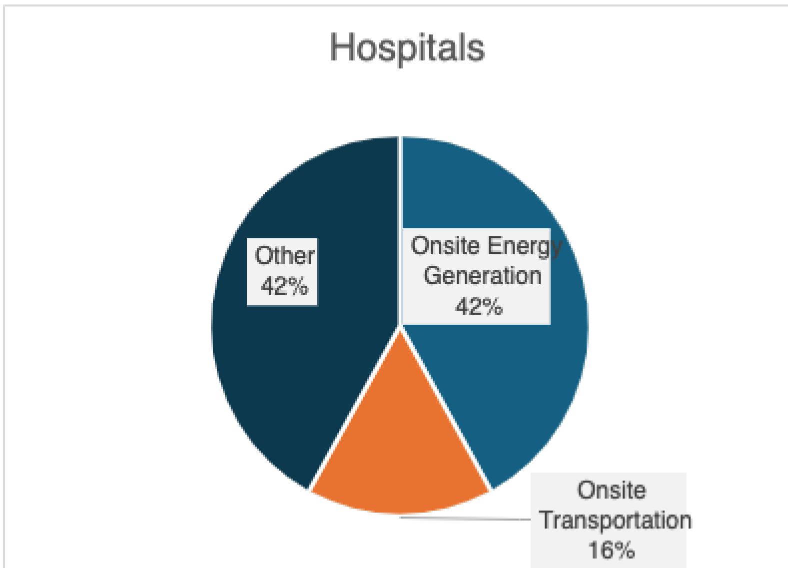
Source of Emissions	Initial Emissions	Reduction Percentage	Final Emissions
Chemical Reactions	0.16 $MMTCO_2e$	90%	0.058 $MMTCO_2e$
Process Heating and Cooling	0.09 $MMTCO_2e$	90%	0.009 $MMTCO_2e$
Total	0.24 $MMTCO_2e$	91%	0.024 $MMTCO_2e$

[190] High temp process electrification emissions

Hospitals: 0.24 $MMTCO_2e$

Hospitals are large consumers of energy due to their 24/7/365 operations, advanced medical equipment, and sterilization processes. Guaranteeing power reliability is crucial for them to provide essential services, and their onsite energy generation in the form of generators is the largest source of emissions. Emissions from anesthetics and water and waste make up another 42% of the emissions.[191] Vehicle emissions from ambulances are included in the emissions from onsite transportation. All the hospitals with emissions data are in Cuyahoga County, but the following strategies could be useful for any hospital in the Cleveland-Elyria MSA

Figure 20: The contributions to emissions in the hospitals subsector



2025 – 2030

Energy Efficiency

Update imaging equipment to the most efficient models by cycling out older models of MRI, CT scanners, etc. to reduce power consumption by 10%.[192]

Using smart scheduling to schedule on/off times for areas of the hospital that don't need to be operating continuously (e.g., operating rooms) reduce energy consumption by turning off HVAC, lighting, and non-critical equipment during low-demand times. This can save up to 10% power consumption.[193]

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[191] NHS hosptial emissions data
[192] Updating imaging equipment
[193] On/off times

For hospitals, building efficiency is critical. Upgrading to energy-efficient HVAC and lighting systems to regulate air quality and temperature and maintain quality lighting can reduce energy consumption by 20%.[194]

Process and Material Efficiency

Some hospitals have onsite IT centers for data storage. Switching to cloud services for data storage to reduce the need for supporting energy-intensive server rooms. This can lead to energy consumption reductions of up to 10%.[195]

Electrification

Hospitals need to maintain high levels of sterilization, and sterilization equipment is often gas-powered. Switching to electric boilers and sterilizers for sterilization can reduce emissions by 10-15%.[196]

2030 – 2040

Process and Material Efficiency

Currently, imaging and diagnostic equipment such as MRIs use rare materials like helium for cooling magnets. Updating imaging and diagnostic equipment that uses a smaller quantity of these limited or scarce materials reduces energy use and rare material consumption.[197]

Some inhaled anesthetics have high global warming potential (GWP).[198] Using lower-GWP anesthetics (e.g., sevoflurane) and switching to a policy of regional anesthesia when appropriate, followed by using intravenous anesthetics, when possible, will reduce emissions by 5-10%.[199] When inhaled anesthetics are needed, using gas capture and recycling systems to minimize gas leakages and improve recycling will minimize quantities of fresh gas flows. Switching to portable tanks rather than centralized nitrous oxide pipelines can also reduce fugitive emissions from these higher GWP gases.

Alternative Fuels

Ambulances currently are diesel or gasoline operated. Switching to battery electric or hydrogen powered ambulances would reduce emissions by 10-20%, reduce noise, and reduce exhaust emissions that could bother patients and EMTs.[200]

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[194] Energy-efficient hvac in hospitals
[195] Cloud services for data storage
[196] Electric sterilizers
[197] Resource-efficient imaging and diagnostic equipment – Philips “Helium-free” MRI uses a sealed cooling system that completely removes helium refilling
[198] desflurane has a global warming potential of 2540. gwp anesthetics
[199] gwp anesthetics
[200] Ambulances

2040 – 2050

Renewable Energy

When new hospital compounds are being built, district geothermal heating could be designed for heating these massive, interconnected buildings.[201] District geothermal heating uses geothermal energy to heat a network of buildings. Since they are operated by a single user, they would be a good case for district geothermal heating, though upgrading buildings without pre-existing district heating systems would be very expensive.[202] District geothermal would reduce the reliance on fossil fuel-based heating systems, leading to emissions reductions of 40-60%.[203]

Emissions Evaluation

By 2050, hospitals could achieve up to 70-85% emissions reductions through a combination of energy efficiency, process and material efficiency, electrification, renewable energy, and alternative fuels.

Table 9: Emissions Reductions by CO_2 Source for the Hospitals Subsector

Source of Emissions	Initial Emissions	Reduction Percentage	Final Emissions
Onsite Energy Generation	0.10 $MMTCO_2e$	100%	0
Other	0.10 $MMTCO_2e$	20%	0.08 $MMTCO_2e$
Onsite Transportation	0.04 $MMTCO_2e$	100%	0
Total	0.24 $MMTCO_2e$	66%	0.08 $MMTCO_2e$

Pipeline Transportation: 0.13 $MMTCO_2e$

Pipeline transportation is the transportation of natural gas via pipeline. The emissions in this industry come from compression and fugitive emissions. Pipeline facilities are located in Cuyahoga and Medina counties.

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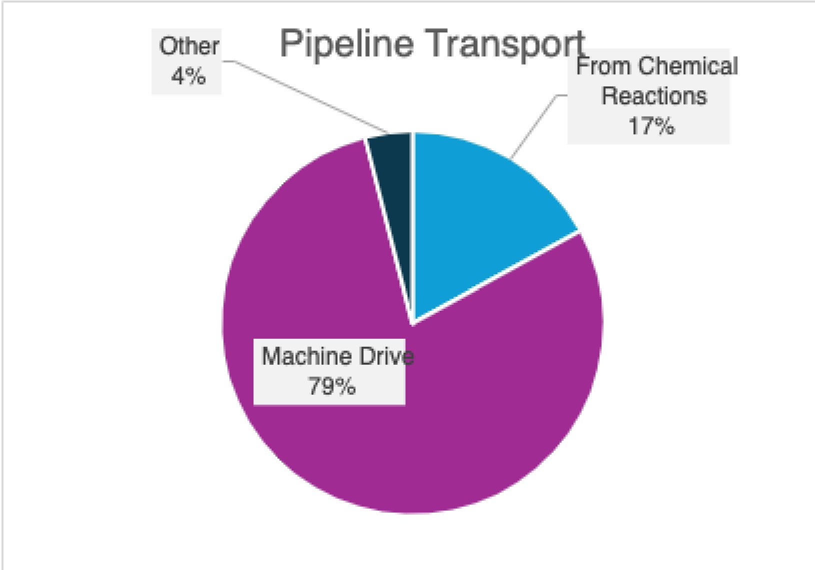
[201] District geothermal
[202] Cost of district geothermal retrofit
[203] Geothermal emissions reductions

Figure 21: The contributions to emissions in the pipeline transport subsector



2025 – 2030

Energy Efficiency

Compression is used to maintain the flow of natural gas within the pipeline, ensuring that compression is optimized by using variable speed drivers and monitoring systems can lead to 10-15% energy savings.[204]

Implementing leak detection equipment to constantly monitor for leaks reduces methane emissions and allows for rapid responses for repairing leaks. This can lead to 5-10% emissions reductions.[205]

2030 – 2040

Electrification

Transitioning from natural gas driven compressors to electric compression can reduce emissions by 30-40%.[206]

Alternative Fuels

Green hydrogen blending is a strategy that companies like Enbridge are currently using in other regions as a method for decarbonization.[207] Blending up to 5% green hydrogen is possible without any upgrades to current natural gas pipelines, and blending can reduce emissions by

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[204] Assessment of electric drive compressor conversion
[205] Monitor leaks emissions
[206] Assessment of electric drive compressor conversion
[207] Enbridge

20-30%.[208] Producing enough green hydrogen cost effectively is the main hurdle for this strategy.[209]

Renewable Energy

A great way to produce green hydrogen is to use excess renewable energy. When solar or wind are overperforming, the excess can be used to produce green hydrogen that can be blended with natural gas to reduce emissions by 20-30%.[210]

2040 – 2050

New Industry Support

In the long term, the only way for our region to continue burning natural gas would be if it were coupled with direct air carbon capture facilities in the region. In the long term, moving away from natural gas completely could present the opportunity to convert existing pipelines to H2 or CO2 pipelines. Currently, companies like Linde have separation technologies that can pull blended H2 from the natural gas pipeline, so if pipelines are upgraded to support larger percentages of H2, then maybe the existing infrastructure can be completely converted to H2 or CO2 pipelines.[211]

Emissions Evaluation

Table 10: Emissions Reductions by CO2 Source for the Pipeline Transport Subsector

Source of Emissions	Initial Emissions	Reduction Percentage	Final Emissions
Machine Drive	0.11 $MMTCO_2e$	60%	0.005 $MMTCO_2e$
Chemical Reactions	0.02 $MMTCO_2e$	50%	0.01 $MMTCO_2e$
Other	0.005 $MMTCO_2e$	20%	0.04 $MMTCO_2e$
Total	0.14 $MMTCO_2e$	59%	0.06 $MMTCO_2e$

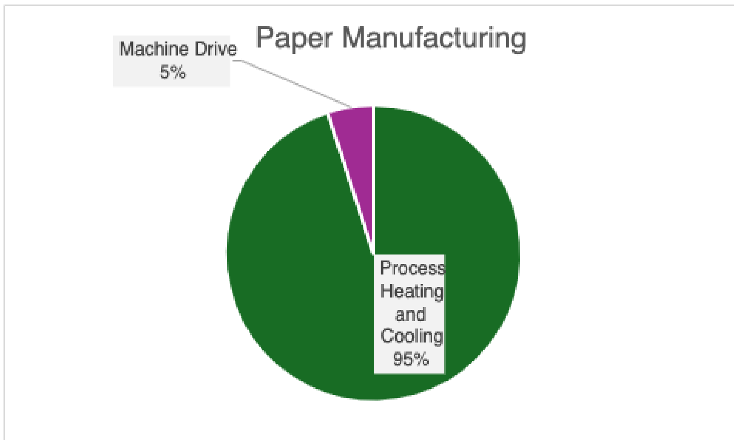
Paper Manufacturing: 0.07 $MMTCO_2e$

Paper manufacturing includes making coated, treated, and converted paper or paper bags. In this process, paper sheets, either made from wood pulp or recycled fibers, or pre-existing sheets are coated with clay, polymers, or chemicals to yield the desired product. Converted paper refers to paper that is cut, folded, and glued to make products like packaging materials. Paper bags are bonded using adhesives or heat sealings. Cuyahoga, Lake, and Medina

208 Hydrogen Blending
209 Cost of green H2 production
210 Hydrogen Blending
211 Linde natl gas grid conversion

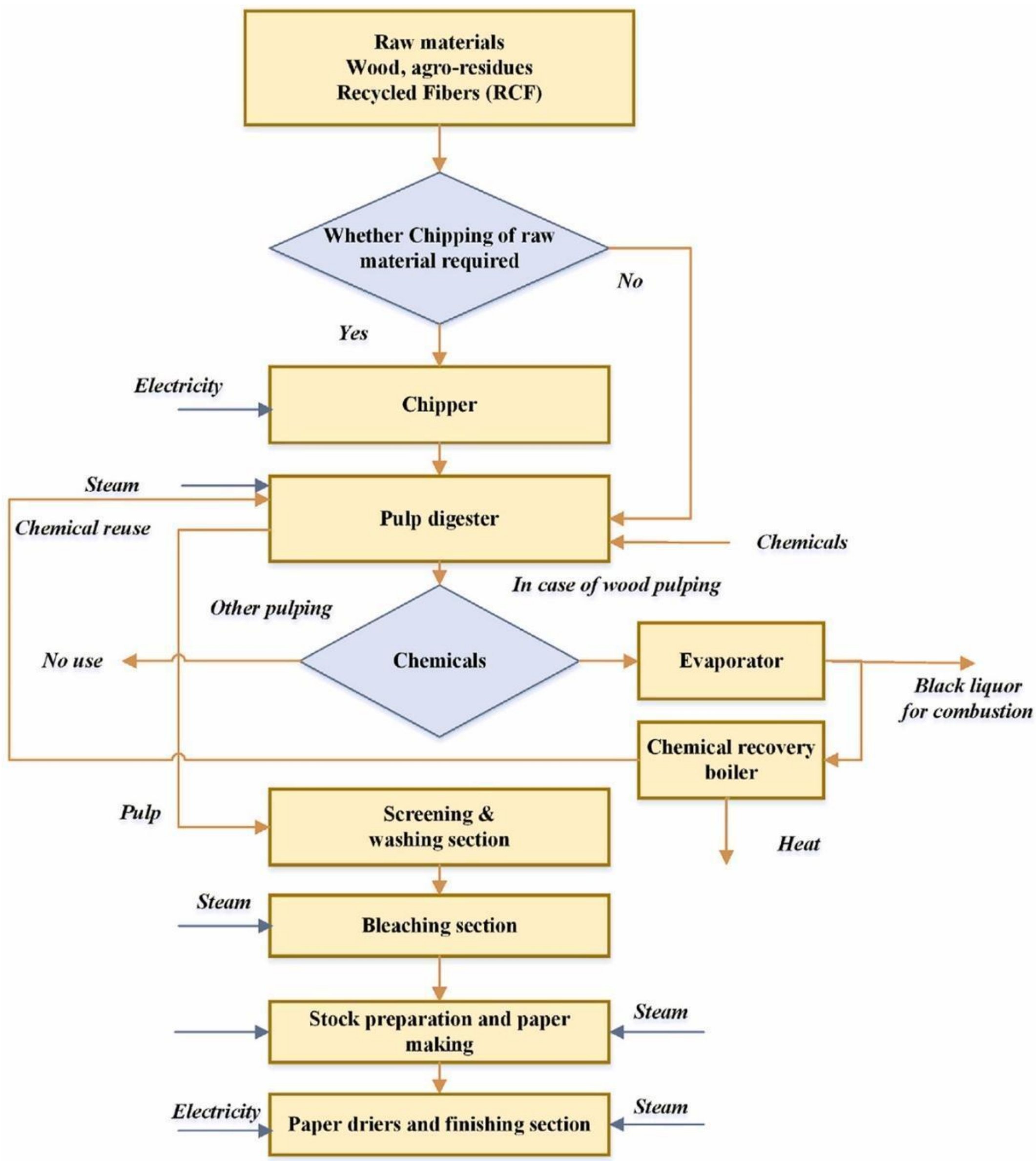
counties all have paper manufacturing facilities. The pulp production part of the paper making process is responsible for 60% of the total emissions due to burning biomass and energy intensive mechanical pulping that grinds wood fibers.[212] Next is the paper formation and drying at 20% emissions due to steam generation for drying. Finally, coating and paper treating makes up about 15% of the emissions with applying lamination or heat sealants and the extra drying needed for coated paper. Overall, 95% of the emissions from paper manufacturing come from the boilers used in the pulping, drying, and bonding processes.[213] Since the largest contributor to the emissions in the paper manufacturing industry is the process heating, the goal will be to electrify that process.

Figure 22: The contributions to emissions in the paper manufacturing subsector



[212] Uncovering energy use, carbon emissions and environmental burdens of pulp and paper industry: A systematic review and meta-analysis
[213] decarbonizing the pulp and paper industry

Figure 24: Schematic showing the paper manufacturing process.[214]



2025 – 2030

The drying process is a higher temperature process, so in the short term, energy efficiency process efficiency methods will be prioritized in reducing the energy demand for producing steam.

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[214] Decarbonizing the pulp and paper industry

Energy Efficiency

Waste heat recovery systems that capture excess heat from boilers, dryers, and exhaust systems should be implemented in preheating upstream processes to reduce the amount of energy needed. This can reduce energy consumption by up to 40%.[215]

Energy-efficient air compressors used in transporting pulp, and furnaces used in the drying process could save up to 12% electrical energy.[216]

Upgraded steam traps that remove water from steam lines without losing the steam pressure reduce steam losses, which in turn prevents excess steam generation for the same results. This can reduce fuel consumption significantly. This can increase condensate return by, which leads to a reduction of steam demand by 11%.[217]

Stationary syphons can be used to remove condensates in higher speed drying applications.[218] When coupled with mechanical vapor compression that concentrates liquid by using the heat from vapor, these can replace traditional energy intensive drying systems.[219] These systems can cost up to $25,000 depending on the size of the mill and the complexity of the system.[220]

Process and Material Efficiency

Conducting an energy audit to determine whether there are opportunities to reduce steam demand would allow for energy savings proportional to the reduction of steam production needed. Steam accounts for 43% of total energy demand, and energy savings would be proportional to the decrease in steam demand.[221] In the case of the upgraded steam traps that reduced steam demand by 11%, the energy demand would decrease by ~4%.

Increasing recycled content can reduce emissions by 0.5% per 1% increase in recycled content due to the reduction of energy demand compared to that of processing wood fibers.[222]

Electrification

Replace current heating with electric boilers or heat pumps where possible. Many processes in paper manufacturing require higher temperatures, and electric boilers and heat pumps are not ideal for high temperature processes. However, electric boilers and heat pumps could be incorporated in preheating, smaller drying applications, small scale production, and heat recovery and condensing.[223] Replacing boilers with heat pumps can reduce emissions by 48-64%.

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215 Waste heat recovery
216 decarbonizing the pulp and paper industry – alternative approaches
217 “Pulpandpaper.”
218 Fluid handling systems
219 stationary syphons and MVR
220 Kramer et al., “Energy Efficiency Improvement and Cost Saving Opportunities for the Pulp and Paper Industry.”
221 Steam demand reduction
222 Recycled Content
223 Deep decarbonization of energy-intensive industries

2030 – 2040

Alternative Fuels

Gas turbines are currently used in paper making as combined heat and power systems and for steam production. Retrofitting gas turbines for green hydrogen, biomass, or wood-derived alternatives could allow for medium term fossil – free solutions while electric alternatives are being developed.[224],[225]

2040 – 2050

The crucial hurdle for decarbonizing paper manufacturing is the electrification of the heat and drying processes.

Electrification

High temperature processes for chemical pulping, steam production, and drying coated paper could be replaced with high temperature electric boilers, heat pumps, infrared, microwave, or electric air convection drying.[226]

Emissions Evaluation

Table 11: Emissions Reductions by CO_2 Source for the Paper Manufacturing Subsector

Source of Emissions	Initial Emissions	Reduction Percentage	Final Emissions
Process Heating and Cooling	0.068 $MMTCO_2e$	90%	0.007 $MMTCO_2e$
Machine Drive	0.004 $MMTCO_2e$	100%	0 $MMTCO_2e$
Total	0.072 $MMTCO_2e$	90%	0.007 $MMTCO_2e$

Emissions Reductions and Health Benefits

Using the 2022 National Emissions Collaborative (NEC) Emissions Modeling Platform (EMP) tool, we established a baseline relationship between CO_2 and other harmful emissions by NAICs code.[227] We assumed that a reduction in CO2 would result in a proportional relative reduction in the other co-pollutants. Once these reductions were evaluated for each subsector, we estimated the avoided health costs for each subsector using the US EPA's COBRA tool.[228]

[224] Overcoming Decarbonization Hurdles in the Pulp and Paper Industry
[225] Alt fuels emissions reduction
[226] electrifying heat
[227] NEC EMP
[228] https://www.epa.gov/cobra

Subsector	Reduction in SO_2 (Tons)	Reduction in NO_x (Tons)	Reduction in VOCs (Tons)	Reduction in $PM_{2.5}$ (Tons)	Avoided Health Costs
Primary Metal Making	1,307	2,206	412	996	$61.1 million
Cement, Concrete, and Asphalt Manufacturing	419	880	183	346	$128.3 million
Fabricated Manufacturing	4.33	253	431	65	$14.9 million
Chemical Manufacturing	46.9	298	663	97.6	$37.2 million
Hospitals	0.82	102	7.22	11.6	$4,370,000
Pipeline Transportation	0.09	77.1	29.3	2.74	$386,000
Paper Manufacturing	0.32	60.9	210	4.60	$2.9 million
Total	**1,778**	**3,877**	**1,936**	**1,524**	**$249.2 million**

Health Co-Benefits of CCS at Cleveland Works
One of the primary additional benefits of strategies such as carbon capture to reduce GHG emissions is the accompanying reduction in co-pollutants. Improvements in air quality resulting from pollutants such as particulate matter (PM) being removed from the atmosphere alongside carbon dioxide can positively impact human health. This benefit can be estimated at the county level using U.S. EPA's Co-Benefits Risk Assessment (COBRA) model.[229] This peer-reviewed screening tool enabled the Study Team to estimate the air quality, human health, and associated economic impacts of carbon capture as an emission reduction strategy specifically for the steel industry.

In the case of fine particulate matter with a diameter of less than 2.5 micrometers—also known as $PM_{2.5}$—the cost to capture the condensable portion of this air pollutant is already reflected in the project cost developed by NETL in the reference case for carbon capture at an integrated

[229] U.S. Environmental Protection Agency, "CO-Benefits Risk Assessment Health Impacts Screening and Mapping Tool (COBRA)."

steel mill.[230] Based on a review of facility-level data for air pollutant emissions reported to the U.S. EPA through its National Emissions Inventory, an estimated 5.14 short tons of condensable $PM_{2.5}$ are emitted per 100,000 $MMTCO_2e$ emissions at Cleveland Works.[231] If the facility were retrofitted with carbon capture and operated at 80% of its productive capacity, the estimated annual CO_2 mitigation would be accompanied by the annual abatement of 147.31 short tons of $PM_{2.5}$.[232] Table 12 illustrates the health benefits of this reduction in $PM_{2.5}$ as estimated using U.S. EPA's COBRA tool, both for NOACA's five-county region and for Ohio overall.[233]

Table 12: Estimated Annual Public Health Benefits of $PM_{2.5}$ Reduction

Health Endpoint	Reduction in annual cases/costs for Cleveland-Elyria MSA	Reduction in annual cases/costs for Ohio
Mortality	2.2	3.2
Nonfatal heart attacks	0.9	1.3
Asthma onset	2.6	3.9
Asthma symptoms	490	730
Minor restricted activity days	800	1,200
Work loss days	135	200
Total health benefits	**$33,050,000**	**$48,840,000**

Health endpoint values reflect the midpoint of high and low estimates from U.S. EPA's COBRA model. Dollar values are in 2024 dollars.[234]

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230 Hughes et al., "Cost of Capturing CO_2 from Industrial Sources"; Great Plains Institute and Carbon Solutions, "Carbon Capture Co-Benefits: Carbon Capture's Role in Removing Pollutants and Reducing Health Impacts." The CANSOLV CO_2 absorption system whose cost was modeled in the NETL study includes a direct contact cooler (DCC) as a pre-scrubber that removes 100% of the *condensable* $PM_{2.5}$ prior to capturing 90 percent of the inlet CO_2. $PM_{2.5}$ is typically divided into two types: filterable and condensable particulates. Condensable particulates are initially emitted as vapors or gases that condense into liquid or solid form after cooling. In contrast, filterable particulates are already in a solid or liquid state at the time of emission.

231 Criteria air pollutants under the National Emissions Inventory (NEI) are reported in short tons, also known as U.S. tons, while greenhouse gas emissions under the EPA's Greenhouse Gas Reporting Program (GHGRP) are reported in MT. For 2020-2022, the three most recent years for which data is available, there were an estimated 163.6 short tons of $PM_{2.5}$ emissions annually at Cleveland Works. During the same period, as reported under the GHGRP program, the facility had 3.18 $MMTCO_2e$ emissions annually on average. For facility-level greenhouse gas and air emissions data, see U.S. Environmental Protection Agency, "Greenhouse Gas Reporting Program. 2023 Data Summary Spreadsheets"; U.S. Environmental Protection Agency, "2020-2022 Air Emissions Modeling Platforms."

232 As previously noted, the Study Team estimated annual emissions for Cleveland Works of nearly 3.6 $MMTCO_2e$ at 100% capacity utilization. The CO_2 absorption system includes a pre-scrubber that would remove 100% of the condensable $PM_{2.5}$ prior to capturing 90 percent of the inlet CO_2. At 80 percent capacity utilization, $PM_{2.5}$ would be removed from approximately 2.9 $MMTCO_2$ annually.

233 Health benefits were estimated using the COBRA Web Edition at https://cobra.epa.gov/. The value of future benefits was calculated using COBRA's default discount rate of 2%.

234 Dollar values were adjusted using GDP Implicit Price Deflator. See U.S. Bureau of Economic Analysis, "Gross Domestic Product: Implicit Price Deflator."

Community Benefits Agreements for Industrial-Scale CCS

Large infrastructure projects—such as industrial-scale carbon capture involving pipeline transportation and geological sequestration—can raise public concerns regarding safety, landowner protections, and the distribution of financial benefits to the communities most affected by the project.[235] If left unaddressed, these concerns may result in delays which, if prolonged for as little as two years, can nearly double overall project costs.[236] One way to address the community's concerns while increasing project certainty for the developer is through a Community Benefits Agreement (CBA) between the two parties.[237]

A CBA is a legally binding contract negotiated between a project developer and a community—often represented by a coalition of local groups—that outlines the specific benefits the community will receive in exchange for their support or lack of opposition to a project. Large-scale energy developments typically require a range of complex permits and land use approvals from various local, state, and federal agencies. The permitting process often includes opportunities for public challenges, which can result in delays or even cancellation of a project. Through a CBA, community representatives agree to support or refrain from opposing a project during these regulatory and permitting stages. A CBA can serve as a collaborative framework for addressing critical project issues, potentially offering increased long-term stability for the development.

What qualifies as a "benefit" in a CBA varies based on the specific needs and priorities of each community. For some, this might include enhancements to local infrastructure—like the development of community centers, green spaces, or services such as childcare and transportation funded by project revenues. Other communities may place greater value on investments in workforce training programs.

Participants in a community benefits agreement should represent a broad spectrum of local priorities, often including labor unions and worker advocacy groups, community organizations and neighborhood associations, environmental advocates, faith-based groups, and other interest-based organizations. However, the specific composition will differ from one community to another. Since one of the key advantages of a CBA is reducing project risk, it is important to involve not only groups that already support the project. Just as important is ensuring that participants are trusted within their communities and genuinely represent their constituents' needs, so the agreement truly addresses the concerns of those most affected by the project.

While the specific benefits outlined in a CBA may differ by community, certain key elements are commonly included:[238]

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[235] Chrysostomidis, Perumalpillai, and Wolff, "CCS Stakeholder Issues Review and Analysis"; Bonham and Chrysostomidis, "Local Community Benefit Sharing Mechanisms for CCS Projects."
[236] Chipman, "America's Corn Belt Bristles at $8 Billion Lifeline."
[237] The framework for Community Benefits Agreements found herein is adapted from U.S. Department of Energy guidance on CBAs. See U.S. Department of Energy, "FAQ: Community Benefits Agreements."
[238] For an extended list of best practices for Community Benefits Agreements, see Eisenson and Webb, "Expert Insights on Best Practices for Community Benefits Agreements."

- Commitment to support or not oppose the project. A central feature of a CBA is the community's pledge to either support or refrain from opposing the project. To ensure clarity and mutual understanding, the agreement should clearly define what constitutes the "project" as well as what is meant by "support" or "non-opposition."
- The CBA is a legally enforceable contract. All parties to the agreement, including community groups and developers, have the right to enforce its terms.
- Steering Committee. Most CBAs involve the creation of a community oversight group, such as a community benefits steering committee, which meets regularly to monitor agreement implementation and manage how community investment funds are allocated. The agreement should clearly define the criteria for committee membership, the length of terms, the selection process, and how appointments are approved.
- Reporting Requirements. The agreement should detail how and when the developer will report on its compliance with CBA terms, including a schedule for demonstrating progress and fulfillment of commitments.
- Specific and measurable terms. CBA commitments should be specific, measurable, and achievable so that agreements have clear outcomes that are easy for all parties and the public to track and examine.
- Commitment to transparency. To foster accountability and public trust, the CBA and related implementation and benefit reports should be made publicly available. Additionally, meetings of the steering committee should be open to the public.

Example of Community Benefits Agreement for CCS

While each CCS project is unique, as would be each Community Benefits Agreement, it is helpful to review existing agreements to better understand the scope of potential benefits available and how community concerns could be addressed under a CBA. In 2024, a first-of-its-kind CBA was signed between a developer and a community coalition concerning a pipeline that will deliver CO_2 captured at an ethanol plant in Nebraska to an underground storage facility in Wyoming.[239] Community concerns centered on landowner protections, public safety, and community investment. To that end, the developer agreed to the following provisions, among others, in exchange for a commitment from the coalition of community groups to not oppose the pipeline project:[240]

- Upfront payments of $500,000 to a community investment fund to support counties along the right-of-way, $100,000 for development of a regional CO_2 emergency alert system, $200,000 for development of a First Responder CO_2 training program, and $400,000 to help emergency response organizations purchase equipment to prepare for, detect, and respond to CO_2 release.
- Ongoing payments of $40,000 per year to replace equipment used by emergency responders to detect and respond to CO_2 release, $0.10 per MT of CO_2 sequestered

[239] Brungard and Fraser, "Community Benefits Snapshot: Tallgras-Bold Alliance CO_2 Pipeline Community Benefits Greement."
[240] For a list of benefits included in the Brungard and Fraser. agreement, see Columbia Law School Sabin Center for Climate Change Law, "Community Benefits Agreements Database."

each year to be contributed to a community investment fund, and a royalty of $0.10 per MT of CO_2 sequestered to landowners along the right-of-way in addition to their easement payment.

Regional Cohesion for a Community Benefits Agreement

The City of Cleveland has an extensive history of utilizing CBAs for projects that receive City financial assistance.[241] In the case of a CCS project, a developer may not seek local financial incentives but instead aim to avoid project delays. Nonetheless, the City's experience with CBAs offers a valuable framework for applying such agreements. This framework could be extended to a regional level to reflect the priorities and concerns of all impacted communities. Given the geographic scale of a potential CO_2 pipeline—particularly if the storage facility lies outside the Cleveland-Elyria MSA—NOACA may need to coordinate with other Metropolitan Planning Organizations and Regional Transportation Planning Organizations to convene the diverse cross-section of communities comprising the coalition that would be party to a CBA.

[241] City of Cleveland, Mayor's Office of Equal Opportunity, "Community Benefits Resource Guide."

5. Appendix A – Estimated GHG reductions from bike infrastructure expansion

Expanding bicycle infrastructure throughout the MSA will make it possible and practical for some residents to choose bicycles over cars, at least for some trips some of the time, thereby reducing vehicle miles travelled (VMT) and greenhouse gas emissions (GHG).

Key Assumptions

1. Lower-stress bicycle facilities, such as protected bicycle lanes, are significantly associated with larger increases in ridership compared with higher-stress facilities such as standard bicycle lanes and shared-lane markings. High-quality protected bike lanes increase cycling by 52.5% compared to standard bike lanes and 281.2% compared to shared-lane marking mileage.[242]
2. 10-40% of new cycling trips replace car trips, with the rest coming from walking, transit, or new trips entirely.

Unit Calculation

Assuming 1 mile of protected bike lane generates 40 new daily bike trips and 25% replace car trips, averaging 3 miles each:

- Daily VMT reduction: 10 trips × 3 miles = 30 VMT
- Annual: 30 × 365 = 10,950 VMT
- CO_2e reduction: 10,950 VMT × 0.36414 kg CO_2/mile = 3,988 kg CO_2/year per mile

Calculation Framework

1: Estimate new cycling trips per mile of infrastructure

- Use local bike count data or apply per-capita cycling rates from similar cities
- Apply a "network effect" multiplier - connected networks generate disproportionately more trips than isolated segments

2: Calculate vehicle miles traveled (VMT) reduction

- New bike trips × mode shift percentage × average trip length × frequency
- For Cleveland area, assume replaced car trips average 2-5 miles

3: Convert to emissions

- VMT reduction × average vehicle emissions factor
- In the MSA, 364.14 g CO_2 per mile for average passenger vehicle (2022)

Data Sources for Cleveland MSA:

- NOACA (Northeast Ohio Areawide Coordinating Agency) travel surveys
- Census journey-to-work data
- Existing bike count data from Cleveland Metroparks or city planning departments

Annual Build-Out Rates

Conservative/Realistic: 2-5 miles per year

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[242] Ferenchak, N., & Marshall, W. (2025). The link between low-stress bicycle facilities and bicycle commuting. *Nature Cities*. https://www.nature.com/articles/s44284-025-00255-5

- Focuses on key corridors and filling critical gaps
- Often tied to street resurfacing schedules to reduce costs

Moderate Growth: 5-15 miles per year

- Requires dedicated funding stream (i.e. federal grants, bonds, or millage)
- Good political support and streamlined approval processes
- May include lower-cost options like painted buffer lanes upgraded to protection

Aggressive: 15+ miles per year

- Usually requires major policy commitment or windfall funding

Cost-Effective Strategies

1. Opportunistic installation - Add protection during routine street maintenance (can cut costs 50-70%)
2. Phased approach - Start with painted lanes, add physical protection later
3. Focus on high-impact corridors - Prioritize routes connecting major destinations over comprehensive coverage initially
4. Leverage existing infrastructure - Convert underused traffic lanes or use park/trail connections
5. Grant funding - Federal (RAISE, CMAQ), state DOT, foundation, or corporate sponsorship

Cleveland Context

Given the region's fiscal constraints but growing cycling advocacy, 3-8 miles annually seems realistic if projects are aligned with resurfacing schedules and grant funding can be secured.

6. Appendix A – Estimated VMT and GHG reductions from Transit-Oriented Development

Transit-Oriented Development (TOD) increases population density, promotes a mix of complementary land uses, makes transit use more convenient, thereby reducing vehicle miles travelled (VMT). The MSA has a rich history of interurban rail connections, and recent TOD research provides solid foundations for projecting GHG reductions.

TOD development is already underway, supported by GCRTA's guidelines for TOD developments which include technical recommendations for communities based on the density, appropriate land use mix, orientation, and overall connectivity; NOACA's TOD Scorecard and Implementation Plan; and the Cuyahoga County Planning Commission's TOD Study, which includes a Model TOD Zoning Overlay.

The MSA also needs specific strategies for communities like Medina and North Ridgeville that are growing but not transit-serviced today and not part of legacy systems. Also, as we consider how the region might grow, new neighborhoods or communities will also need to be transit connected. For example, if a new sports and entertainment district in Brook Park materializes, TOD principles can help to reduce adverse impacts on existing communities and GHG emissions

Key Assumptions

1. Estimated VMT reductions for TOD residents of 20-40% compared to residents of traditional suburban development.
2. Estimated building efficiency gains of 15-30% for the denser housing in TODs.

Estimated VMT annual reductions and emissions reductions for a typical-sized TOD of 500 households

Assuming average vehicle emissions of 0.44 $MTCO_2e$ $_2$ per 1,000 VMT and 15-25% higher transit usage for TOD residents over regional average; and 8,500 VMT per person per year and 2 residents per household; then 500 TOD households (approx. # of households in catchment area for W. 25th Street TOD) would result in:

- 20-30% VMT reduction (approx. 2,400-3,600 miles) per year per household x 500 households = 1.7-2.5 million miles per year VMT reduction
- CO_2e reduction of 750-1,100 MT/year

Estimated density increases across the MSA

2025-2030

Assumptions: Existing TODs in the MSA will more fully develop to the point where their GHG reduction benefits are apparent and can be accurately documented. Estimated impacts:

W. 25th Street TOD - the basis for "typical TOD" calculations above

- 1.7-2.5 million miles per year VMT reduction

- CO_2e reduction of 750-1,100 MT/year

Van Aken District TOD
- 1.2-1.6 million miles per year VMT reduction
- CO_2e reduction of 530-700 $MTCO_2$e/year

HealthLine BRT (assuming 5,000 TOD households in corridor)
- 15-21 million miles annually
- CO_2e reduction: 6,600-9,200 $MTCO_2$e annually

Estimated impacts across all three TODs:
- Total VMT reduction: 17.4-24.4 miles/year
- Total CO_2e reduction: 7,660-10,690 MT/year

2030-2040
Assumptions: Five additional successful TODs will emerge, focused in some of the neighborhoods that currently meet half or more of the Cleveland's 15-minute city criteria, and inner-ring suburban neighborhoods including:

Shaker Square (Cleveland/Shaker Heights) - Historic transit hub with Blue/Green line access
- Estimated new TOD households by 2040: 800-1,200 units
- VMT reduction per capita: 35-45% (3,063-3,938 miles/year)
- Total VMT reduction: 4.9-9.4 million miles/year (assuming 2 people per unit)
- Total CO_2e reduction: 2,160-4,140 MT/year

Gordon Square (Detroit-Shoreway) - Arts district with existing walkability and transit access
- Estimated new TOD households by 2040: 600-900 units
- VMT reduction per capita: 30-40% (2,625-3,500 miles/year)
- Total VMT reduction: 3.2-6.3 million miles/year (assuming 2 people per unit)
- CO_2e reduction: 1,410-2,770 MT annually

University Circle/Little Italy (Cleveland) - Major employment/institutional hub with multiple transit and bus lines
- Estimated new TOD households by 2040: 1,000-1,500 units
- VMT reduction per capita: 40-50% (3,500-4,375 miles/year)
- Total VMT reduction: 7.0-13.1 million miles/year (assuming 2 people per unit)
- CO_2 reduction: 3,080-5,760 MT annually

79th Street/Opportunity Corridor (Cleveland) - Employment-focused TOD model based on Green/Blue/Red Line access; industrial & commercial development for vacant sites along Opportunity Corridor
- Estimated new employees: 2,000-3,500 positions (15-25% of workforce using transit)
- Estimated new TOD households by 2040: 200-400 units (primarily along E. 105th near Cedar/Carnegie in Fairfax)

- VMT reduction from employment access: 1.9-6.6 million miles/year (300-875 workers × 25-30 miles/day × 250 work days)
- VMT reduction from residential TOD: 1.4-3.5 million miles/year (200-400 units × 3,000-4,200 miles/year reduction)
- Total VMT Reduction: 3.3-10.1 million miles/year
- Total CO_2e Reduction: 1,450-4,440 MT/year

Windermere/Euclid Avenue (East Cleveland) Rail and bus service to downtown, University Circle, and airport

- Estimated new TOD households by 2040: 400-700 units
- VMT reduction per capita: 30-40% (2,625-3,500 miles/year)
- Total VMT reduction: 2.1-4.9 million miles/year
- CO_2e reduction: 920-2,160 MT/year

Estimated impacts across all five TODs:

- 2,900-4,300 new TOD households
- 2,000-3,500 new transit-accessible jobs
- Total VMT Reduction: 20.5-43.8 million miles/year
- Total CO_2e Reduction: 9,020-19,270 MT/year

2040-2050
TOD investments extend to established cities and towns (Chardon, Elyria, Medina, and Painesville) and a smaller legacy city (Lorain) in the MSA

Assumptions:

- TOD development roughly aligned with stops on the region's historic interurban rail system
- Local zoning changes, investment levels, and community acceptance of denser development patterns
- 15-30% of new development concentrated within ½ mile of transit stations
- Stable population across MSA, with modest population growth (1-3%) in TOD areas
- Affordable TOD housing will cut VMT for households in the five cities, which will reduce GHG emissions [Transit-Oriented Development | Location Efficiency Hub]
- 20-40% reduction in household VMT for TOD residents vs. suburban counterparts
- Mixed-use development with employment opportunities reducing commute distances

Estimated impacts across all five cities & towns:

- 2,000-3,000 new TOD households
- Total VMT Reduction: 2,500 households × 6,500 miles = 16.25 million miles/year
- Total CO_2 Reduction: 8,125 MT/year

7. Appendix A – Estimate Co-Benefits from Reduced Traffic Crashes and Increased Physical Activity from VMT Reduction

Reducing VMT by promoting the shift to other, sustainable transportation modes, including public transit, bicycling, walking, and remote work, will provide substantial co-benefits from reduced traffic crashes and increased physical activity. The following section outlines the methodology used to quantify these co-benefits, including their economic value. To review the calculations developed for this analysis, review Appendix J.

VMT Reduction Data

The City of Cleveland used data for 2018, 2030, and 2050 provided by NOACA. The City used 2018 data to estimate a 15% reduction in VMT by 2030 and a 30% reduction by 2050. VMT by County for 2018 and 2030 and 2050 under both Business As Usual (BAU) and VMT Reduction scenarios are listed in Table 14, below.

Table 14: VMT by County Under BAU and VMT Reduction Scenarios (Billions of Miles)

Year/Scenario	Cuyahoga	Geauga	Lake	Lorain	Medina	Total
2018 Observed	9.42	0.84	1.91	2.55	1.99	16.71
2030 BAU	10.14	0.91	2.01	2.70	2.10	17.87
2030 15% Reduction	8.01	0.72	1.62	2.16	1.69	14.20
2050 BAU	8.89	0.95	1.78	2.68	2.06	16.37
2050 30% Reduction	6.60	0.59	1.34	1.78	1.39	11.69

Using these data, the City estimated annual VMT from 2025-2050 under BAU and VMT Reduction scenarios. The City assumed that VMT would decrease from 2018 to 2030 and from 2030 to 2050. Staff then used the difference between VMT in the BAU and VMT Reduction scenarios to quantify co-benefits.

Reduced Traffic Crashes – Fatalities and Serious Injuries Assumptions

Staff assumed that the rates of traffic fatalities and serious injuries would remain constant at 2022 levels from 2025-2050.

- Traffic Fatality Rate
    - Impact factor: 1.144 deaths per hundred million VMT (HMVMT)
    - Source: 2022 data, *Ohio Highway Safety Improvement Program 2023 Annual Report,* https://highways.dot.gov/sites/fhwa.dot.gov/files/2024-04/HISP(Ohio)%202023%20Report.pdf
- Serious Injury Rate

    - Impact factor: 6.703 serious injuries per HMVMT
    - Source: 2022 data, *Ohio Highway Safety Improvement Program 2023 Annual Report*

Increased Cyclist & Pedestrian Fatalities Assumptions
Staff assumed that the rates of cyclist and pedestrian fatalities would remain constant from 2025-2050.

- Cyclist Fatality Rate
    - Impact factor: 3.09 deaths per hundred million person miles traveled (HMPMT)
    - Source: World Health Organization (WHO) Health Economic Assessment Tool (HEAT) for walking and cycling national crash data for the United States, https://www.who.int/tools/heat-for-walking-and-cycling.
- Pedestrian Fatality Rate
    - Impact factor: 9.76 deaths per HMPMT
    - Source: WHO HEAT tool data

Health Co-Benefits from Increased Physical Activity Assumptions
To estimate the share of reduced VMT that shift to walking and biking, the City of Cleveland pulled data on commute mode share for each of the counties in the Cleveland-Elyria MSA from 2018-2022 5-year American Community Survey (ACS) data. The City determined the share of commutes occurring via alternative travel modes (public transit, walking, cycling, remote work, and other) for each county in the MSA. Staff then calculated the percentage of alternative commutes that walking and biking accounted for in each county from 2018-2022. These data appear in Table 15.

Table 15: Alternative Commute Mode Share by County, 2018-2022

Year/Scenario	Cuyahoga	Geauga	Lake	Lorain	Medina	Total
Walking	2.7%	1.5%	1.4%	1.8%	0.9%	2.2%
Biking	0.3%	0%	0.1%	0.2%	0.1%	0.2%
Total Alternative Commute Mode Share	19.1%	15.9%	13.2%	12.0%	13.9%	16.8%
Walking % of Alternative Commutes	14.1%	9.4%	10.6%	13.3%	6.5%	12.7%
Biking % of Alternative Commutes	1.6%	0.0%	0.8%	1.7%	0.7%	1.3%

Using these data, the City estimated the share of avoided VMT that would shift instead to biking and walking. Staff then used these data on person miles traveled (PMT) for walking and biking to estimate the health benefits from increased physical activity. Staff assumed that the rates of cyclist and pedestrian fatalities would remain constant from 2025-2050.

- Avoided Premature Deaths from Cycling
  - Impact factor: 82 avoided deaths HMPMT
  - Source: Cambridge Systematics, Inc. 2023 analysis for Georgetown Climate Center, using data from WHO HEAT tool, https://www.georgetownclimate.org/files/report/GCC_Investment_Tool.pdf
- Avoided Premature Deaths from Walking
  - Impact factor: 26 avoided deaths per HMPMT
  - Source: Cambridge Systematics, Inc. 2023 analysis for Georgetown Climate Center, using data from WHO HEAT tool, https://www.georgetownclimate.org/files/report/GCC_Investment_Tool.pdf

Economic Value of Co-Benefits from VMT Reduction

To estimate the economic value of the co-benefits of VMT reduction, the City of Cleveland relied on estimates of value of prevented deaths and prevented disabling injuries from the U.S. Department of Transportation (USDOT). Staff completed all estimates in 2022 U.S. dollars (USD) and converted totals into the net present value (NPV) using a 2% discount rate.

- Value of Statistical Life (VSL) for Traffic Fatalities
  - Value: $12.5 million (2022 USD)
  - Source: USDOT 2021 guidance, https://www.transportation.gov/office-policy/transportation-policy/revised-departmental-guidance-on-valuation-of-a-statistical-life-in-economic-analysis
- Value of Disabling Injuries
  - Value: $673,750 (2022 USD)
  - Source: Federal Transit Administration (FTA) 2013 guidance, adjusted to 2022 USD, https://www.apta.com/wp-content/uploads/Resources/gap/fedreg/Documents/NS-SS_Final_PolicyGuidance_August_2013.pdf
- Discount Rate
  - Value: 2% per year
  - Source: Office of Management and Budget (OMB) Circular A-4 Appendix (2021), https://bidenwhitehouse.archives.gov/wp-content/uploads/2023/11/CircularA-4Appendix.pdf

8. Appendix A – Estimated GHG calculations for demolition vs. rehabilitation

This framework provides a methodology for calculating carbon emissions from demolition versus rehabilitation of vacant buildings in Cleveland and surrounding counties (Cuyahoga, Lake, Geauga, Medina, Lorain). The analysis includes equipment emissions, transportation, landfill impacts, and embodied carbon considerations.

Carbon Emission Sources

Demolition

Equipment operations (excavators, trucks)
Transportation of debris (averaging 25+ miles in the MSA)
Landfill methane emissions from organic materials
Lost embodied carbon from existing materials (typically 20-40 tons CO_2e per residential building)
Future replacement construction emissions

Rehabilitation

Construction equipment (much lower equipment emissions - 60-80% reduction vs demolition)
Material transportation
Waste generation (Selective demolition)
Retained embodied carbon

Carbon Calculation Methodology

Demolition Carbon Accounting

1. Equipment Emissions
    a. Excavators/Demolition Equipment: 25-35 kg CO_2/hour operation
    b. Average demolition time: 2-5 days for typical residential building
    c. Formula: Equipment hours × fuel consumption × emission factor
    d. Typical Range: 500-2,000 kg CO_2 per residential building
2. Transportation Emissions
    a. Debris volume: 150-300 tons per average house
    b. Transportation distance: Average 25 miles to landfill/processing
    c. Truck capacity: 20-25 tons per load
    d. Formula: (Total waste ÷ truck capacity) × distance × 2 × emission factor
        i. Emission factor: 0.16 kg CO_2/ton-mile for heavy trucks
    e. Typical Range: 400-800 kg CO_2 per building
3. Landfill Emissions
    a. Methane generation: 0.05-0.1 kg CO_2e per kg of organic waste
    b. Concrete/masonry: Minimal direct emissions but lost carbon storage
    c. Wood waste: 0.5-1.0 kg CO_2e per kg (methane generation)

    d. Typical Range: 200-500 kg CO_2e per building
4. Lost Embodied Carbon
    a. Concrete: 0.1-0.15 kg CO_2 per kg
    b. Steel: 1.8-2.5 kg CO_2 per kg
    c. Wood: 0.4-0.8 kg CO_2 per kgTypical residential building: 20-40 tons CO_2e in embodied carbon lost

<u>Rehabilitation Carbon Accounting</u>

1. Construction Equipment
    a. Renovation equipment: 60-80% lower emissions than demolition
    b. Selective demolition: 10-20% of full demolition emissions
    c. Typical Range: 100-400 kg CO_2
2. New Materials
    a. Energy efficiency upgrades: Insulation, windows, HVAC
    b. Structural repairs: Concrete, steel, lumber as needed
    c. Typical Range: 5-15 tons CO_2e (varies significantly by scope)
3. Retained Embodied Carbon
    a. Foundation retention: 8-12 tons CO_2e typically saved
    b. Structural elements: 5-10 tons CO_2e saved
    c. Total retention: 60-80% of original embodied carbon

Spatial Impact Analysis on Carbon Emissions / Geographic Clustering Effects

<u>High-Density Demolition Areas (Legacy Cities)</u>

- Equipment utilization: 15-25% lower emissions per building due to continuous operation
- Transportation efficiency: Shared truck loads reduce per-building transport emissions by 20-40%
- Centralized processing: Shorter aggregate distances to processing facilities
- Infrastructure amortization: Temporary facilities (debris sorting, material recovery) become cost-effective
- Local air quality: Cumulative dust and equipment emissions in neighborhoods
- Infrastructure strain: Repeated heavy truck traffic on local roads
- Community disruption: Concentrated demolition creates additional social costs

<u>Scattered Suburban and Rural Demolitions</u>

- Higher per building emissions
- Equipment mobilization: 30-50% higher emissions due to travel between sites
- Transportation inefficiency: Partial truck loads, longer distances to facilities
- No economies of scale: Each demolition operates independently
- Higher fuel consumption: Equipment idle time between projects

<u>Clustering Impact on Rehabilitation</u>

- Reduced travel time between projects (10-20% emission reduction)
- Bulk deliveries to multiple nearby sites
- Specialized tools shared across multiple projects
- Contractors develop expertise, reducing waste and rework

<u>Transportation Distance Analysis</u>

- Legacy Cities (Higher density)
  - Average distance to C&D facilities: 15-25 miles
  - Multiple trip efficiency: Coordinated hauling reduces empty return trips
  - Local recycling capacity: Higher utilization of nearby processing facilities

- Suburbs & Established Cities/Towns (Medium Density)
  - Average distance to facilities: 25-40 miles
  - Mixed efficiency: Some clustering benefits, but more dispersed
  - Regional facility access: Better access to specialized recycling facilities

- Rural Areas (Low Density)
  - Average distance to facilities: 40-60+ miles
  - Transport penalty: 60-100% higher transportation emissions per building
  - Limited local capacity: Often bypass local facilities for distant specialized ones

Regional Calculation Framework - Demolition

<u>High-Density Urban Areas (Legacy Cities)</u>

- Residential Buildings
  - Demolition carbon cost: 20-35 tons CO_2e per building (15-25% reduction from economies of scale)
  - Rehabilitation carbon cost: 6-14 tons CO_2e per building (20-30% reduction from clustering)
  - Transportation factor: 0.8x (shorter distances, higher efficiency)

- Commercial/Industrial Buildings
  - Demolition carbon cost: 40-160 tons CO_2e per building
  - Rehabilitation carbon cost: 12-48 tons CO_2e per building
  - Specialized equipment sharing: Additional 10-15% efficiency gains

<u>Inner Ring Suburbs. Established Cities & Towns (Medium-Density)</u>

- Residential Buildings
  - Demolition carbon cost: 25-45 tons CO_2e per building (baseline)
  - Rehabilitation carbon cost: 8-18 tons CO_2e per building
  - Transportation factor: 1.0x (regional average)

<u>Rural Areas (Low-Density)</u>

- Residential Buildings

- Demolition carbon cost: 35-60 tons CO_2e per building (40-80% penalty)
- Rehabilitation carbon cost: 10-25 tons CO_2e per building (25-40% penalty)
- Transportation factor: 1.6x (longer distances, lower efficiency)
- Mobilization penalty: Additional 2-5 tons CO_2e per project for equipment transport

Targeted Demolition Strategy

Cleveland - High-Volume Demolition Context

Current Patterns:

- Annual demolitions: 800-1,200 buildings/year in concentrated distressed neighborhoods
- Typical clustering: 5-15 buildings per city block in targeted areas
- Major demolition corridors: East Side neighborhoods, portions of West Side
- Transport advantages: Multiple C&D facilities within 15-25 mile radius

Carbon Optimization Approach:

- Target 50-100 building areas for coordinated demolition
- Establish temporary debris sorting/processing in each targeted neighborhood
- Keep demolition equipment in area for 2-3 month campaigns
- Schedule coordinated truck routes to maximize loads
- Estimated carbon reduction: 20-30% per building compared to scattered demolitions

Lorain - Medium-Volume Demolition Context

Current Patterns:

- Annual demolitions: 50-150 buildings/year, less concentrated than Cleveland
- Mixed residential/commercial: Industrial legacy buildings alongside residential
- Transport considerations: 25-35 miles to major C&D facilities

Carbon Optimization Approach:

- Quarterly campaigns: Batch demolitions into seasonal concentrated efforts
- Cross-project equipment sharing: Coordinate with Cleveland operations
- Local material recovery: Establish temporary brick/masonry recovery for historic buildings
- Estimated carbon reduction: 15-25% per building through coordination

Suburban Strategy-Varied Demolition Context

Primary Focus Areas:

- East Cleveland, Euclid, Cleveland Heights: Higher vacancy rates, older housing stock
- Lakewood, Parma, Garfield Heights: Selective demolition of deteriorated buildings
- Brook Park, Middleburg Heights: Mixed residential/commercial projects

Carbon Optimization Approach:

- Schedule demolitions across municipal boundaries
- Joint purchasing/leasing of specialized equipment
- Coordinate with Cleveland operations for equipment efficiency

- Estimated carbon reduction: 10-20% reduction through coordination vs. independent municipal actions

Targeted Rehabilitation Strategy

- Target aging commercial strips and residential blocks
- Concentrate rehabilitation within 0.5-mile radius
- Focus on streets with 40-60% occupancy rates
- Cross-train contractors across multiple communities
- Bulk purchasing of rehabilitation materials
- Estimated carbon reduction: 25-35% per building for clustered rehabilitation

Considerations for Lake, Geauga, Medina Counties

<u>Lake County</u>

- Annual demolitions: 20-50 buildings/year, highly scattered
- Focus areas: Painesville, Mentor industrial legacy buildings
- Transport considerations: 40-60 miles to major C&D facilities

<u>Geauga County</u>

- Annual demolitions: 10-30 buildings/year, mostly agricultural/residential
- Transport considerations: 50-70 miles to processing facilities

<u>Medina County</u>**:**

Annual demolitions: 15-40 buildings/year, mixed agricultural/suburban
Growing areas: Some new construction, selective old building removal
Transport considerations: 35-55 miles to facilities

Demolition Strategy for Lake, Geauga, Medina Counties

<u>Quarterly Batching System</u>

- Batch projects by county for quarterly campaigns
- Bring equipment to region for multi-week campaigns
- Establish temporary rural processing capability
- Coordinate timing across Lake, Geauga, and Medina counties

<u>Transportation Optimization</u>

- Coordinate waste streams across counties
- Explore satellite C&D processing facilities
- Higher economic incentive for material recovery in rural areas
- Estimated carbon reduction: 30-50% reduction through coordination vs. isolated projects

Rehabilitation Strategy for Lake, Geauga, Medina Counties

- Focus on architecturally significant rural buildings
- Specialize in barn and agricultural structure rehabilitation
- Traveling rehabilitation crews serving multiple counties

- Estimated carbon reduction: 20-30% carbon reduction through specialized approaches

Geographic-Specific Carbon Factors

Legacy Cities (Cleveland/Lorain)

- Demolition efficiency factor: 0.75-0.85x (high clustering benefits)
- Rehabilitation efficiency factor: 0.70-0.80x (workforce/material benefits)
- Transportation factor: 0.8-0.9x (shorter distances, higher capacity utilization)

Suburbs and Established Cities/Towns

- Demolition efficiency factor: 0.85-0.95x (moderate clustering benefits)
- Rehabilitation efficiency factor: 0.80-0.90x (some coordination benefits)
- Transportation factor: 0.9-1.0x (near regional average)

Rural Areas

- Demolition efficiency factor: 1.3-1.6x (high mobilization/transport penalties)
- Rehabilitation efficiency factor: 1.2-1.4x (specialized workforce, material transport)
- Transportation factor: 1.4-1.8x (long distances, partial loads)
- Coordination benefit: 30-40% carbon reduction when properly batched

Average Estimated Carbon Savings

- Residential rehabilitation vs. demolition: 60-75% carbon reduction
- Commercial rehabilitation vs. demolition: 50-70% carbon reduction
- Regional impact: With 12,000 vacant buildings, rehabilitation offers a potential savings of 200,000-400,000 tons CO_2e

Appendix B

Energy Demand Forecasting for a Zero-Emissions Projection

Projecting Energy Requirements in the Cleveland-Elyria MSA

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June 2025

Executive Summary

This document presents an analysis of current energy usage in the Cleveland-Elyria MSA and outlines the projected demand necessary to support a fully zero-emissions future. This future entails a complete transition away from fossil fuels—including natural gas, propane, fuel oil, gasoline, and diesel—and toward a fully electrified energy economy.

The challenge is twofold: to understand the scale of current fossil-based energy consumption across key sectors, and to translate that consumption into equivalent electric demand, accounting for system efficiencies, sectoral variation, and projected growth patterns.

This report serves as a foundation for assessing infrastructure needs, electrification strategy, and policy prioritization over the coming decades.

Baseline Energy Usage by Sector (2022)

Table 1: Energy Usage by Sector and Fuel Source (2022)[1]

Sector	Fuel or Source	Usage (2022)	Unit
Residential Energy	Electricity	7,503,332,440	kWh
	Natural Gas	77,316,450	MMBtu
	Propane	1,160,042	MMBtu
	Fuel Oil	439,171	MMBtu
Commercial Energy	Electricity	7,061,745,524	kWh
	Natural Gas	39,939,787	MMBtu
Industrial Energy	Electricity	6,744,776,571	kWh
	Natural Gas	10,426,661	MMBtu
Transportation & Mobile Sources	Gasoline	16,221,006,125	VMT
	Diesel	1,171,752,406	VMT
Total Electricity Use		**21,309,854,535**	**kWh**

[1] City of Cleveland Mayor's Office of Sustainability, *Cleveland-Elyria MSA 2022 Inventory*.

Introduction and Methodology

The table above summarizes baseline energy consumption by sector. To achieve a zero-emissions future, all fossil-derived energy sources must be replaced with renewable, electric alternatives. This includes complete phase-out of natural gas, propane, fuel oil, gasoline, and diesel.

However, converting non-electric energy sources to electric equivalents is not straightforward. For instance, conversion from MMBtu to kWh is subject to variation in system efficiency, technological maturity, and infrastructure quality—each of which differs across residential, commercial, and industrial settings.

Moreover, not all sectors are projected to grow linearly. In particular, transportation electrification is expected to follow nonlinear uptake patterns, which may differ under business-as-usual (BAU), moderate, or aggressive adoption scenarios.[2]

As such, this report is organized by sector and presents estimated conversion strategies, efficiency assumptions, and projected electric demands under several transition models.

[2] S&P Global and PJM Interconnection, *ATSI Forecast*.

Residential, Commercial, and Industrial Energy

Due to the similarity in their corresponding data, we shall analyze the Residential, Commercial, and Industrial sectors next to one another, to avoid repetition.

In analyzing these sectors, we focus on two interrelated considerations: (1) electrification—replacing direct fossil-fuel powered systems with electric alternatives, and (2) total energy consumption—including both current demand and expected changes due to environmental or behavioral trends.

To simplify our projections, we make a key infrastructural assumption: the population **and** building stock in the MSA will remain largely constant through 2050. However, we do not assume that energy consumption itself will remain flat. Instead, we allow for changes in demand intensity due to factors such as climate trends, electrification efficiency, and shifting appliance use.

This section is divided into two parts:

- **Section 1: Baseline Electrification Demand.** This subsection estimates the electric load required to replace all residential, commercial, and industrial fossil-fuel usage with electric systems, assuming no change in total energy consumption.
- **Section 2: Climate-Adjusted Demand Projection.** Here, we adjust baseline demand based on projected shifts in heating and cooling loads due to climate change. While rising temperatures may reduce heating demand, increasing humidity and dew point levels may intensify cooling needs. This subsection models those effects and proposes a revised electricity forecast for 2050.

Section 1: Baseline Electrification Demand

Residential Energy

The residential sector is of critical importance in any zero-emissions strategy. Beyond its sizable share of overall energy consumption, it directly impacts the daily lives of households—particularly in disadvantaged or energy-insecure communities. Electrification of residential energy use thus represents not only a technical transformation, but a social one.

This section models the total electricity required to fully electrify all residential fossil-fuel end uses in Greater Cleveland, assuming no change in total energy consumption. That is, we estimate how much electricity would be needed if current natural gas, propane, and fuel oil usage were replaced one-to-one with electric systems that deliver equivalent useful energy.

To perform this conversion, we use standard energy equivalence factors. For each fuel source, its usage in MMBtu is multiplied by a constant representing kilowatt-hours per MMBtu. For perfect 100% efficiency, this factor is 293.07107 kWh/MMBtu[3]. This provides an upper-bound estimate, assuming no efficiency improvements are gained during electrification.

The following table summarizes this upper-bound scenario:

Table 2: Residential Upperbound on Electrification Need

Sector	Fuel or Source	Conversion Factor	Usage (kWh)
Residential Energy	Electricity	1	7,503,332,440
	Natural Gas	293.07107	22,659,214,743
	Propane	293.07107	339,974,750
	Fuel Oil	293.07107	128,708,315
Total Electricity Before Conversion			**7,503,332,440**
Total Electricity Added/Converted			**23,127,897,808**
Total Electricity Use After Fossil-Fuel Conversion			**30,631,230,248**

This scenario results in a total added electric load of over 23 TWh annually, reflecting a direct, unadjusted replacement of fossil fuel energy input with electricity. However, this assumes highly efficient natural gas, propane, and fuel oil systems, and does not account for efficiency gains that may arise from the use of modern electric heat pumps, resistive heating, or building envelope improvements.

[3] U.S. Energy Information Administration, "Energy Conversion Calculators."

To produce a more realistic lower-bound estimate, we incorporate average equipment efficiency. Fossil-fuel systems such as natural gas furnaces often operate at Annual Fuel Utilization Efficiency (AFUE) ratings between 56% and 98%.[4] To identify this lower-bound, we apply a conservative efficiency of 56%—representing outdated or poorly maintained systems—to show the reduced electricity required to deliver the same useful heat.

This results in lower conversion factors (164.1198 kWh/MMBtu), calculated as:

$$\text{Adjusted kWh/MMBtu} = 293.07107 \text{ kWh/MMBtu} \times 0.56$$

The table below reflects this adjustment:

Table 3: Residential Lowerbound on Electrification Need

Sector	Fuel or Source	Conversion Factor (kWh/MMBtu)	Usage (kWh)
Residential Energy	Electricity	1	7,503,332,440
	Natural Gas	164.1198	12,689,160,256
	Propane	164.1198	190,385,860
	Fuel Oil	164.1198	720,766,656
Total Electricity Before Conversion			**7,503,332,440**
Total Electricity Added/Converted			**12,951,622,773**
Total Electricity Use After Fossil-Fuel Conversion			**20,454,955,213**

As such, from both of these tables we reach a lower- and upperbound on the electrification need. More specifically, we can expect an electrification need of between 12.95 and 23.13 TWh, which is a very large range. Therefore, we will want to have an expected value within this range.

This value will be found through the assumption that the majority of electrification need will stem from heating; specifically, water-heating and furnaces. We will then make use of data to find an expected average number of homes that rely on new or old technologies, and multiply out to find an average conversion efficiency. Using this, we'll define an expected conversion factor and use it to calculate expected electrification need.

Assuming the **ratio** of old-to-new furnaces stayed approximately the same from 2015 (the large percentage of old, unrenovated homes in Cleveland supports such an assumption), we'll

[4] U.S. Department of Energy, "Furnaces and Boilers."

assume that 0-9 year old units are high efficiency, 10-19 year old units are medium efficiency, and 20+ year old units are low efficiency.[5]

Thus, we arrive at the following table:

Table 4: Residential Average Heating Efficiencies and Unit Age

Sector	Age of Unit (years)	Percentage of Units	Assumed AFUE (Efficiency %)
Residential Energy	0-9	49.47	94
	10-19	32.74	81.5
	20+	17.79	63
Weighted Average of AFUE (Efficiencies)			**84.39**

As such, using this weighted average of 84.39%, we get:

$$0.8439 \times 293.07107 \text{ kWh/MMBtu} \approx 247.323 \text{ kWh/MMBtu}$$

Extrapolating to all residential appliances, and using for our estimated required electrification need:

Table 5: Residential Expected Electrification Need

Sector	Fuel or Source	Conversion Factor (kWh/MMBtu)	Usage (kWh)
Residential Energy	Electricity	1	7,503,332,440
	Natural Gas	247.323	19,122,136,363
	Propane	247.323	286,905,068
	Fuel Oil	247.323	108,617,089
Total Electricity Before Conversion			**7,503,332,440**
Total Electricity Added/Converted			**19,517,658,520**
Total Electricity Use After Fossil-Fuel Conversion			**27,020,990,960**

[5] U.S. Energy Information Administration, *"2015 Residential Energy Survey."*; U.S. Department of Energy, Residential Furnaces, 271.

Thus, we'd expect that to completely electrify the Residential Sector by 2050, we'd need to produce an extra $\sim$ 19.5 TWh of electricity.

Commercial Energy

The commercial sector in the MSA comprises offices, schools, hospitals, retail, warehouses, and other non-industrial non-residential buildings. Electrification in this sector represents a major opportunity to reduce emissions from space heating, water heating, and cooking—currently dominated by natural gas, with some limited use of fuel oil.

This section models the total electricity demand resulting from a full electrification of commercial fossil fuel energy, assuming a one-to-one replacement by electric systems that supply the same useful energy.

As in the residential case, we begin by applying a direct energy-equivalence conversion using the standard factor of 293.07107 kWh/MMBtu to provide an upper-bound estimate:

Table 6: Commercial Upperbound on Electrification Need

Sector	Fuel or Source	Conversion Factor	Usage (kWh)
Commercial Energy	Electricity	1	7,061,745,524
	Natural Gas	293.07107	11,705,196,112
Total Electricity Before Conversion			**7,061,745,524**
Total Electricity Added/Converted			**11,705,196,112**
Total Electricity Use After Fossil-Fuel Conversion			**18,766,941,636**

For the commercial sector, we're making the estimate that, like we did for the residential sector, most of the natural gas usage is for heating the spaces. As such, for a lower-bound estimate, we again assume fossil fuel systems operate at a conservative 56% efficiency. This yields an adjusted conversion factor of 164.1198 kWh/MMBtu:

Table 7: Commercial Lowerbound on Electrification Need

Sector	Fuel or Source	Conversion Factor (kWh/MMBtu)	Usage (kWh)
Commercial Energy	Electricity	1	7,061,745,524
	Natural Gas	164.1198	6,554,909,854
Total Electricity Before Conversion			**7,061,745,524**
Total Electricity Added/Converted			**6,554,909,854**
Total Electricity Use After Fossil-Fuel Conversion			**13,616,655,378**

Due to a lack of available data, we'll assume that the expected conversion factor is the same as in the Residential Sector: 247.323 kWh/MMBtu. This gives us the following table:

Table 8: Commercial Expected Electrification Need

Sector	Fuel or Source	Conversion Factor (kWh/MMBtu)	Usage (kWh)
Commercial Energy	Electricity	1	7,061,745,524
	Natural Gas	247.323	9,878,027,940
Total Electricity Before Conversion			**7,061,745,524**
Total Electricity Added/Converted			**9,878,027,940**
Total Electricity Use After Fossil-Fuel Conversion			**16,939,773,464**

Thus, we'd expect to electrify the Commercial Sector by 2050 that we'd need to add ∼9.88 TWh to the grid worth of electricity.

Industrial Energy

The industrial sector is the most varied and technically complex of the three, encompassing activities such as manufacturing, steel-making, chemical processing, and bulk storage. Electrification in this sector is difficult due to high process temperatures, equipment specificity, and economic inertia. In fact, it is important to note that there does exist some industrial processes that currently have no electric alternative (such as CHP, Combined Heat and Power, methods). However, some process heating, motor drives, and building systems still rely on fossil fuels and can be targeted for electrification.

As before, we first estimate the upper-bound electricity needed for direct one-to-one replacement of fossil fuel inputs, assuming 100% efficient electric systems and using the same conversion factor of 293.07107 kWh/MMBtu:

Table 9: Industrial Upperbound on Electrification Need

Sector	Fuel or Source	Conversion Factor	Usage (kWh)
Industrial Energy	Electricity	1	6,744,776,571
	Natural Gas	293.07107	3,055,752,696
Total Electricity Before Conversion			**6,744,776,571**
Total Electricity Added/Converted			**3,055,752,696**
Total Electricity Use After Fossil-Fuel Conversion			**9,800,529,267**

Whereas we were able to make the assumption that heating made up a majority of the energy usage in the Residential and Commercial Sectors, the same cannot so easily be said about the Industrial Sector. More specifically, this sector is characterized by its variety of processes and methods used for production. As such, we necessarily must analyze it in a separate, more methodical way.

In order to make an overall estimate on what we'd actually expect the conversion factor within this range to be, we must necessarily look at the different end uses and respective efficiency ratios compared to electrical generation methods. Thus, we get the following table, listing the percentage of natural gas each method uses from the whole and the ratio of efficiency between electrical and non-electrical methods[6]:

[6] National Renewable Energy Laboratory, *Electrification Futures Study*.

Table 10: Industrial End Uses and Efficiencies

End Use	Percentage of Total Non-Electrical Energy Consumption	Natural Gas Efficiency	Electric Efficiency	Efficiency Ratio
Conventional Boiler Use	7.19	75	90	0.833
CHP and/or Cogeneration Process	42.39	∼72.5	—	N/A
Process Heating	40.18	12	40	0.3
Process Cooling and Refrigeration	0.25	80	95	0.842
Machine Drive	1.04	27	75	0.36
Other Process Use	1.43	40	70	0.571
Facility HVAC	6.64	30	100	0.3
Other Facility Support	0.49	30	100	0.3
Onsite Transportation	0.31	25	90	0.278
Other Nonprocess Use	0.08	30	100	0.3
Weighted Average Conversion Percentage				**21.69%**
Estimated Conversion Factor (kWh/MMBtu)				**63.57**

The conversion percentage, and thus the conversion factor (calculated as the percentages of total non-electrical energy consumption multiplied by the efficiency ratio and summed), is very low. The reasoning for this is twofold; firstly, the efficiency ratios are low because the electrical alternatives are much more efficient, on average, than the methods relying mostly on natural gas usage.

The second reason, however, is an issue we inevitably must face in the industrial sector: there is no good electrical alternative to replace CHP and Cogeneration Processes. As such, unless the process itself is replaced, we can't consider electrification of this specific process.

We'll thus face this issue by calculating the amount of electrification needed for the known methods, while noting the amount of carbon emissions that need to be offset or captured to reverse the impact of this end use.

Thus, given a total energy of:

$$42.39\% \times 72.5\% \times 10,426,661\frac{\text{MMBtu}}{\text{year}} \times \frac{1\text{ MWh}}{3.412142\text{ MMBtu}} \times \frac{1\text{ year}}{8760\text{ hours}} \approx 107.21\text{ MW}$$

We know CHP would produce about[7]:

$$107.21\text{ MW} \times 4200\frac{\text{tons}}{\text{MWyear}} \approx 450,000\text{ MTCO}_2\text{e/year}$$

Which would need to be offset.

As such, using the estimated conversion factor, we get the following table:

Table 11: Industrial Estimated Electrification Need

Sector	Fuel or Source	Conversion Factor	Usage (kWh)
Industrial Energy	Electricity	1	6,744,776,571
	Natural Gas	63.57	662,822,840
Total Electricity Before Conversion			**6,744,776,571**
Total Electricity Added/Converted			**662,822,840**
Total Electricity Use After Fossil-Fuel Conversion			**7,407,599,411**
Total Carbon Offsetting Required (MTCO_2)			**450,000**

Thus, the total additional electricity needed to be added to the grid by 2050 would be ∼0.662 TWh. Keep in mind, the carbon offsetting is something that needs to be considered, however.

More specifically, of the methods available for use in removal of these CO_2 emissions, the two most notable are DAC (Direct Air Capture) and post-combustion capture. As post-combustion is more efficient and suited towards combating the carbon emissions of a specific end like this, we'll be using it as the preferred and expected method for calculation.

Thus, using modern post-combustion capture technology we can get an energy efficiency of about 908.33 kWh/MTCO_2e[8]. This gives us:

$$908.33\text{ kWh/MTCO}_2\text{e} \times 450,000\text{ MTCO}_2\text{e} \approx 0.41\text{ TWh}$$

As such, we get the resulting table:

[7]U.S. Environmental Protection Agency, "CHP's Role in Decarbonization."
[8]Raganati, Miccio, and Ammendola, "Adsorption of Carbon Dioxide."

Table 12: Industrial Estimated Electrification Need

Sector	Fuel or Source	Usage (kWh)
Industrial Energy	Non-Carbon-Capture Electricity	6,744,776,571
	Natural Gas	662,822,840
	Post-Combustion Capture Electricity	410,000,000
Total Electricity Before Conversion		**6,744,776,571**
Total Electricity Added/Converted		**1,072,822,840**
Total Electricity with Conversion and Carbon Capture		**7,817,599,411**

Section 2: Climate-Adjusted Demand Projection

When it comes to looking at the expected change in buildings' energy usages with a changing climate, the first and most obvious consideration is the increasing temperature's impact on a need to heat or cool. Indeed, this initial instinct yields results—namely, you'd find an expectation in a decrease in required heating of buildings. However, there is more nuance than that, unfortunately.

It turns out, in fact, that there are a variety of changing factors which dictate the average energy consumption of buildings. Amongst these factors is, for instance, both the dew point and the highest average daily maximum temperature recorded over a month.[9]

That's to say, we cannot properly expect the energy need in these sectors to stay constant with the changes in climate. As such, we will outline 3 potential scenarios based upon models on potential energy trends.

While listing these three scenarios, keep in mind that we will be omitting the Industrial Sector, as it's been shown not to very much with climatic change (mostly due to its processes mainly not being in maintaining temperatures, like it is for the Residential and Commercial sectors). We will, however, note differences in the impact of each scenario on the Residential and Commercial sectors.

The three scenarios will be: Constant, Moderate Climatic Change, and Extreme Climatic Change. These scenarios are determined by the standard deviation in the mean dew point temperature, which is a good indicator of humidity, making it important to determining the impacts of climate (especially with regards to how hard cooling systems must work). The moderate scenario will have one standard deviation, while the extreme scenario will have two.

[9] Mukherjee et al., *A Data-Driven Approach to Assessing Supply Inadequacy Risks Due to Climate-Induced Shifts in Electricity Demand.*

Thus, we get the following table:

Table 13: Energy Usage by Sector and Fuel Source (2022)

Sector	Scenario	Base Percentage	Total Need (kWh)	Total Energy Increase (kWh)
Residential Energy	Constant	100	27,020,990,960	19,517,658,520
	Moderate	107.5	29,047,565,282	21,544,232,842
	Extreme	115	31,074,139,604	23,570,807,164
Commercial Energy	Constant	100	16,939,773,464	9,878,027,940
	Moderate	103	17,447,966,668	10,386,221,144
	Extreme	108	18,294,955,341	11,233,209,817
Industrial Energy	All Scenarios	100	7,817,599,411	1,072,822,840

Taking the Constant and Extreme scenarios, we then end up with a new estimation (a combination of our scenarios and our estimated conversion factors) of 30.47-35.88 TWh needed electrical increase, depending mostly on the impact of climate change on humidity in the area. Keep in mind that the Constant scenario is very unlikely, and serves the purpose of lower-bounding, as there is expected climatic change. As such, if we assumed BAU being the Moderate scenario, we'd expect a 33.00 TWh needed electrical increase.

For the sake of getting an absolute upper- and lower-bound, we'll also calculate the expected energy increase in the Extreme scenario:

$$(115\% \times 30.6) + (108\% \times 18.8) + (100\% \times 9.8) \approx 65.3\text{TWh}$$

$$65.3 - (7.5 + 7.1 + 6.7) = 44.0\text{TWh}$$

Thus, 44.0 TWh is the upper-bound on the electrification need. If we add up the Constant scenario lower-bounds, we get:

$$13.0 + 6.5 + 1.1 \approx 20.6\text{TWh}$$

Thus, amongst the Residential, Commercial, and Industrial sectors, we have an electrification need range of 20.6-44.0 TWh; however, we expect an actual electrification need of 30.06-35.47 TWh depending on how the climate impacts the humidity in the area, with our most reasonable estimate being 33.00 TWh.

Transportation & Mobile Sources

This following section is concerning the remaining Sector: Transportation and Mobile Sources. While the previous section was based most notably upon the conversion of MMBtu from a variety of sources (mostly natural gas) into energy (kWh), this section is instead defined more by its conversion of VMT (vehicle miles traveled) into energy (kWh).

In doing this, it is specifically important to split this section into two subsections: Light-Duty and Heavy-Duty. The Light-Duty section will be focused on the statistic for gasoline usage, with a focus of transition over to Light-Duty (HPMS 10 and 25) electric vehicles. On the other hand, the Heavy-Duty section will be focused on the statistic for diesel usage, with a focus of transition over to hydrogen-based Heavy-Duty vehicles.

In both of these sections, we will focus upon 3 scenarios: BAU (business as usual), Moderate Uptake, and Aggressive/Complete Uptake. Of course, the goal for the Greater Cleveland Area that we are pursuing is the latter option; complete uptake. However, it is important to understand the implications and possibilities within this sector, especially given the difficulty of implementation that this sector faces compared to the others.

Light-Duty EVs

For light-duty EVs, we have the following table[10]:

Table 14: Light-Duty VMT Projections (BAU)

Year	Total VMT	EV VMT
2025	16,483,096,382	149,880,233
2050	17,169,298,729	5,488,129,543
Net Increase	686,202,347	5,338,249,310

As this data is more recent than that from Table 1, we will be using it instead. Furthermore, the data being represented specifically in VMT is very convenient for our calculations. Using an average kWh/VMT of 0.307[11]we get:

[10]U.S. Energy Information Administration, "Energy Conversion Calculators."
[11]EV Database, "Energy Consumption of Electric Cars."

Table 15: Light-Duty VMT Energy-Projection Scenarios

Scenario	EV Market Share (%)	VMT Net Increase	Energy Increase (kWh)
BAU	36.5[12]	5,338,249,310	1,638,842,538
Moderate Uptake	68.25	11,568,166,150	3,551,427,008
Complete Transition	100	17,019,418,496	5,224,961,478

Here, the Moderate Uptake being the midpoint between the BAU and Complete Transition scenarios. As we can see, following current trends, we expect an energy-need increase of 1.64 TWh. However, given our aggressive scenario whereby we plan to completely transition to light-duty EVs, we instead expect a 5.22 TWh increase in energy-use.

Heavy-Duty EVs

As mentioned previously, the conversion from VMT for diesel-fuel-based vehicles will be considered as a transition from those vehicles over to hydrogen-based EVs. Thus, this section will be divided into three main areas: (1) calculating the hydrogen-need for the different uptake scenarios, (2) calculating the energy needed to produce the hydrogen, and (3) calculating the energy needed if we were instead relying completely on charging via electricity.

For the first part, we need to do a variety of conversions to get the VMT into a more useful (for our calculations) measurement. For convenience, we will be assuming that a majority of the diesel VMT comes from Class 8 Trucks. Class 8 trucks have an average mpgG (miles per gallon of gasoline) of 5.70.[13]Dividing this by the conversion factor for kWh,

$$5.70 \text{ mi/gallon} \div 33.7 \text{ kWh/gallon} = 0.1691 \text{ mi/kWh}$$

Keep in mind that we are converting directly to energy, and thus don't need to convert the GGE (gasoline gallon equivalent) over to the diesel equivalent. Dividing the VMT from Table 1, we get:

$$1,171,752,406 \text{ mi} \div 0.1691 \text{ mi/kWh} = 6,929,345,985 \text{ kWh}$$

However, as always, we need to keep in mind the conversion efficiency of everything, specifically diesel engines here, compared to hydrogen fuel cell efficiency.

The efficiency of a diesel engine of the type we're looking at is about 39.1%.[14]On the other hand, a study by the DOE found that hydrogen fuel cells can get an efficiency of, on average, 57%. Multiplying by the ratio of the two efficiencies, we get:

$$6,929,345,985 \text{ kWh} \times \frac{39.1\%}{57\%} = 4,753,288,211 \text{ kWh}$$

[12] S&P Global and PJM Interconnection, *ATSI Forecast.*
[13] Alternative Fuels Data Center, "Average Fuel Economy."
[14] International Council on Clean Transportation, *Engine Efficiency Evaluation.*

Thus, we're looking at a need for about 4.75 TWh worth of energy produced from hydrogen. Taking the energy content of a kg of hydrogen to be 33.3 kWh, we get:

$$4,753,288,211 \text{ kWh } \div 33.3 \text{ kg/kWh} = 142,741,388 \text{ kg Hydrogen}$$

That is, we would need approximately 142,741 metric tons of hydrogen produced per year.

Taking that we could produce approximately 500 kg of hydrogen per MW per day, we can calculate:

$$142,741,388 \text{ kg/year } \times \frac{1 \text{ year}}{365 \text{ days}} \div 500 \text{ kg/(MW } \times \text{ day)} \approx 782.374 \text{ MW}$$

Converting this to kWh/year:

$$782.374\,\text{MW} \times 1000\,\frac{\text{kW}}{\text{MW}} \times 24\,\frac{\text{hr}}{\text{day}} \times 365\,\frac{\text{days}}{\text{year}} = 6{,}854{,}595{,}840\,\text{kWh/year}$$

Thus, we'd need approximately 6.85 TWh of energy to produce the amount of hydrogen required.

For the sake of consistency, we'll adopt the same definitions for three scenarios: Lesser Uptake, Moderate Uptake, and Complete Transition. With such scenarios, we get the following table:

Table 16: Heavy-Duty Hydrogen Energy-Projection Scenarios

Scenario	EV Market Share (%)	Energy Increase (kWh)
Lesser Uptake	36.5	2,501,927,482
Moderate Uptake	68.25	4,678,261,661
Complete Transition	100	6,854,595,840

These scenarios are selected to match with the light-duty EV scenarios so they can be grouped together conveniently; hence why the scenario here is not called BAU, as we do not have the data required to call it "Business as Usual."

Doing this allows us to group both EV categories together, producing a composite projection:

Table 17: All EVs Energy-Projection Scenarios With Hydrogen Heavy Duty

Scenario	EV Market Share (%)	Energy Increase (kWh)
BAU/Lesser Uptake	36.5	4,409,038,421
Moderate Uptake	68.25	8,244,297,870
Complete Transition	100	12,079,557,318

However, it's also important to consider the possibility of completely charging these heavy-duty vehicles with electricity instead of using hydrogen. In this case, we will once again assume only class 8 trucks for consistency. In this case, we find that an average class 8 EV takes about 2.16 kWh/mile[15]. As such, we get:

$$2.16 \text{ kWh/mile } \times 1,171,752,406 \text{ VMT} = 2,530,985,197 \text{ kWh}$$

As such, electrifying, rather than switching to hydrogen, would actually take around 4.32 TWh less energy per year.

A final possibility that needs consideration is the scenario of transitioning to hydrogen production but only producing some of the hydrogen in-region. According to our previous calculations, we'd need about 391.07 MT/day of hydrogen to supply a complete transition. This is *a lot*. Instead, it'd be more reasonable to assume that, by 2050, the area could produce 200 MT/day.

Assuming such a production, we'd get the following table:

[15]Gao Z. et al, *Energy Consumption and Cost Savings of Truck Electrification*

Table 18: All EVs Energy-Projection Scenarios With Heavy Duty Switch-Type

Type of Switch	Scenario	EV Market Share (%)	Energy Increase (kWh)
Hydrogen	Lesser Uptake	36.5	4,409,038,421
	Moderate Uptake	68.25	8,244,297,870
	Complete Transition	100	12,079,557,318
	Complete Transition with Partial In-Region Hydrogen Production[16]	100	8,730,509,963
Electrification	Lesser Uptake	36.5	2,562,652,135
	Moderate Uptake	68.25	5,278,824,405
	Complete Transition	100	7,755,946,675

[16] With an outsourced production of about 191.07 MT/day of hydrogen.

Energy Production

Something important to understand with these calculations is the plausibility of the Cleveland-Elyria MSA to produce the required power itself, without external purchase. As such, it's important to make a general estimate of a scenario for power-production within the MSA.

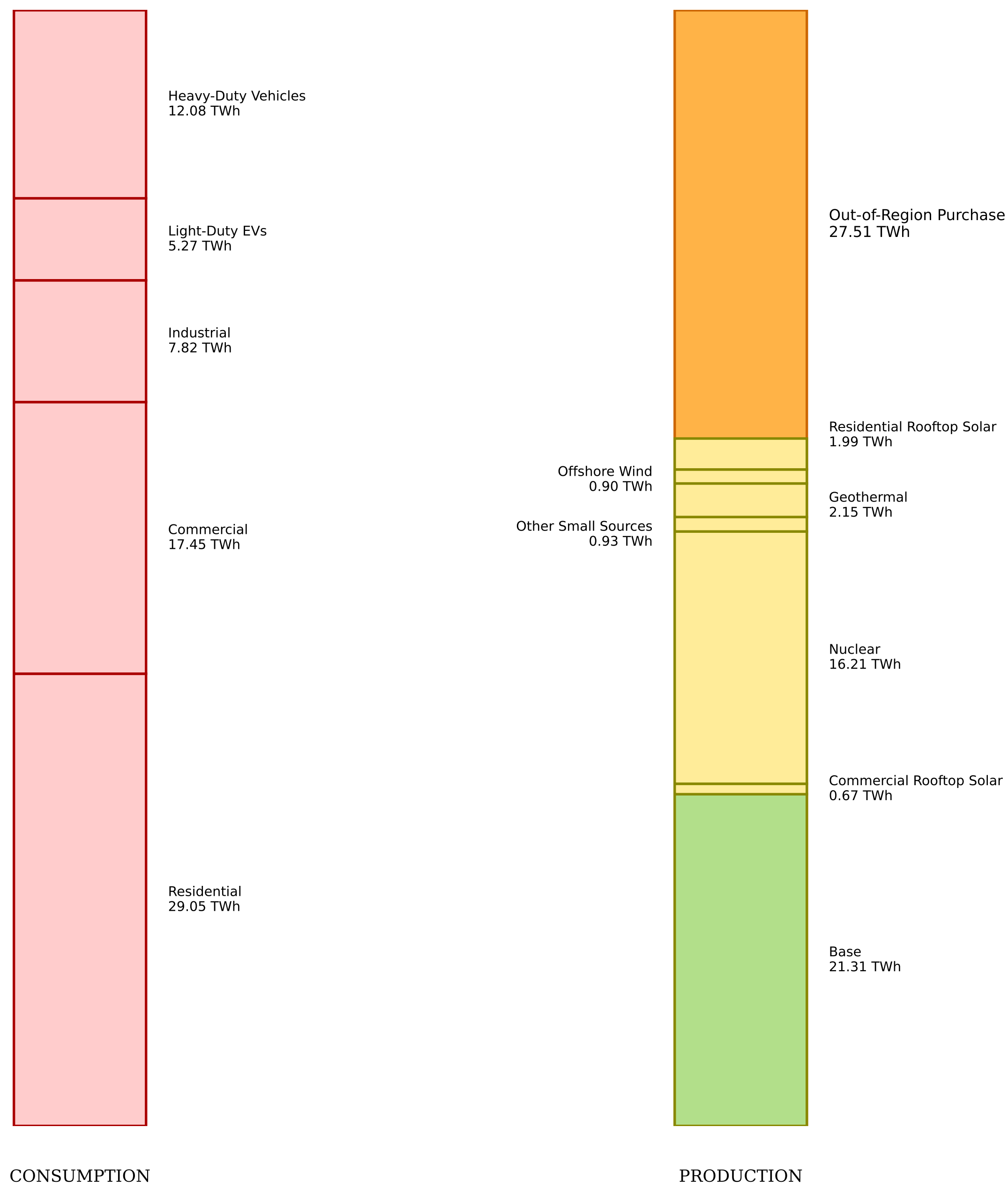
We'll propose the following scenario:

Table 19: Projected Energy Production Capacity (2050)

Production Source	Output (TWh)
Nuclear	16.21
Geothermal	2.15
Offshore Wind	0.90
Residential Rooftop Solar	1.99
Commercial Rooftop Solar	0.67
Solar Utility-Scale	0.31
5 MW Community Microgrids	0.40
Short Duration Energy Storage	0.02
Long Duration Energy Storage	0.20
Total Production	**22.85**

Given these numbers, we get the following figure:

Figure 1: Comparison of Expected Energy Consumption to Potential Production



As can be seen, this projected scenario results in an under-production of about 27.51 TWh/year. However, this is to be expected; in the first place, the MSA gets a large amount of energy through outside purchase. Our estimate here has a total of about 66.4 TWh/year, which is around 3 times the amount of energy currently used in the area. Thus, it's only natural that it would be difficult to create the additional infrastructure required to produce double the 2025 energy usage.

This means that the purchase of energy from outside of the MSA is a necessity to meet the 2050 carbon-neutral goal, or else (even with conservative estimates like electrification instead of hydrogen heavy-duty vehicles, limited climatic impact, low conversion efficiencies, etc.) the area would be lacking in energy of a magnitude close to its current use. This is an extremely large gap.

However, the importance of MSA-produced green energy can obviously also not be undercut; the production of energy through within-region means in this scenario is about 22.85 TWh/year, which is, of course, very significant. Furthermore, these numbers underscore the importance of nuclear-produced energy, as 71% of that figure is composed of nuclear energy. Thus, the production of in-region green energy, especially nuclear, is very important. However, it must also be duly noted that it would be difficult to completely produce the required energy in-region.

Conclusion

This analysis has detailed the electricity demand required to fully transition the MSA to a zero-emissions energy system by 2050. Using a sector-by-sector approach, we estimated the additional electric load necessary to replace all fossil-fuel-based energy in the residential, commercial, industrial, and transportation sectors. The table below summarizes the projected increases under a complete electrification scenario:

Table 20: Expected Electricity Demand Increase by 2050 (Complete Transition)

Sector	Expected Increase (TWh)
Residential Energy	21.54
Commercial Energy	10.39
Industrial Energy	1.07
Light-Duty Electric Vehicles	5.22
Heavy-Duty Hydrogen Vehicles	6.85
Total (Baseline Climate)	**45.07**

When added to the region's existing 2022 electricity consumption of 21.31 TWh, this scenario implies a total demand of approximately 66.38 TWh per year—roughly three times the current load. It is important to recognize that this figure is based on several simplifying assumptions, including a stable population and building stock, and omits consideration of potential efficiency improvements or behavioral adaptations. Additionally, due to technical limitations in industrial electrification, this scenario assumes 450,000 $MTCO_2$/year must be offset through specifically post-combustion carbon removal technologies, with the energy cost of such technologies built in to the industrial sector's expected energy calculation.

Across all sectors, we estimate the electrification need could realistically fall within a range of 32.7 to 56.1 TWh/year, with an expected range of 42.54–47.95 TWh/year depending on climatic impacts—particularly rising temperatures and dew point levels that affect building energy use. Overall, the expected required energy increase with our presumed scenarios is 45.07 TWh/year.

Furthermore, this increase does also depend on whether or not the MSA decides to produce hydrogen or electrify their heavy duty vehicles. With our calculations, electrifying would result in about 4.32 TWh less energy per year, resulting in about 40.75 TWh estimated. That being said, there are, of course, several factors to be considered beyond just energy consumption, and thus the decision between the two solutions (or their ratio of implementation) cannot be trivialized.

These findings underscore the urgent need for large-scale investment in renewable and zero-carbon energy infrastructure. Meeting this future demand will require not only capacity expansion—via solar, wind, nuclear, and potentially green hydrogen production—but also strategic grid modernization, demand-side management, and policy support.

Furthermore, from our consideration of energy-production we know that it would be very difficult to fully produce the required energy in-region using green methods. As such, its evident that the MSA will require a hefty increase in purchased energy from outside the reason.

Thus, the path to full decarbonization is feasible but difficult, and success will depend on careful planning, adaptive strategies, and sustained commitment from both public and private sectors.

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Appendix C - List of 2010 Census Tracts - LIDACs

County	City	Census Tract
Cuyahoga County	Cleveland	
		39035124202
		39035123800
		39035103500
		39035119300
		39035124500
		39035112100
		39035103602
		39035119600
		39035124600
		39035112200
		39035103800
		39035103300
		39035120200
		39035124300
		39035112301
		39035103900
		39035109801
		39035102101
		39035196400
		39035112400
		39035110901
		39035102102
		39035119402
		39035112500
		39035105700
		39035101200
		39035102200
		39035119502
		39035112600
		39035105900
		39035103400
		39035102300
		39035112800
		39035106200
		39035101901
		39035102401

		39035114600
		39035118602
		39035106300
		39035103100
		39035102402
		39035114900
		39035106400
		39035101800
		39035115100
		39035106500
		39035107802
		39035115200
		39035123501
		39035106600
		39035115300
		39035123900
		39035106800
		39035101300
		39035115400
		39035124100
		39035106900
		39035117900
		39035115700
		39035124201
		39035126100
		39035115800
		39035123502
		39035111500
		39035113101
		39035115900
		39035123602
		39035111600
		39035113500
		39035110501
		39035114501
		39035111700
		39035113600
		39035110801
		39035114700

		39035111800
		39035114100
		39035111902
		39035196500
		39035105400
		39035120400
		39035111202
		39035105500
		39035120500
		39035105602
		39035114300
		39035105100
		39035102800
		39035108701
		39035121700
		39035102700
		39035102900
		39035109301
		39035121800
		39035105300
		39035104900
		39035113801
		39035121900
		39035104100
		39035108201
		39035122100
		39035104400
		39035108301
		39035109701
		39035122200
		39035104200
		39035108400
		39035122300
		39035104600
		39035198900
		39035116900
		39035119701
		39035104800
		39035111401
		39035117102

		39035119702
		39035118700
		39035116100
		39035117300
		39035119800
		39035118800
		39035116200
		39035117400
		39035119900
		39035118900
		39035116300
		39035117500
		39035120701
		39035119202
		39035116400
		39035117800
		39035120702
		39035116500
		39035101101
		39035120801
		39035121100
		39035116600
		39035101400
		39035120802
		39035121200
		39035116700
		39035101501
		39035117101
		39035121300
		39035116800
		39035101603
		39035117201
		39035121401
		39035118101
		39035101700
		39035121403
		39035118200
		39035117600
		39035121500
		39035118400

		39035117700
		39035127501
		39035118500
		39035117202
		39035120600
		39035118301

County	City	Census Tract
Cuyahoga County	Bedford	39035132302
	Bedford Hts	39035133104
	Brooklyn	39035137101
	Brook Park	39035138105
		39035138106
	Cleveland Hts	39035140100
		39035140301
		39035140500
		39035140701
		39035140702
		39035141000
	East Cleveland	39035150100
		39035150300
		39035150400
		39035151100
		39035151200
		39035151300
		39035151400
		39035151500

		39035151600
		39035151700
		39035151800
	Euclid	39035152201
		39035152202
		39035152302
		39035152303
		39035152400
		39035152501
		39035152502
		39035152603
		39035152604
		39035152701
		39035152702
		39035196200
	Garfield Hts	39035154100
		39035154200
		39035154300
		39035154501
		39035154601
		39035154700
	Lakewood	39035160602
		39035161600
		39035161700
		39035161800
	Maple Hts	39035171102

		39035171103
		39035171104
		39035171203
	North Olmsted	39035174103
	Parma	39035177104
		3903517.7202
		3903517.7304
	Parma Hts	39035178204
	Richmond Hts	39035180104
	Shaker Hts	39035183603
	Warrensville Hts	39035188103
		39035188105
		39035188106
		39035188107
	North Randall	39035193800
	Highland Hills	39035193900
	Cuyahoga Hts	39035196100

County	City	Census Tract
Lorain County	Lorain	39093022200
		39093022400
		39093022601
		39093022800
		39093023000
		39093023100

		39093023200
		39093023300
		39093023400
		39093023500
		39093023600
		39093023700
		39093023800
		39093023900
		39093024000
		39093024100
		39093097300
	Elyria	39093070300
		39093070400
		39093070500
		39093070700
		39093070800
		39093070901
		39093071000
		39093071201
		39093071400

County	**City**	**Census Tract**
Geauga County	Huntsburg	39055311000
	Middlefield	39055312400

County	**City**	**Census Tract**
Lake County	Painesville	39085204200
		39085204400

		39085204500

Appendix D - CCAP Measure Funding Opportunities

Sector	Measure	Funding Opportunities
Electricity	community enrollment in renewable energy CCA	Not needed - CCA does not require a downpayment.
Electricity	Opt-in Public Pricing Program for mercantile customers, including local govts, political subdivisions, non-profit and faith-based orgs	Not-needed - Opt-in requires only that the entity is located within a SOPEC member.
Electricity	physical PPA	The terms of a PPA may be improved, depending on the incentives the out-of-state project qualifies for; most renewable projects continue to qualify for ITC and PTC federal tax credits.
Electricity	intelligent grid management systems	Self-pay; Ohio's PUC is managing a grid reslience formlua grant: https://puco.ohio.gov/utilities/electricity/resources/ohio-grid-resilience-formula-grant-program-faq
Electricity	Grid-scale power systems modernization	Self-pay
Electricity	Community-serving microgrid and mini grid systems.	(1) OH Dept of Development has a program that can support microgrid development for grid resilience, up to $500K (2) The PUC of Ohio is distributing $14.2M for grid resiliency, including microgrids, from DOE's grid resiliency program.
Electricity	Convert lighting to energy efficient light-emitting diode (LED) light bulbs	Brightening Ohio Communities Grant Program: https://development.ohio.gov/community/redevelopment/brightening-ohio-communities
Electricity	utility-scaled solar (in-region)	(1) Depending on how the project is structured, the Federal Solar Investment Tax Credit of 30% applies; (2) The Ohio Air Quality Development Authority may approve additional Solar Developers for Solar RECS of up to $9 per MWh - current program ends in 2028.
Electricity	offshore wind	renewable electricity production tax credit (PTC) is a per kilowatt-hour (kWh) federal tax credit included under Section 45; wind equipment eligible for 10 years after entering service. https://www.epa.gov/lmop/renewable-electricity-production-tax-credit-information
Electricity	Repurpose brownfields into clean energy hubs	Depending on how the project is structured, the Federal Solar Investment Tax Credit of 30% applies; "energy community" designation can earn additional 10%; low-income

		communities qualify for additional 10%. https://rmi.org/time-for-communities-to-embrace-clean-energy-on-brownfields/
Electricity	residential rooftop solar	(1) Federal Solar Investment Tax Credit - up to 30% through 2032. (2) For Ohio homeowners, Ohio Treasurer's ECO-Link program offers an interest rate reduction of up to 3% on loans up to $50K for energy efficiency and renewable energy improvements on homes.
Electricity	commercial-scale rooftop & parking lot solar	(1) Solar systems that are placed in service in 2022 or later and begin construction before 2034 are eligible for a 30% Federal ITC or a 2.75 ¢/kWh5 PTC if they meet labor requirements issued by the US Treasury, or are under 1 MW. https://www.energy.gov/sites/default/files/2024-02/508%20Federal%20Solar%20Tax%20Credits%20for%20Businesses_Feb24.pdf in size. (2) Ohio's Facilities Construction Commission's "School Energy Performance Contracting Program allows K-12 schools to borrow money to make energy savings facilities improvements without passing a ballot issue. https://ofcc.ohio.gov/our-programs/k-12-schools/energy-services/school-energy-performance-contracting-program
Electricity	district thermal energy systems	(1) Property-Assessed Clean Energy (PACE) Financing (in PACE-eligibile communities); (2) Green-Bonds for bond-financing; (3) Tax-exempt municipal bonds. Also an opportunity for public-private financing, esp. if the "district" includes industry.
Electricity	district or utility-scale battery storage - Long duration (>10 hrs)	(1) Property-Assessed Clean Energy (PACE) Financing (in PACE-eligibile communities); (2) Green-Bonds for bond-financing; (3) Tax-exempt municipal bonds. Finances for projects can be supported by maximizing tariff-eligible use cases approved by the PUCO, such as Demand Response programs, Frequency Regulation, and Voltage regulation.
Electricity	Hydrogen as an energy carrier	(1) A hydrogen production facility would qualify for JobsOhio incentives, based on construction employment and full-time hires. (2) Green Bonds
Electricity	New Nuclear at Perry	(1) Civil Nuclear Credit Program under the US DOE; (2) §45U (zero-emission nuclear power production) Federal Tax Credits; (3) Expansion of Perry, in creating new jobs, would qualify for JobsOhio incentives. (4) Green Bonds offer attractive financing.
Electricity	Geothermal electricity generation	renewable electricity production tax credit (PTC) is a per kilowatt-hour (kWh) federal tax credit included under Section 45; geothermal electricity equipment eligible for 10 years after entering service. https://www.epa.gov/lmop/renewable-electricity-production-tax-credit-information

Electricity	district or utility-scale battery storage - short duration (<4 hrs)	(1) Property-Assessed Clean Energy (PACE) Financing (in PACE-eligibile communities) (2) Green-Bonds for bond-financing (3) Tax-exempt municipal bonds. Finances for projects can be supported by maximizing tariff-eligible use cases approved by the PUCO, such as Demand Response programs, Frequency Regulation, and Voltage regulation.
Commercial & Residential Energy	Increasing Retrofit Envelope Efficiency (Deep retrofit)	For Ohio homeowners, (1) Home Weatherization Assistance Program (HWAP) provides home energy audit and assistance with weatherization improvements. https://development.ohio.gov/individual/energy-assistance/6-home-weatherization-assistance-program (2) Ohio Treasurer's ECO-Link program offers an interest rate reduction of up to 3% on loans up to $50K for energy efficiency and renewable energy improvements on homes.
Commercial & Residential Energy	Building System Electrification (Deep Retrofit)	The Ohio Home Energy Savings Program has $249M from the IRA to support energy efficiency improvements, pending final approval from DOE. https://development.ohio.gov/individual/energy-assistance/energy-savings
Commercial & Residential Energy	Incentive programs	Incentive programs may rely significantly on Community Foundation Support, or local municipality self-pay. From Ohio, See C1-1 and C1-2; also OH's Electric Partnership Plan (EPP), which provides in-home energy audits, guidance on reducing energy use, and support electrification and energy efficiency measures to reduce energy use. https://development.ohio.gov/individual/energy-assistance/5-electric-partnership-plan
Commercial & Residential Energy	Implementation of the latest state adopted building standards and codes	Self-Pay; OH Dept of Commerce is providing additional training from 2025-2027 to municipalities on buidling codes standards and enforcement. https://com.ohio.gov/about-us/media-center/news/Ohio-Department-of-Commerce-Board-of-Building-Standards-receives-1.6-million-grant-to-streamline-building-code-modernization-enforcement-process
Commercial & Residential Energy	Smart Energy Management Systems - SEMS (**Commercial Buildings**)	Primarily self-pay with private financing.
Commercial & Residential Energy	Material Substitution	Primarily self-pay with private financing.
Commercial & Residential Energy	Modular and Prefabricated Construction	Primarily self-pay with private financing.
Commercial & Residential Energy	Automated Building Systems and Smart Devices	Primarily self-pay with private financing.

Commercial & Residential Energy	Active Energy Adjustment for Grid Support (Demand Response)	Demand Response programs where utilities/PJM currently pay enrolled commercial or industrial customers to reduce electricity consumption during high use events could provide a mechanism to finance these building improvements. Additional funding sources beyond private financing are not available.
Industrial Energy	energy audits	Free industrial energy assessments using the Industrial Assessment Centers (IAC); historical DOE funding for energy efficiency projects; Ohio Department of Development State Energy Program funded implementation of energy efficiency projects for manufacturers with the Ohio Energy Efficiency Program (OEEP) – Implementation funds for energy efficiency retrofits; bank financing
Industrial Energy	waste heat recovery and utilization systems	Federal Tax Credits in §48C for Industrial Decarbonization; Ohio Department of Development State Energy Program funded implementation of energy efficiency projects for manufacturers with the Ohio Energy Efficiency Program (OEEP) – Implementation funds for energy efficiency retrofits; bank financing
Industrial Energy	Monitoring Systems	Ohio Department of Development State Energy Program funded implementation of energy efficiency projects for manufacturers with the Ohio Energy Efficiency Program (OEEP) – Implementation funds for energy efficiency retrofits; bank financing
Industrial Energy	Energy Efficient Equipment	Ohio Department of Development State Energy Program funded implementation of energy efficiency projects for manufacturers with the Ohio Energy Efficiency Program (OEEP) – Implementation funds for energy efficiency retrofits; bank financing
Industrial Energy	Automation	Ohio Department of Development State Energy Program funded implementation of energy efficiency projects for manufacturers with the Ohio Energy Efficiency Program (OEEP) – Implementation funds for energy efficiency retrofits; bank financing; venture capital investors for new technologies; partnerships with emerging industries to test decarbonization technologies
Industrial Energy	reduce industrial waste	self pay
Industrial Energy	Use lower GWP gases for anesthetics	self pay
Industrial Energy	Install leak detection equipment	Ohio Department of Development State Energy Program funded implementation of energy efficiency projects for manufacturers with the Ohio Energy Efficiency Program (OEEP) – Implementation funds for energy efficiency retrofits; bank financing; venture capital investors for new technologies; partnerships with emerging industries to test decarbonization technologies
Industrial Energy	electrification of industrial process heat (boilers, industrial heat pumps, eaf) in synergy with grid development	Federal Tax Credits in §48C for Industrial Decarbonization; Ohio Department of Development State Energy Program funded implementation of energy efficiency projects for manufacturers with the Ohio Energy Efficiency Program (OEEP) – Implementation funds for energy efficiency retrofits; bank financing; venture capital investors for new

		technologies; partnerships with emerging industries to test decarbonization technologies
Industrial Energy	Replace BF-BOF system at Cleveland Works with a green steel alternative	Federal Tax Credits in §48C for Industrial Decarbonization; Ohio Department of Development State Energy Program funded implementation of energy efficiency projects for manufacturers with the Ohio Energy Efficiency Program (OEEP) – Implementation funds for energy efficiency retrofits; bank financing; venture capital investors for new technologies; partnerships with emerging industries to test decarbonization technologies; University partnerships; hydrogen production partnerships to offset hydrogen costs; combined effort across industries
Industrial Energy	electrify machine drives in synergy with grid decarbonization	Ohio Department of Development State Energy Program funded implementation of energy efficiency projects for manufacturers with the Ohio Energy Efficiency Program (OEEP) – Implementation funds for energy efficiency retrofits; bank financing; venture capital investors for new technologies; partnerships with emerging industries to test decarbonization technologies
Industrial Energy	Carbon capture at Cleveland Works w/ geologic sequestration in Geauga, Portage, Summit, Trumbull, Mahoning, and/or Stark Counties.	45Q Federal tax credit could return / survive; bank financing; venture capital investors for new technologies; partnerships with emerging industries to test decarbonization technologies
Industrial Energy	In cases where processes cannot electrify or switch to hydrogen due to production costs or processes, post combustion carbon capture (relevant to cement making)	45Q Federal Tax credit; bank financing; venture capital investors for new technologies; partnerships with emerging industries to test decarbonization technologies
Industrial Energy	Invest in a regional direct air capture facility to help decarbonize industries that are challenging to decarbonize and serve as an additional source of CO2 for utilization industries.	45Q Federal tax credit could return / survive; bank financing; venture capital investors for new technologies; partnerships with emerging industries to test decarbonization technologies
Industrial Energy	in cases where processes cannot electrify - switch to hydrogen (relevant for steel, cement, and chemical manufacturing - all others should be able to electrify)	bank financing; venture capital investors for new technologies; partnerships with emerging industries to test decarbonization technologies
Transportation	Expand BEV charging infrastructure	Congestion Mitigation and Air Quality (CMAQ) program administered by NOACA. https://www.noaca.org/home/showpublisheddocument/32640/638778119536900000
Transportation	BEV/FCEV adoption in government fleets	Climate Mayors EV Purchasing Collaborative; Congestion Mitigation and Air Quality (CMAQ) program administered by NOACA.

		https://www.noaca.org/home/showpublisheddocument/32640/638778119536900000
Transportation	BEV adoption of light-duty passenger vehicles by households	Federal EV Tax Credit of up to $7,500 for new BEVs and FCEVs, and up to $4000 for used vehicles. In force in 2025. https://afdc.energy.gov/laws/409
Transportation	Reducing Fuel Cost Access to Electric Vehicle Infrastructure	*Congestion Mitigation and Air Quality (CMAQ) program administered by NOACA. https://www.noaca.org/home/showpublisheddocument/32640/638778119536900000*
Transportation	Expand BEV charging infrastructure	Congestion Mitigation and Air Quality (CMAQ) program administered by NOACA. https://www.noaca.org/home/showpublisheddocument/32640/638778119536900000
Transportation	Expand FCEV fueling infrastructure	Congestion Mitigation and Air Quality (CMAQ) program administered by NOACA. https://www.noaca.org/home/showpublisheddocument/32640/638778119536900000
Transportation	BEV/FCEV adoption in government fleets	Congestion Mitigation and Air Quality (CMAQ) program administered by NOACA. https://www.noaca.org/home/showpublisheddocument/32640/638778119536900000
Transportation	Advance the use of sustainable liquid and gaseous fuels at regional maritime ports	Congestion Mitigation and Air Quality (CMAQ) program administered by NOACA. https://www.noaca.org/home/showpublisheddocument/32640/638778119536900000
Transportation	Advance the use of sustainable aviation fuel at regional airports	Congestion Mitigation and Air Quality (CMAQ) program administered by NOACA. https://www.noaca.org/home/showpublisheddocument/32640/638778119536900000
Transportation	Intercity Passenger Rail and Coordinated Transportation Planning	Federal-State Partnership for Intercity Passenger Rail (FSP) Grant Program provides funding for capital projects that expand or establish new intercity passenger rail service. Infrastructure Investment and Jobs Act (IIJA/Bipartisan Infrastructure Law) - This legislation provides significant funding for rail projects, though "most funding in this bill must be allocated by the end of 2026.
Transportation	Expand networks of protected bike lanes, off-street trails, and lane conversions	ODOT Transportation Alternatives Set-Aside / Highway Safety Improvement Program (HSIP) grants; also CMAQ program under NOACA. Active Transportation Infrastructure Investment Program (ATIIP) focuses on building networks of connected bicycle and pedestrian infrastructure improvements
Transportation	Increase density and mix of uses around transit stations and BRT stops	FTA Pilot Program for Transit-Oriented Development Planning funds the integration of land use and transportation planning, economic development, accessibility, and multimodal connectivity, and mixed-use development in new capital projects.
Waste & Material Management	install gas capture systems for landfill methane	If landfill gas used for electricity generation, renewable electricity production tax credit (PTC) is a per kilowatt-hour (kWh) federal tax credit included under Section 45; landfill gas-electricity equipment eligible for 10 years after entering service. https://www.epa.gov/lmop/renewable-electricity-production-tax-credit-information

Waste & Material Management	Restaurant and grocery food waste reduction/composting program	USDA composting and food waste reduction cooperative; closed loop partners composting consortium
Waste & Material Management	Add compost bins to public facilities, parks, and sports stadiums to divert organic waste from land fills	USDA composting and food waste reduction cooperative; closed loop partners composting consortium
Waste & Material Management	Support composting and food waste reduction with organic waste diversion from landfills	USDA composting and food waste reduction cooperative; closed loop partners composting consortium
Waste & Material Management	post incineration scrubbers installed at wastewater treatment facilities with fluidized bed incinerators	great lakes environmental infrastructure loan
Waste & Material Management	Invest in high-tech equipment to help detect water leaks in municipal water infrastructure - saving water and energy once repaired	great lakes environmental infrastructure loan; H2Ohio grant
Waste & Material Management	use climate friendly refrigerants	EPA HFC Reclaim and Innovative Destruction Grants
Waste & Material Management	end of equipment life facilities, dropoff/collection programs to ensure proper containment of refrigerants	EPA HFC Reclaim and Innovative Destruction Grants
AFOLU	Support habitat restoration and conservation to increase carbon sequestration, prevent land degradation, and promote healthy lands	Cleveland Tree Coalition for tree plantings, H2Ohio for wetland restoration
AFOLU	Expand Wetland Restoration Programs	Great Lakes Restoration Initiative (GLRI) EPA Wetland Program Development Grants (WPDG)
AFOLU	Reforest agriculture lands no longer in use, increasing the regional tree canopy	Ohio's Ag-Link Program allows farm owners to receive a 3% interest rate reduction on operating loans.
AFOLU	Tree carbon-capture	Cleveland Tree Coalition
AFOLU	Reduce tree loss Model mature tree protection ordinance	Cleveland Tree Coalition

AFOLU	Expand agriculture practices to restore soil health and increase carbon sequestration in rural parts of the region, through peer-to-peer learning exchange	USDA Conservation Innovation Grants
AFOLU	Digital twin to track trees planted, removed, or replaced annually, including old growth trees	NSF Smart and Connected Communities (S&CC)
AFOLU	Land bank set-asides for carbon storage	Land bank resources
AFOLU	Support community greenspace programs for small scale community-based native urban gardens, greenspaces, and tree planting	Neighborhood Connections, NEORSD green infrastructure grants

CCAP Measure Funding Opportunities

Sector	Measure	Funding Opportunities
Electricity	community enrollment in renewable energy CCA	Municipalities, local elected officials
Electricity	Opt-in Public Pricing Program for mercantile customers, including local govts, political subdivisions, non-profit and faith-based orgs	Mercantile customers, including local governments, political subdivisions and faith-based organizations
Electricity	physical PPA	Larger mercantile, commercial and industrial
Electricity	intelligent grid management systems	Municipal Utilities, Investor-owned utilities
Electricity	Grid-scale power systems modernization	Municipal Utilities, Investor-owned utilities
Electricity	Community-serving microgrid and mini grid systems.	Municipal Utilities; campus or large farm operators
Electricity	Convert lighting to energy efficient light-emitting diode (LED) light bulbs	Municipalities, political subdivisions, park districts
Electricity	utility-scale solar (in-region)	Municipal Utilities, Investor-owned utilities; or Larger mercantile, commercial and industrial through in-region PPA
Electricity	offshore wind	Clean-energy developer; Municipal Utilities, Investor-owned utilities; or Larger mercantile, commercial and industrial through in-region PPA
Electricity	Repurpose brownfields into clean energy hubs	Municipal Utilities, Investor-owned utilities; or Larger mercantile, commercial and industrial through in-region PPA
Electricity	residential rooftop solar	Homeowners, Homeowner Associations
Electricity	commercial-scale rooftop & parking lot solar	Building owners, school management.
Electricity	district thermal energy systems	Campuses, District energy operators

Electricity	district or utility-scale battery storage - Long duration (>10 hrs)	Most likely a large municipal utility - CPP or Cuyahoga Green Energy.
Electricity	Hydrogen as an energy carrier	Factory owners / operators. Heavy lift transportation operators. Ohio Dept of Transportation, Turnpike Authority
Electricity	New Nuclear at Perry	Vistra (current Perry owner), Investor owned utility, or new nuclear power developer (like Elementl Power)
Electricity	Geothermal electricity generation	Investor owned utility, or geothermal electrical company like Fervo
Electricity	district or utility-scale battery storage - short duration (<4 hrs)	Campus or district facilities or municipal utilities
Commercial & Residential Energy	Increasing Retrofit Envelope Efficiency (Deep retrofit)	* Federal, State, and local governments. * Utilities. * Building owners and managers.
Commercial & Residential Energy	Building System Electrification (Deep Retrofit)	* Federal, State, and local governments. * Utilities. * Building owners and managers.
Commercial & Residential Energy	Incentive programs	Federal agencies, State and Local Governments, Utilities, and non-Government partners such as Ohio Partners for Affordable Energy and CHN Housing Partners
Commercial & Residential Energy	Implementation of the latest state adopted building standards and codes	Municipalities and City officials
Commercial & Residential Energy	Smart Energy Management Systems - SEMS (**Commercial Buildings**)	Local and Regional Government authorities, utilities, Housing Development Agencies, Cleveland Energy Bank, Midwest Energy Efficient Alliance
Commercial & Residential Energy	Material Substitution	County and Municipal Housing authorities, Ohio Department of Development, and Ohio Board of Building Standards.
Commercial & Residential Energy	Modular and Prefabricated Construction	City housing authority or city building departments. County planning commission, NOACA, public utilities, local developers, local labor unions, and research institutions.
Commercial & Residential Energy	Automated Building Systems and Smart Devices	Local electric Utilities, Public Utility Commission of Ohio, Regional Planning bodies, State Energy Office
Commercial & Residential Energy	Active Energy Adjustment for Grid Support (Demand Response)	Local electric Utilities, Public Utility Commission of Ohio, Regional Planning bodies, State Energy Office
Industrial Energy	energy audits	specific industry; industry standards board; ohio manufacturing association; incentive system at the city or county level

Industrial Energy	waste heat recovery and utilization systems	specific industry; industry standards board; ohio manufacturing association; incentive system at the city or county level
Industrial Energy	Monitoring Systems	specific industry; industry standards board; ohio manufacturing association; incentive system at the city or county level
Industrial Energy	Energy Efficient Equipment	specific industry; industry standards board; ohio manufacturing association; incentive system at the city or county level
Industrial Energy	Automation	specific industry; industry standards board; ohio manufacturing association; incentive system at the city or county level
Industrial Energy	reduce industrial waste	specific industry; industry standards board; ohio manufacturing association; incentive system at the city or county level
Industrial Energy	Use lower GWP gases for anesthetics	specific industry; industry standards board; ohio manufacturing association; incentive system at the city or county level
Industrial Energy	Install leak detection equipment	specific industry; industry standards board; ohio manufacturing association; incentive system at the city or county level
Industrial Energy	electrification of industrial process heat (boilers, industrial heat pumps, eaf) in synergy with grid development	specific industry; industry standards board; ohio manufacturing association; incentive system at the city or county level
Industrial Energy	Replace BF-BOF system at Cleveland Works with a green steel alternative	specific industry; industry standards board; ohio manufacturing association; incentive system at the city or county level
Industrial Energy	electrify machine drives in synergy with grid decarbonization	specific industry; industry standards board; ohio manufacturing association; incentive system at the city or county level
Industrial Energy	Carbon capture at Cleveland Works w/ geologic sequestration in Geauga, Portage, Summit, Trumbull, Mahoning, and/or Stark Counties.	specific industry; industry standards board; ohio manufacturing association; ohio department of agriculture for pipeline construction; ohio EPA; incentive system at the city or county level
Industrial Energy	In cases where processes cannot electrify or switch to hydrogen due to production costs or processes, post combustion carbon capture (relevant to cement making)	specific industry; industry standards board; ohio manufacturing association; ohio department of agriculture for pipeline construction; ohio EPA; incentive system at the city or county level
Industrial Energy	Invest in a regional direct air capture facility to help decarbonize industries that are challenging to decarbonize and serve as an additional source of CO2 for utilization industries.	specific industry; industry standards board; ohio manufacturing association; ohio department of agriculture for pipeline construction; ohio EPA; incentive system at the city or county level

Industrial Energy	in cases where processes cannot electrify - switch to hydrogen (relevant for steel, cement, and chemical manufacturing - all others should be able to electrify)	specific industry; industry standards board; ohio manufacturing association; incentive system at the city or county level
Transportation	Expand BEV charging infrastructure	Municipal utilities; investor-owned utilities; PUCO; municipalities
Transportation	BEV/FCEV adoption in government fleets	Municipal utilities; investor-owned utilities; municipalities (codes & standards offices); industrial gas companies
Transportation	BEV adoption of light-duty passenger vehicles by households	Individual vehicle owners
Transportation	Reducing Fuel Cost Access to Electric Vehicle Infrastructure	City Department of Transportation; Local Utility
Transportation	Expand BEV charging infrastructure	Municipal utilities; investor-owned utilities; PUCO; municipalities
Transportation	Expand FCEV fueling infrastructure	Municipalities (codes & standards offices); industrial gas companies
Transportation	BEV/FCEV adoption in government fleets	Municipal utilities; investor-owned utilities; municipalities (codes & standards offices); industrial gas companies
Transportation	Advance the use of sustainable liquid and gaseous fuels at regional maritime ports	Port authorities
Transportation	Advance the use of sustainable aviation fuel at regional airports	Municipalities or counties with airport oversight.
Transportation	Intercity Passenger Rail and Coordinated Transportation Planning	ODOT, Amtrak, Federal Railroad Administration
Transportation	Expand networks of protected bike lanes, off-street trails, and lane conversions	Cities, counties, ODOT, NOACA
Transportation	Increase density and mix of uses around transit stations and BRT stops	GCRTA; municipal and county governments/zoning authorities
Waste & Material Management	install gas capture systems for landfill methane	municipal landfills

Waste & Material Management	Restaurant and grocery food waste reduction/composting program	local government
Waste & Material Management	Add compost bins to public facilities, parks, and sports stadiums to divert organic waste from land fills	local government
Waste & Material Management	Support composting and food waste reduction with organic waste diversion from landfills	local government; municipal landfills
Waste & Material Management	post incineration scrubbers installed at wastewater treatment facilities with fluidized bed incinerators	wastewater treatment facilities; local government
Waste & Material Management	Invest in high-tech equipment to help detect water leaks in municipal water infrastructure - saving water and energy once repaired	wastewater treatment facilities; local government
Waste & Material Management	use climate friendly refrigerants	Ohio EPA
Waste & Material Management	end of equipment life facilities, dropoff/collection programs to ensure proper containment of refrigerants	Local governments; waste management companies
AFOLU	Support habitat restoration and conservation to increase carbon sequestration, prevent land degradation, and promote healthy lands	Ohio Dept of Agriculture, Ohio DNR
AFOLU	Expand Wetland Restoration Programs	Ohio Dept of Agriculture, Ohio DNR, County Soil Water Districts
AFOLU	Reforest agriculture lands no longer in use, increasing the regional tree canopy	Farmers and Farm Owners; Ohio Dept of Agriculture, Ohio DNR, Local governments
AFOLU	Tree carbon-capture	Cle Tree Coalition, Cle Metro Parks, Local governments
AFOLU	Reduce tree loss Model mature tree protection ordinance	Local governments
AFOLU	Expand agriculture practices to restore soil health and increase carbon sequestration in rural parts of the region, through peer-to-peer learning exchange	Ohio Dept of Agriculture
AFOLU	Digital twin to track trees planted, removed, or replaced annually, including old growth trees	Municipalities

AFOLU	Land bank set-asides for carbon storage	Municipalities, Counties
AFOLU	Support community greenspace programs for small scale community-based native urban gardens, greenspaces, and tree planting	Municipalities