Technical Appendix – 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/ft²/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/ft² (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):
4.

Scenario	**Energy Savings ($unit/year)**	**GHG Reduction (kgCO_2e/ft²/year)**
Full (Deep retrofit)	$1,200	10
No HVAC/Lighting	$600	5
Envelope-only	$550	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 home: 2.5 metric tons CO_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 metric tons CO_2e reduced per year
  - Residential: 150,000 homes x 2.5 metric tons CO_2e = 375,000 metric tons CO_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 metric tons of CO_2e reduced each year. For residential buildings, with typical savings of 2-3 metric tons CO_2e per home annually, total reductions would be approximately 375,000 to 450,000 metric tons of CO_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/ft^2):
    - 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 metric tons CO_2e/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 CO_2e reduction is approximately 19,280 metric tons (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 metric tons of CO_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 metric tons CO_2e per ft² annually, complemented by avoided emissions from energy savings, calculated using a PJM regional grid emissions factor[1] 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
   - 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.

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[1] 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).

- 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/MTCO_2e	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/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	\$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 ft^2 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/ft^2) for residential buildings and 3% of the construction cost (\$250/ft^2) 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 ft^2 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 metric tons of CO_2e 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 metric tons of CO_2e 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.