The Hidden Cost of Solar Shortfalls (mp4 video and PowerPoint presentation (8-30-26)
Western Massachusetts Clean Energy Network

Principal Assumptions and Sources

Parameter	Assumption	Source
Existing Massachusetts forest	3,000,000 acres	Rounded up from 2.9 mil. for simplicity of calculations as well as to acknowledge hundreds of thousands of urban tree/forest acres. https://www.mass.gov/info-details/2023-massachusetts-climate-report-card-natural-working-lands#feedback)
Forest carbon released upon conversion	283 MT CO_2e/acre	Catanzaro, P. F., & D'Amato, A. W. (2019). Forest carbon: An essential natural solution for climate change. University of Massachusetts Amherst, MassWoods Program; University of Vermont Extension.: total for all above and below ground carbon CO2 is 283 MT/acre (average of carbon values for 4 major Mass. forest types multiplied by 3.67 for CO2; see page 4)
Forest CO2 sequestration rate	1.5 MT CO_2e/acre/year or 37.5 MT/acre/25 yrs.	Catanzaro, P. F., & D'Amato, A. W. (2019). Forest carbon: An essential natural solution for climate change. University of Massachusetts Amherst, MassWoods Program. Smith et al. (2006), Appendix A, Table A2, reports total non soil carbon stocks of 74.1 and 82.3 metric tons C/acre for Northeast maple–beech–birch stands at ages 85 and 105. The implied 20-year average net accumulation is 0.41 metric tons C/acre/year, equivalent to 1.50 metric tons CO_2/acre/year.
Carbon fiber recovery at harvest to long duration storage	20% of harvested carbon (live above ground CO2 average for 4 New England forest classes)	Based on D'amato and Catanzaro average of 4 new england forest types live above ground carbon quantity - 99.09 MT CO2e. D'Amato & Catanzaro cite this source: Oswalt 2017 https://doi.org/10.2737/WO-GTR-97 Forest Resources of the United States, 2017 A Technical Document Supporting the Forest Service 2020 RPA Assessment Sonja N. Oswalt, W. Brad Smith, Patrick D. Miles, and Scott A. Pugh.

Analysis period	**25 years – 2026-2050**	**Massachusetts Executive Office of Energy and Environmental Affairs (EEA). *Massachusetts Clean Energy and Climate Plan for 2050* (December 2022).: https://www.mass.gov/info-details/massachusetts-clean-energy-and-climate-plan-for-2050?utm_source=chatgpt.com**
Solar Land Requirement & Packing Density	**5.42 total cleared acres / MW_{DC}, *or*, 1.667 cleared acres / direct array acre*)***	**3.25 direct array acres / MW_{DC} (0.308 MW_{DC}/array acre). Direct PV equipment occupies 60% of total cleared area, with 40% reserved for shading buffers, access roads, and BESS infrastructure.** **Rogan, J., Heltzel, E., Tao, S., Ye, S., Geron, N., & Godwin, D. (2023). *Where Has Solar Been Developed with Respect to Land Use in Massachusetts?* Western Massachusetts Solar Forum, Session 2, UMass Extension presented at WM Solar Forum Session 2: Solar & Land Use in Massachusetts - https://umass-my.sharepoint.com/:b:/g/personal/agweb_umass_edu/ERbwYo76QT5Jg6hSEJJDFXUBaQUomb2oIAAeHTilk61ThQ?e=hq5aC1**
Solar Generation (Direct Array AC Output)	**306.85 MWh / direct array acre / year *(Yields 184.07 MWh / cleared acre / year net of land factor)***	**Reflects delivered AC electrical generation per direct array footprint acre. Derived directly from local irradiance and capacity factors (~ 240 kW_{DC}/acre $\times 1,285$ kWh/kW_{DC}/year), requiring no separate DC/AC conversion division** **Bolinger, M., & Bolinger, G. (2022). Land Requirements for Utility-Scale PV: An Empirical Update on Power and Energy Density. IEEE Journal of Photovoltaics.**
Solar PV 25 year generation with degradation rate adjustments	**2.5% production loss relative to nameplate after year 1, and .5%/year thereafter. See table below with detailed calculations**	**Jordan, D. C., & Kurtz, S. R. (2013). *Photovoltaic Degradation Rates—An Analytical Review*. Progress in Photovoltaics: Research and Applications, 21(1), 12–29. https://doi.org/10.1002/pip.1182; Also: https://www.osti.gov/biblio/1045052?utm_source=chatgpt.com**

Gross marginal grid emissions factor (GEF) for ISO-NE grid –	**1,014 lbs CO_2e/MWh**	**https://www.epa.gov/avert/avoided-emission-rates-generated-avert (https://www.epa.gov/system/files/documents/2024-04/avert_emission_rates_04-11-24_0.xlsx - 2023 tab, cell F25 "Utility PV – Plus Storage." Use Eastern Interconnect value since specific ISO-NE value unavailable.**
Net Lifecycle CO_2 Mitigation Rate for Ground-Mounted Solar + BESS on Cleared Forest Land	**748 lbs. CO2/MWh (net of solar/BESS embodied CO2/cleared acre & per cleared acre forest CO2 losses). This is the product of the calculation shown below – rather than an assumption or input from another source**	**A scenario-specific net lifecycle mitigation rate derived from:** **1. an assumed AVERT avoided-emissions rate;** **2. minus solar/BESS embodied emissions;** **3. minus forest conversion emissions and foregone sequestration.** **See math calculations below: Ratio gross/net GEF lbs. CO2/MWh – 1,014/748 = 1.356/1** **748 lbs. CO2/MWh applied within the Hidden Costs of Solar Delay presentation**
Solar + BESS embodied carbon	**~1,310 MT CO_2e/MWac (lifetime) or 184.5 MT CO2e/acre**	**Peiseler, L., Schenker, V., Schatzmann, K., Pfister, S., Wood, V., & Schmidt, T. S. (2024). Carbon footprint distributions of lithium-ion batteries and their materials. Nature Communications, 15, 10301. https://doi.org/10.1038/s41467-024-54634-y** **Gan, Y., Elgowainy, A., Lu, Z., Kelly, J. C., Wang, M., Boardman, R. D., & Marcinkoski, J. (2023). *Greenhouse Gas Emissions Embodied in the U.S. Solar Photovoltaic Supply Chain*. *Environmental Research Letters*, 18(10), 104012.**
Solar curtailment	**Linear increase from 0% in 2026 to 10% in 2050. See table below with detailed calculations**	**Massachusetts EEA (2020). Energy Pathways to Deep Decarbonization Technical Report, Fig. 27. All Options pathway projects approximately 5% variable renewable energy (VRE) curtailment by 2040 and up to 10% by 2050.** **Ardani, K., et al. (2021). *Solar Futures Study*. NREL/TP-6A20-80594, National Renewable Energy Laboratory; Section 2.2.3 Curtailment.**

Forest footprint multiplier (to account for non-pv footprint land use)	**Ancillary areas constitute 40% of total cleared acreage, corresponding to a land clearing multiplier of 1.667 total cleared acres per 1.0 acre of direct PV footprint.**	**Rogan, J., Heltzel, E., Tao, S., Ye, S., Geron, N., & Godwin, D. (2023*). Where Has Solar Been Developed with Respect to Land Use in Massachusetts?* Western Massachusetts Solar Forum, Session 2, UMass Extension presented at WM Solar Forum Session 2: Solar & Land Use in Massachusetts; p4, p10 - https://umass-my.sharepoint.com/:b:/g/personal/agweb_umass_edu/ERbwYo76QT5Jg6hSEJJDFXUBaQUomb2oIAAeHTilk61ThQ?e=hq5aC1** **For comparison, see - Harvard Forest & University of Massachusetts Amherst. (2025). *Forest Carbon Study: The Impact of Alternative Land-Use Scenarios on Terrestrial Carbon Storage and Sequestration in Massachusetts*. Prepared for the Massachusetts Executive Office of Energy and Environmental Affairs (EEA). "The Moderate Footprint and Conservation Siting scenario uses a 'improving' LUI factor that decreases linearly from 2.75 ha/MW in 2020 to 1.46 ha/MW by 2050," p. 72-73. These translate to 6.8 and 3.6 acres/MW, respectively.**
Grid gross loss	**4.2% of generated electricity for distribution and transmission losses is not applied here.**	**The EPA's current eGRID Frequently Asked Questions reports Grid Gross Loss (GGL)—its estimate of transmission and distribution (T&D) losses—for the major U.S. interconnections. For 2023: Grid Eastern Interconnection (includes ISO-NE) -Grid Gross Loss - 4.2%. Not appropriate to include this penalty to solar lifetime output (MWh) since solar is replacing fossil fuel generation on the grid and the latter also faces grid losses from the point of generation, i.e., they cancel each other out.** **U.S. EPA. *Emissions & Generation Resource Integrated Database (eGRID2022)*, Massachusetts State Output Emission Rate (CO_2e), 2024.**

Statement of Methodology and Calculations

Executive Summary

This methodology calculates a scenario-specific **Net Lifecycle** CO_2e **Mitigation Rate** for ground-mounted solar photovoltaic (PV) systems paired with Battery Energy Storage Systems (BESS) installed on converted forest land in Massachusetts over a 25-year operational timeframe (2026–2050).

The net rate adjusts the ISO-New England marginal avoided-emissions factor ($1{,}014$ lb CO_2e/MWh) for:

1. Cradle-to-gate embodied carbon of solar PV and BESS equipment.
2. Upfront forest carbon released during land conversion.
3. Foregone forest carbon sequestration over 25 years.
4. Offsetting carbon retained in long-duration harvested-wood products.

Step-by-Step Derivation

Step 1: Net Lifetime Solar Generation per Cleared Acre

- ***Direct PV Array AC Generation*:** Based on LBNL (Bolinger & Bolinger, 2022) utility-scale tracking power/energy density benchmarks adjusted for Massachusetts solar irradiance (~ 3.95 kWh/m^2/day GHI) and standard state capacity factors ($\sim 1{,}285$ kWh/kW_{DC}/year), delivered AC generation per direct array footprint acre is established at 306.85 MWh/acre/year.

- **Land Clearing Multiplier:** 1.667 total cleared acres per direct PV footprint acre (where ancillary cleared area represents 40% of total cleared acreage)
- **Annual Output per Cleared Acre:**

$$\frac{306.85 \text{ MWh/array acre/year}}{1.667 \text{ cleared acres/array acre}} = 184.07 \text{ MWh/cleared acre/year}$$

- **Undegraded 25-Year Generation:** $184.07 \times 25 = 4{,}601.75$ MWh

- **Adjustments for Degradation & Curtailment:**
  - *Degradation:* 2.5% initial loss in Year 1, followed by 0.5% annual compound loss through Year 25 → yields $4{,}227.55$ MWh.
  - *Curtailment:* Escalating linearly from 0% in 2026 to 10% in 2050 → reduces generation by 206.79 MWh.
- **Net Lifetime Generation:** $4{,}020.76$ MWh per cleared acre.

Step 2: Gross Avoided Grid Emissions

Applying the ISO-New England marginal avoided-emissions factor ($1{,}014$ lb CO_2e/MWh):

$$\text{Gross Avoided Emissions} = \frac{4{,}020.76 \text{ MWh} \times 1{,}014 \text{ lb } CO_2\text{e/MWh}}{2{,}204.62 \text{ lb/MT}} = 1{,}849.0 \text{ MT } CO_2\text{e/cleared acre}$$

Step 3: Solar PV and Battery Embodied Carbon

- **Combined Equipment Footprint:** $1{,}000$ MT CO_2e per MW_{dc} (750 MT for PV panel supply chain $+250$ MT for 2 MWh BESS).
- **Cleared Land Allocation:** 5.42 total cleared acres per MW_{dc}.
- **Embodied Carbon per Cleared Acre:**

$$\frac{1{,}000 \text{ MT } CO_2\text{e}}{5.42 \text{ acres}} = 184.5 \text{ MT } CO_2\text{e/cleared acre}$$

Step 4: Net Forest Carbon Impact

- **Biomass & Soil Stock Released:** 283.0 MT CO_2e/acre
- **Foregone 25-Year Sequestration:** 1.5 MT/acre/year $\times$ 25 years $=$ 37.5 MT CO_2e/acre
- **Harvested Wood Product Credit:** 20% retention of live above-ground carbon (99.09 MT CO_2e/acre $\times$ 20% $=$ 19.82 MT CO_2e/acre).
- **Net Forest Carbon Loss:**

$$283.0 + 37.5 - 19.82 = 300.68 \text{ MT } CO_2e\text{/cleared acre}$$

Step 5: Lifecycle Net Mitigation & Rate Calculation

Calculation Component	Impact (MT CO2e per Cleared Acre)
Gross Avoided Grid Emissions	$+1{,}849.00$
Less: Solar PV & BESS Embodied Carbon	-184.50
Less: Existing Forest Carbon Stock Loss	-283.00
Less: 25-Year Foregone Forest Sequestration	-37.50
Add: Long-Duration Wood Product Credit	$+19.82$
Net 25-Year Carbon Mitigation	$1{,}363.82$ MT CO_2e

Final Net Lifecycle CO_2e Mitigation Rate:

$$\text{Net Rate} = \frac{1{,}363.82 \text{ MT } CO_2e \times 2{,}204.62 \text{ lb/MT}}{4{,}020.76 \text{ MWh}} = \mathbf{747.9} \text{ lb } CO_2e\text{/MWh}$$

*(Recommended Presentation Value: **748 lb** CO_2e**/MWh**)*

1. Solar PV degradation table (starting at 4,601 MWh/year)

This uses:

Initial annual generation = **4,601 MWh**
2.5% degradation in Year 1
0.5% compounded annual degradation thereafter

Year	Cumulative degradation	Annual MWh
2026	2.50%	4,486.00
2027	2.99%	4,463.50
2028	3.47%	4,441.20
2029	3.96%	4,419.00
2030	4.44%	4,396.90
2035	6.80%	4,288.10
2040	9.11%	4,182.00
2045	11.36%	4,078.50
2050	13.55%	3,977.50

25-year total after degradation = 4,227.6 MWh per cleared acre

2. Annual curtailment table

We then applied **linearly increasing curtailment**:

0% in 2026
10% in 2050
Increase each year = **0.4167 percentage point**

Year	Degraded MWh	Curtailment	Net MWh
2026	4,486.00	0.00%	4,486.00
2027	4,463.50	0.42%	4,444.90
2028	4,441.20	0.83%	4,404.20
2029	4,419.00	1.25%	4,363.80
2030	4,396.90	1.67%	4,323.60
2035	4,288.10	3.75%	4,127.30
2040	4,182.00	5.83%	3,938.00
2045	4,078.50	7.92%	3,755.60
2050	3,977.50	10.00%	3,579.80

See also:

[The Hidden Costs of Solar Shortfall - Slide Notes]