Marginal Cost of Emissions Reductions in Massachusetts

November 2019 – White Paper

Applied Economics Clinic

Prepared for: Green Energy Consumers Alliance

Authors:
Elizabeth A. Stanton, PhD
Tanya Stasio
Bryndis Woods

www.aeclinic.org

November 21, 2019

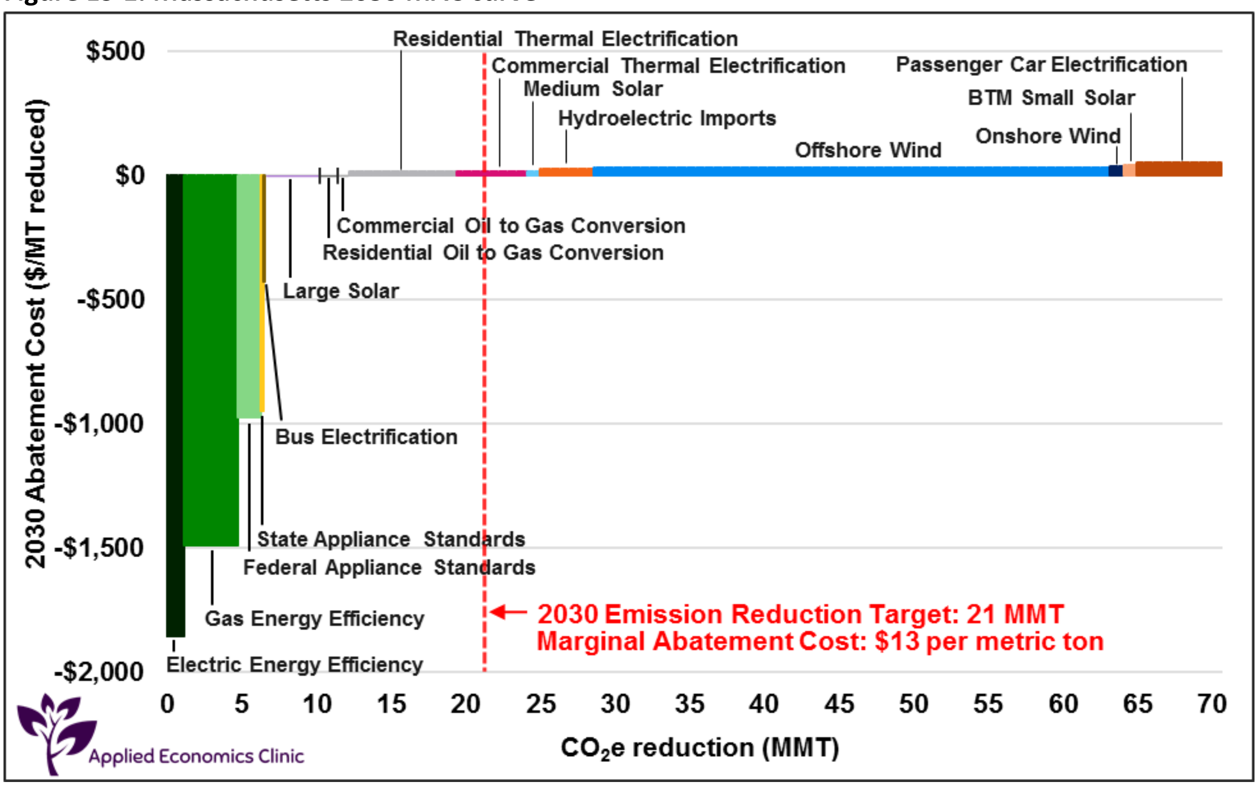
[AEC-2019-11-WP-01]

Executive Summary

While important progress has been achieved in greenhouse gas emission reductions since Massachusetts' Global Warming Solutions Act (GWSA) was enacted in 2008, an additional 21 million metric tons (MMT) of carbon dioxide-equivalent (CO_2-e) emission reduction is needed by 2030 in order to stay on track with 2050 requirements. This Applied Economics Clinic analysis—prepared on behalf of the Green Energy Consumers Alliance—estimates the per ton cost of the most expensive measure needed to achieve that 21 MMT reduction by 2030. Called the "marginal" cost of emission reduction, this measure estimates the maximum cost of adding additional greenhouse gas mitigation in the Commonwealth, a value often used in calculating the avoided costs associated with energy efficiency and other demand or peak reduction efforts.

In 2030, we project that the most expensive (per ton of CO_2-e) measure needed to comply with the GWSA will be residential and commercial thermal electrification: switching from burning gas to using electric heat pumps. The estimated cost of switching from gas to electric heat pumps in 2030 is $13 per ton of avoided CO_2-e (see Figure ES-1). In total, 12.2 MMT of CO_2-e reductions in 2030 can be achieved at zero or net negative cost. An additional 64.0 MMT are available for under $50 per ton. In sum, there are sufficient cost-effective opportunities to meet and even exceed the reductions needed to stay on track with GWSA targets.

Figure ES-1. Massachusetts 2030 MAC curve



Applied Economics Clinic
Economic and Policy Analysis of Energy, Environment and Equity

Table of Contents

1. Overview

The Commonwealth of Massachusetts has committed to reduce its greenhouse gas emissions 80 percent below 1990 levels by 2050 in "an efficient and cost-effective manner".[1] Success in achieving this mandate will require careful analysis of abatement measures' costs and potential to reduce greenhouse gas emissions. A marginal abatement cost (MAC) curve is a visual tool that can be used to present the greenhouse gas emission reduction potential of different abatement measures along with their economic cost. MAC curves provide a snapshot of mitigation options that can be used as a starting point for policy discussion and further analysis.

This Applied Economics Clinic white paper begins with a review of Massachusetts' emission reduction obligations (Sections 2 and 3). Section 4 presents the history of how MAC curves have been used as a policy tool in the Commonwealth and around the world. Section 5 discusses the limitations of MAC curves. Section 6 presents a MAC curve for Massachusetts in 2030, and Section 7 presents a detailed methodology for the development of this curve.

2. Massachusetts must lower emissions by 21 MMT by 2030

Massachusetts' 2008 Global Warming Solutions Act (GWSA) requires an 80 percent reduction in greenhouse gas emissions from 1990 levels by 2050 and interim emissions limits that "maximize the ability of the Commonwealth" to achieve the 2050 mandate.[2] In 2010, an interim limit was set mandating that emissions should be no greater than 71 million metric tons (MMT) by 2020—a 25 percent reduction from 1990 levels.[3,4] While an emission limit for 2030 has not been set (but is required to be announced by December 31, 2020[5]), any limit less than a 43 percent reduction from 1990 levels by 2030—the result of drawing a straight line between 25 percent in 2020 and 80 percent in 2050—would slow Massachusetts' progress towards the 2050 mandate. This 43 percent reduction by 2030 would cap the Commonwealth's emissions at 54 MMT[6]—or a reduction of 21 MMT from today's levels (see Figure

---

[1] Massachusetts General Laws Chapter 298 (GWSA), Section 4(a) (2008). *An Act Establishing the Global Warming Solutions Act.* Available online: https://malegislature.gov/Laws/SessionLaws/Acts/2008/Chapter298.

[2] GWSA. Section 3(a).

[3] Massachusetts Secretary of Energy and Environmental Affairs. December 28, 2010, *Determination of Greenhouse Gas Emission Limit for 2020.* Available at: https://www.mass.gov/files/documents/2017/12/06/Former%20Secretary%20Bowles%E2%80%99%20Determination%20of%20the%20Greenhouse%20Gas%20Emission%20Limit%20for%202020.pdf

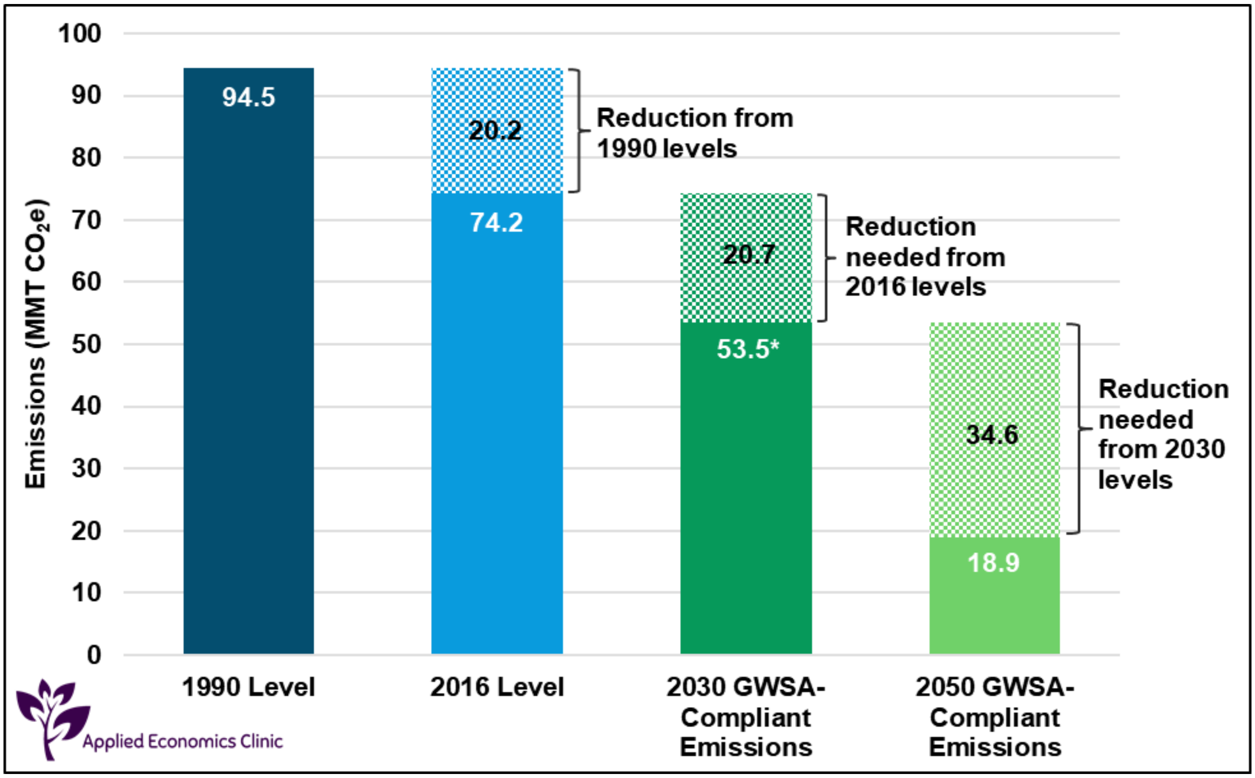
[4] Data showing whether or not Massachusetts achieves this 25 percent reduction are unlikely to be available before 2022.

[5] Massachusetts Governor Baker. September 16, 2016. Executive Order No. 569. *Establishing an Integrated Climate Change Strategy for the Commonwealth.* Available at: https://www.mass.gov/files/documents/2016/10/tx/eo569.pdf.

[6] Massachusetts statewide emissions in 1990 were 94.5 MMT. Massachusetts Department of Environmental Protection (MassDEP). December 2018. *Statewide Greenhouse Gas Emissions Level: 1990 Baseline and 2020.*

1 below).[7] Massachusetts must reduce emissions by an average of 2 MMT each year to meet this requirement.

Figure 1. Massachusetts progress towards 2030 GWSA compliance



Data source: MassDEP. December 2018. "Summary" tab.

**Note: 2030 GWSA-Compliant emissions level was calculated using an estimated annual linear emissions reduction rate derived from MA GWSA 2020 and 2050 emissions reduction targets. Emissions and emission reductions shown in graph are rounded.*

3. An efficient and cost-effective manner

GWSA requires not only that emissions be reduced but that these emission abatement activities be "adopted and implemented…in an efficient and cost-effective manner," requiring state agencies to "evaluate the total potential costs and economic and noneconomic benefits of various reduction measures to the economy, environment and public heath, using the best available economic models, emissions estimation techniques and other scientific methods."[8] GWSA does not, however, specify a

Business As Usual Projection Update: Appendix C, "Summary" tab. Available at: https://www.mass.gov/lists/MassDEP-emissions-inventories.

[7] Massachusetts statewide emissions in 2016 were 74.2 MMT. MassDEP. December 2018. *Statewide Greenhouse Gas Emission Level. Appendix C.* "Summary" tab.

[8] GWSA. Section 4(a) and (d) (2008).

definition of "cost effective" or the specific impacts to be included for a comprehensive assessment of costs effectiveness.

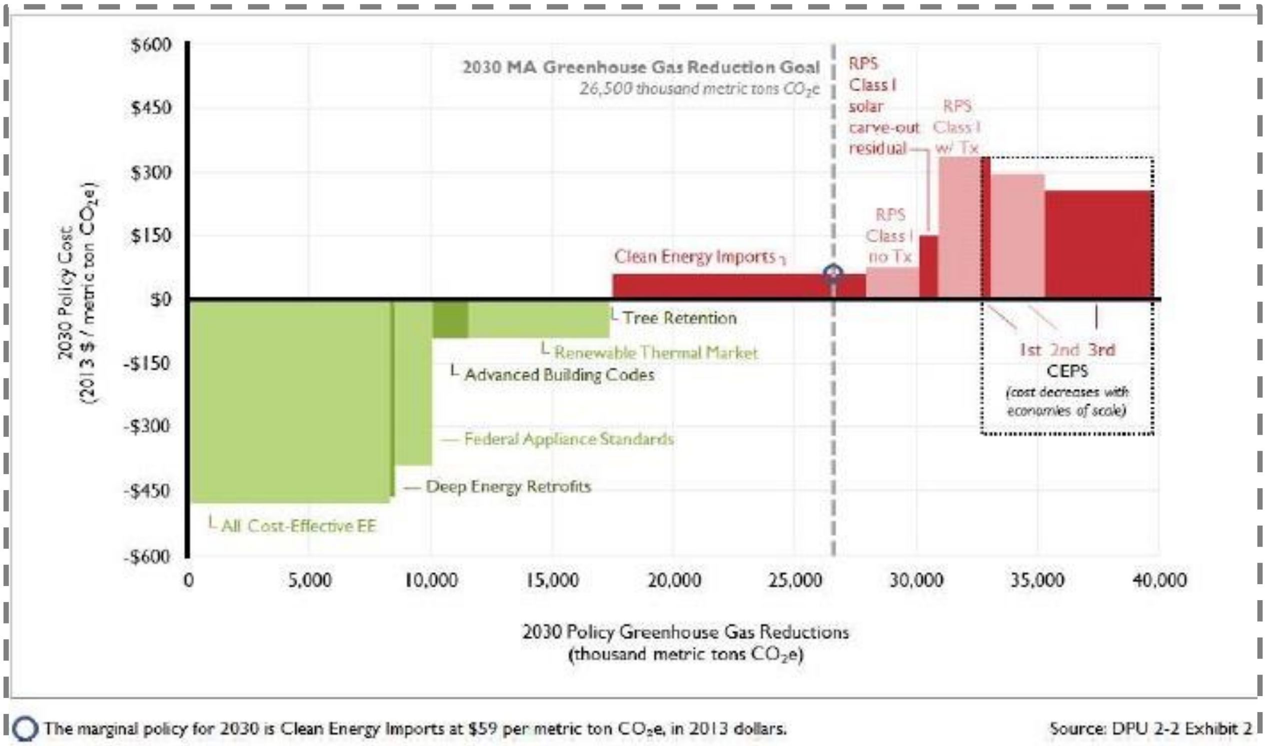
The Massachusetts Departments of Environmental Protection (MassDEP) and Energy Resources (MassDOER) have offered evaluations of the expected cost of emission reduction measures necessary to comply with GWSA in the form of a MAC curve. A 2014 assessment on behalf of MassDEP and MassDOER[9] (by one of the authors of this AEC white paper) concluded that the 26 MMT emission reduction needed at that time to achieve the 2030 limit would have a "marginal cost" of $64 per metric ton[10] of CO_2e.[11] A 2009 order from the Massachusetts Department of Public Utilities allows the costs associated with energy efficiency measures that reduce greenhouse gas emissions to be included in the calculation of avoided energy costs to extent that they avoid reasonably foreseen costs of complying with GWSA.[12]

A "marginal cost" is the cost of one additional unit; in this case, the cost per ton of emissions reduction achieved by the marginal, or last and most expensive, measure needed to reduce emissions to the target level. MassDEP and MassDOER's 2014 evaluation found that if available emission reduction measures were implemented in the order of their cost (per ton of emission reduction)—from lowest to highest cost—the final, and therefore most expensive, emission reduction measure needed to achieve the 2030 limit would be to import hydroelectric generation from Canada (called "Clean Energy Imports" in red in the center of **Figure 2** below). The cost of the marginal abatement measure represents Massachusetts highest expected cost of emission reduction at that time.

---

[9] Stanton, E. A. 2014. *Regarding the Cost of Compliance with the Global Warming Solutions Act.* Corrected Amended Direct Testimony in Massachusetts Department of Public Utilities (MassDPU) Docket 14-86 on Behalf of MassDOER and MassDEP. Available at: https://eeaonline.eea.state.ma.us/DPU/Fileroom.
[10] Dollar value was converted from 2013$ to 2018$ using a CPI inflation rate of 1.08 (original value: $59).
[11] CO_2e, or carbon dioxide equivalent, is a standard unit for measuring greenhouse gas emissions. CO_2e is the amount of CO_2 emissions with the same global warming potential as one unit of another greenhouse gas.
[12] MassDPU. March 16, 2009.Investigation by the Department of Public Utilities on its own Motion into Updating its Energy Efficiency Guidelines Consistent with An Act Relative to Green Communities. Order DPU 08-50-A.

Figure 2. 2014 MA DPU Docket 14-86 Stanton testimony: 2030 MAC curve for GWSA Compliance



Source: Reproduced from Stanton 2014, Figure 6.

A 2018 study prepared for the MassDOER and MassDEP outlines potential emission reduction measures for Massachusetts' electric sector and estimates the average weighted cost of all available measures necessary to reach the 2030 target to be $25 per metric ton.[13] The agencies' analysis, however, does not present a marginal (high end) cost for the last, most expensive abatement measure or a cost estimate for the total emission reduction necessary to achieve the 2030 limit.[14]

Other recent Massachusetts-specific analyses that touch on the marginal cost of greenhouse gas emissions abatement measures include:

- **Carbon Free Boston**: The 2019 *Carbon Free Boston Summary Report* outlines the actions the City of Boston must take to achieve carbon neutrality by 2050.[15] Within the report, MAC curves for

[13] Value was converted from short ton to metric ton using conversion rate of 0.91 (original value: $28). Knight, P., Camp, E., Glick, D., & Chang, M. 2018. *Analysis of the Avoided Costs of Compliance of the Massachusetts Global Warming Solutions Act -Supplement to 2018 AESC Study*. Synapse Energy Economics, Inc. Available at: http://www.synapse-energy.com/sites/default/files/MA-GWSA-Supplement-AESC-2018-18-066.pdf.

[14] Stanton, E.A. 2018. *Comment on August 2018 Analysis of the Avoided Costs of Compliance of the MA GWSA*. Applied Economics Clinic. Available at: https://aeclinic.org/publicationpages/2018/9/10/comment-on-august-2018-analysis-of-the-avoided-costs-of-compliance-of-the-ma-gwsa-5d2z2.

[15] Boston Green Ribbon Commission (GRC) and Boston University Institute for Sustainable Energy (ISE). 2019. *Carbon Free Boston Summary Report*. Available online: https://www.greenribboncommission.org/document/executive-summary-carbon-free-boston/.

Boston's buildings[16] and transportation[17] sectors compare emission reduction measures by cost per ton.

- **MassDOT**: A 2017 Massachusetts Department of Transportation (MassDOT) study presents achieved emission reductions and costs per ton of recent town-level transportation measures undertaken in the Commonwealth.[18]

Building on these and other recent marginal abatement cost studies from around the world, Section 6 of this AEC white paper presents an updated MAC curve analysis for Massachusetts with the goals of (1) identifying the technologies and measures available to achieve GWSA compliance and (2) estimating the marginal cost of compliance.

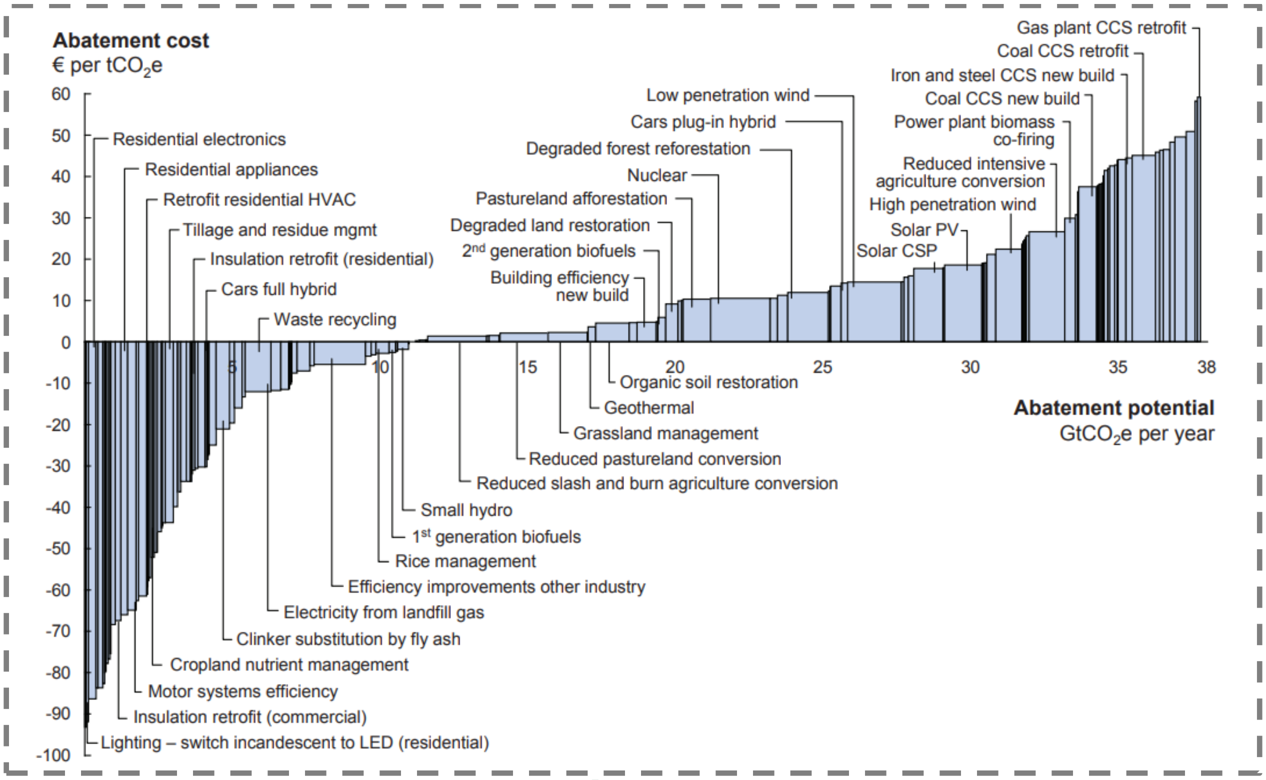
4. Marginal abatement curves in recent literature

MAC curves are commonly used to provide an accessible representation of potential greenhouse gas emission reduction measures and their costs. Given an emission reduction target, a MAC curve can provide an important initial assessment of the marginal cost of emissions abatement. Much of the greenhouse gas MAC curve literature follows the general methodology set out in a series of studies published by the consulting firm McKinsey & Company between 2007 and 2013 that included national greenhouse gas abatement curves for: the United States (see Figure 3 below), China, India, Brazil, Russia, Germany, the United Kingdom, and Sweden,[19] as well as several iterations of global greenhouse gas MAC curves.[20]

---

[16] Ibid. p. 44.
[17] Ibid. p. 65.
[18] Baker, E.D., and Khatami, S.N. 2017. *Developing a metric for the cost of greenhouse gas abatement*. University of Massachusetts-Amherst, Prepared for the Massachusetts Department of Transportation (MassDOT). Available online: http://www.umasstransportationcenter.org/Document.asp?DocID=309.
[19] McKinsey & Company. "Greenhouse gas abatement cost curves." *McKinsey*. Available online: https://www.mckinsey.com/business-functions/sustainability/our-insights/greenhouse-gas-abatement-cost-curves.
[20] McKinsey & Company. 2013*. Pathways to a Low-Carbon Economy: Version 2 of the Global Greenhouse Gas Abatement Cost Curve*. Available at: https://www.mckinsey.com/business-functions/sustainability/our-insights/pathways-to-a-low-carbon-economy.

Figure 3. 2013 McKinsey global MAC curve beyond business-as-usual for 2030



Source: Reproduced from McKinsey & Company 2013. Exhibit A.VI.3

5. Limitations of MAC curves

Key limitations to the application of MAC curves have led analysts to call for caution for their use in policymaking decisions. The main concerns raised in the literature typically focus on what is *not* included in a MAC curve, for example:

- **Indirect costs** are not directly related to the abatement measure and are difficult to assign a monetary value. Examples of indirect costs are implementation costs—such as delayed return on investment for measures like new insulation or solar panel installation—and ancillary benefits of mitigation measures, such as reductions in water and air pollution.
- **Intersectoral, international, and intertemporal interactions** are the potential effects that changes in one sector, nation, or period of time may have on another. These effects are difficult to incorporate into MAC curves, which typically consider abatement measures in isolation when, in fact, there may be important synergies among abatement measures.
- **Behavioral responses** are consumer reactions driven by psychological, emotional, or cultural factors that are difficult to quantify or predict. For example, installation of new energy efficiency equipment could allow consumers to increase other types of energy use while spending the same amount of money.

- **Omitted benefits** are unquantified or unmonetized benefits of emission reduction policy that are often not included in assessed net costs, for example: reduced heath costs; impacts on labor productivity; and avoided damages to human communities and natural ecosystems.

An additional concern is that MAC curves, including the one developed in this white paper, often show measures that have a negative abatement cost, meaning that the measure essentially pays for itself. Under perfect market conditions, these measures would have already been adopted. It is possible that negative costs signal omitted cost considerations such as non-financial implementation barriers. For example, individuals may lack information about the energy efficiency measures available to them at little to no cost or may prefer to maintain their current behavior despite more affordable options (known as “status-quo bias”).

In addition to the general limitations of MAC curves, it is important to note that each MAC curve is sensitive to its underlying assumptions and its results. Therefore, all MAC curves should be interpreted in the context of multiple underlying uncertainties, including future energy prices and political conditions. As a matter of best practice, MAC curves should serve as one of many decision-making tools used in climate policy decisions and should be accompanied by transparent information regarding their underlying assumptions and related limitations.[21]

6. Massachusetts 2030 marginal abatement cost curve

This AEC white paper presents a MAC curve for Massachusetts using 2030 costs and emissions reduction potentials compiled from the most recent public sources including the Massachusetts Executive Office of Energy and Environmental Affairs,[22] the Boston University Institute for Sustainable Energy (ISE),[23] and the Massachusetts Energy Efficiency Advisory Council (MA EEAC).[24] Our analysis finds that the marginal measure (i.e. the last, most expensive abatement measure) needed to achieve a 21 MMT CO_2e emission reduction in 2030 is residential and commercial thermal electrification (or conversion to electric heat pumps) at a cost of $13 per metric ton. We evaluate 16 potential measures, totaling 70.6 MMT of potential emission reduction. A full description of sources, assumptions, and methods used to develop this MAC curve is presented in Section 7. Because each measure’s cost and emission reduction potential is gleaned from different sources there is some variation in the techniques used to estimate these costs and benefits. Which benefits are or are not included also varies by measure: most measures’ benefit valuations do not include avoided social, health, or carbon costs. Emissions reduction potentials are

[21] Kesicki, F. and Ekins, P. 2012. “Marginal abatement cost curves: a call for caution.” *Climate Policy*, 12(2), 219-236. doi: https://doi.org/10.1080/14693062.2011.582347.
[22] Beaton, M. 2015. 2015 Update Massachusetts Clean Energy and Climate Plan for 2020. Massachusetts Executive Office of Energy and Environmental Affairs. p.12.
[23] Boston University ISE. 2018. Background spreadsheets to the Carbon Free Boston Report.
[24] MA EEAC. October 31, 2018. "2019-2021 Three-Year Energy Efficiency Final Plan". Exhibit 1, Appendix C - Data Tables, Statewide, Electric. http://ma-eeac.org/plans-updates/.

direct (at point of emission) only, and do not include upstream emissions from extraction, transmission, or distribution.

Out of the 16 electric, buildings, and transportation sector measures included in the MAC analysis, five had negative net costs (that is, their benefits outweigh their financial costs):

- Electric energy efficiency
- Gas energy efficiency
- Bus electrification
- State appliance standards
- Federal appliance standards

Three measures have zero costs (that is, their benefits cancel out their financial costs):

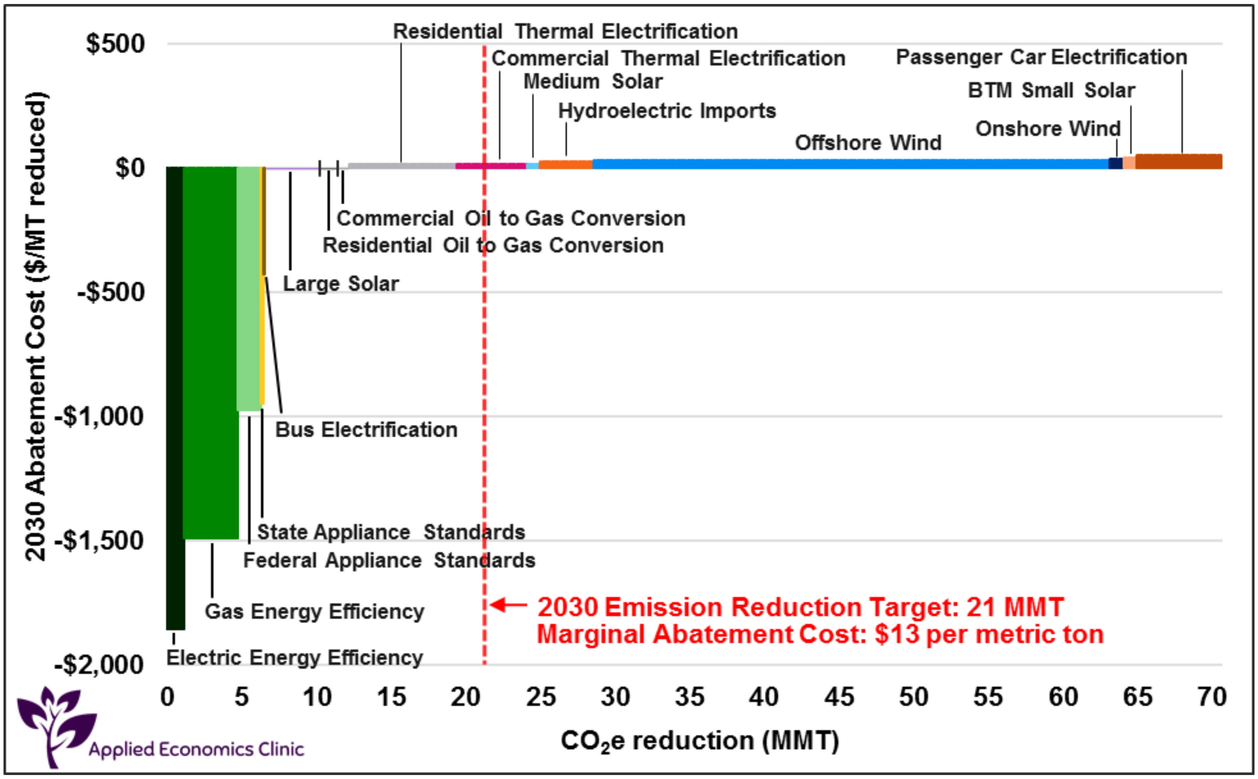
- Large solar
- Residential oil to gas conversion
- Commercial oil to gas conversion

The remaining eight measures have costs of $50 per metric ton or less:

- Residential thermal electrification
- Commercial thermal electrification
- Medium solar
- Offshore wind
- Onshore wind
- Small (behind-the-meter) solar
- Passenger car electrification
- Hydroelectric imports

In summary, Massachusetts' total potential emission reduction is composed of 12.2 MMT of negative or zero cost measures (17 percent) and 58.4 MMT of positive cost measures (83 percent) for a total of 70.6 MMT of potential emission reductions. Achieving a 21 MMT emission reduction requires the adoption of all negative and zero cost measures and an additional 9 MMT reduction from residential and commercial heat pumps at a cost of $13 per metric ton (see Figure 4 below).

Figure 4. Massachusetts 2030 MAC curve



Data source: See in-text citations in Section 7 below.

Table 1. Massachusetts 2030 MAC curve summary

	Measure	CO_2e reduction (MMT)	Cost ($/MT reduced)
Negative cost	Electric Energy Efficiency	1.1	-$1,855
	Gas Energy Efficiency	3.6	-$1,486
	Federal Appliance Standards	1.5	-$976
	State Appliance Standards	0.2	-$948
	Bus Electrification	0.1	-$426
Zero cost	Large Solar	3.8	$0
	Residential Oil to Gas Converstion	1.4	$0
	Commercial Oil to Gas Converstion	0.4	$0
Positive cost	Residential Thermal Electrification	7.2	$13
	Commercial Thermal Electrification	**4.7**	**$13**
	Medium Solar	0.9	$15
	Hydroelectric Imports	3.6	$25
	Offshore Wind	34.5	$30
	Onshore Wind	1.0	$34
	Small (Behind-the-Meter) Solar	0.8	$44
	Passenger Car Electrification	5.7	$50

Data source: See in-text citations in Section 7 below.

7. Methodology and assumptions

Electric Energy Efficiency

- Emission Reduction Potential: 1.1 MMT CO_2e
  Electric energy efficiency emission reduction potential is Massachusetts 2030 electric sales (44 terawatt-hours (TWh)) multiplied by the forecasted 2030 New England electric grid emissions rate (0.336 lbs. CO_2e per kilowatt-hour) multiplied by the Massachusetts expected energy efficiency potential in 2030 (17 percent). Massachusetts 2030 electric sales are calculated by escalating 2017 values (53 TWh per the U.S. Energy Information Administration (EIA)[25]) by the EIA's forecast of New England gas annual sales growth from 2017 to 2030 (-1.4 percent in the AEO 2019 base case[26]). The 2030 New England electric grid emissions rate is taken from Lopez et

[25] U.S. EIA. 2017. Form 861. Available at: https://www.eia.gov/electricity/data/eia861/.
[26] U.S. EIA. 2019. *Annual Energy Outlook (AEO) Data.* Available at: https://www.eia.gov/outlooks/aeo/.

al. (2019).[27] In the absence of Massachusetts-specific long-term energy efficiency research, 2030 energy efficiency potential is forecast by updating the method presented in a 2012 ACEEE report, which compares forecasts from several sources.[28] The estimate used in this MAC analysis takes the average 2030 energy efficiency potential from International Energy Agency (IEA) (2017)[29] and Rocky Mountain Institute (2014).[30]

- Savings: -\$1,855/MT CO_2e [31]
  Electric energy efficiency cost savings are the three-year average net benefits (benefits less costs) divided by annual CO_2e reductions from the Massachusetts' energy efficiency program administrators 2019-2021 three-year plan,[32] divided by the 2030 emission reduction potential.

Gas Energy Efficiency

- Emission Reduction Potential: 3.6 MMT CO_2e
  Gas energy efficiency emission reduction potential is Massachusetts 2030 gas emissions (21.3 MMT CO_2e) multiplied by the Massachusetts expected energy efficiency potential in 2030 (17 percent). Massachusetts 2030 gas emissions are calculated by escalating 2016 values (22.9 MMT CO_2e (per MassDEP[33]) by the U.S. Energy Information Administration's forecast of New England gas annual sales growth from 2017 to 2030 (-0.6 percent in the AEO 2019 base case[34]). In the absence of Massachusetts-specific long-term energy efficiency research, 2030 energy efficiency potential is forecast by updating the method presented in a 2012 ACEEE report, which compares forecasts from several sources.[35] The estimate used in this MAC analysis takes the average 2030 energy efficiency potential from IEA (2017)[36] and Rocky Mountain Institute (2014).[37]

- Savings: -\$1,486/MT CO_2e

[27] Lopez R, Comings T, Stanton E, Tavares E. 2019. *Home Heat Pumps in Massachusetts*. Applied Economics Clinic. Available at: https://aeclinic.org/publicationpages/2019/5/29/home-heat-pumps-in-massachusetts.
[28] Laitner, J., Nadel, S., Elliot, R., Sachs, H., Khan, A. 2012. *The Long-Term Efficiency Potential: What the Evidence Suggests?* ACEEE. Available at: https://aceee.org/sites/default/files/publications/researchreports/e121.pdf.
[29] International Energy Agency (IEA). 2017. *Energy Technology Perspectives*. Available at: https://www.oecd.org/about/publishing/Corrigendum_EnergyTechnologyPerspectives2017.pdf.
[30] Lovins, A. 2014. *Reinventing Fire.* Rocky Mountain Institute. Available at: https://rmi.org/insight/reinventing-fire/
[31] All dollar values presented in 2018 dollars, converted (when necessary) using the CPI-U.
[32] MassDPU Docket No. 18-110 – 18-119. October 31, 2019. *Three-Year Plan.* Submitted by: Massachusetts energy efficiency program administrators. Available at: http://ma-eeac.org/wordpress/wp-content/uploads/Exh.-1-Final-Plan-10-31-18-With-Appendices-no-bulk.pdf.
[33] Massachusetts statewide emissions in 1990 were 94.5 MMT. MassDEP. December 2018. *Statewide Greenhouse Gas Emissions Level: 1990 Baseline and 2020 Business As Usual Projection Update: Appendix C,* "CO2_FFC" tab. Available at: https://www.mass.gov/lists/MassDEP-emissions-inventories.
[34] U.S. EIA. AEO 2019.
[35] Laitner et al. 2012.
[36] International Energy Agency (IEA). 2017.
[37] Lovins. 2014.

Gas energy efficiency cost savings are the three-year average net benefits (benefits less costs) divided by annual CO_2e reductions from the Massachusetts' energy efficiency program administrators 2019-2021 three-year plan,[38] divided by the 2030 emission reduction potential.

Federal Appliance Standards

- Emission Reduction Potential: 1.5 MMT CO_2e

  Federal Appliance Standard emission reduction potential for Massachusetts is 2030 annual savings less 2015 annual savings in kWh and Btu (per ASAP and ACEEE[39]), multiplied by 2030 emission rates for New England.

- Savings: -$976/MT CO_2e

  Federal Appliance Standard cost savings for Massachusetts are 2030 annual utility bill savings[40] less 2015 annual utility bill savings (per ASAP and ACEEE[41]), divided by the 2030 emission reduction potential.

State Appliance Standards

- Emission Reduction Potential: 0.2 MMT CO_2e

  Massachusetts State Appliance Standard emission reduction potential is the average of 2025 and 2035 CO_2e emission reductions (per ASAP[42]).

- Costs: -$948/MT CO_2e

  Massachusetts State Appliance Standard cost savings are the average of 2025 and 2035 utility bill savings (per ASAP[43]), divided by the 2030 emission reduction potential.

Bus Electrification

- Emission Reduction Potential: 0.1 MMT CO_2e
  Bus electrification emission reduction potential is the Boston potential escalated to reflect potential for the Commonwealth as a whole. Emission reductions from Boston bus electrification are taken from the 2018 Carbon Free Boston[44] study and assume that 2050

[38] MassDPU Docket No. 18-110 – 18-119. October 31, 2019.
[39] deLaski, A., and Mauer, J. February 2017. *Energy-Saving States of America: How Every State Benefits from National Appliance Standards*. ASAP and ACEEE White Paper. Available at: https://aceee.org/white-paper/energy-saving-states-america. Table C3.
[40] Includes all utility bills: electric, gas, oil, water, etc.
[41] Ibid. Table C2.
[42] ASAP. 2019. *2019 State Appliance Standards Recommendations – Savings estimates for: Massachusetts*. Available at: https://appliance-standards.org/sites/default/files/state_savings_state_standards/Massachusetts.pdf.
[43] Ibid.
[44] Boston GRC and Boston University ISE. 2019. *Carbon Free Boston Summary Report.* p. 65.

potentials are technically achievable by 2030.[45] Boston bus transit represents 45 percent of total MBTA transit (per Carbon Free Boston[46]) and MBTA bus transit represents 52 percent of total Massachusetts transit (per MassDOT)[47]). Emissions reduction from Boston bus electrification was multiplied by the inverse of the percentage of MBTA bus transit in Boston and the inverse of the percentage of Massachusetts bus transit that corresponds to the MBTA.

- Savings: -$426/MT CO_2e
  Bus electrification cost savings are the Carbon Free Boston forecasted savings divided by the Boston emission reduction potential.[48]

Large Solar

- Emission Reduction Potential: 3.8 MMT CO_2e

  Massachusetts emission reduction potential from utility-scale (in front of the meter) photovoltaic solar installations is identified in the avoided cost of Global Warming Solutions Act (GWSA) compliance supplement to the 2018 New England *Avoided Energy Supply Components* study.[49]

- Costs: $0/MT CO_2e

  The 2018 AESC's GWSA compliance supplement estimated a $0 per MT cost for utility-scale solar, net of the expected wholesale cost of electricity.[50]

Residential Oil to Gas Heating Conversion

- Emission Reduction Potential: 1.4 MMT CO_2e

  The emission reduction potential from converting Massachusetts residential oil heating to gas is estimated as 2016 emissions from residential heating oil consumption (5.3 MMT CO_2e per MassDEP[51]) multiplied by one minus the ratio of emissions from gas heating to emissions from oil heating assuming 2019 gas system efficiencies (1 minus 0.7 per Lopez et al. 2019[52]). Note this analysis treats emissions from heating system updates as if they were taken in two discreet steps: (1) residential oil to gas heating conversion, and (2) thermal electrification (gas to heat

[45] Porter, Christopher, Martin Milkovits, Xiao Yun (Jane) Chang, Scott Boone, Michael J. Walsh, Joshua R. Castigliego, and Cutler J. Cleveland. 2019. *Carbon Free Boston: Transportation Technical Report* (Boston University Institute for Sustainable Energy, Boston, MA, USA). Available at http://sites.bu.edu/cfb/technical-reports. Figure 39.
[46] Ibid.
[47] MassDOT. 2015-2017. Bus Ridership Data. Available at: http://www.mbtabackontrack.com/performance/index.html#/download.
[48] Boston GRC and Boston University ISE. 2019. *Carbon Free Boston Summary Report.*
[49] Knight et al. 2018. p. 8.
[50] Ibid. p.5, 8.
[51] MassDEP. December 2018. "CO2_FFC" tab.
[52] Lopez et al. 2019.

pump). Conversion from oil directly to heat pump would achieve the sum of these two measures emissions reductions.

- Costs: $0/MT CO_2e

  An incremental cost of $0 per MT assumes that all oil heating systems are replaced at the end of their lifetime and not before.

Commercial Oil to Gas Heating Conversion

- Emission Reduction Potential: 0.4 MMT CO_2e
- The emission reduction potential from converting Massachusetts commercial oil heating to gas is estimated as 2016 emissions from commercial heating oil consumption (1.3 MMT CO_2e per MassDEP[53]) multiplied by one minus the ratio of emissions from gas heating to emissions from oil heating assuming 2019 gas system efficiencies (1 minus 0.7 per Lopez et al. 2019[54]).
- Costs: $0/MT CO_2e

  An incremental cost of $0 per MT assumes that all oil heating systems are replaced at the end of their lifetime and not before.

Residential Thermal Electrification: Gas to Heat Pump

- Emission Reduction Potential: 7.2 MMT CO_2e

  The emission reduction potential of adopting heat pumps in place of residential gas heating and central air conditioning (AC) includes the emissions reduced from converting all oil *and* gas residential heating to heat pumps. (The incremental emissions savings of switching from oil to gas heating is included as a separate measure: oil to gas heating conversion.) Massachusetts residential gas heating (after adjusting for oil systems assumed to have been converted to gas) emitted 9.8 MMT CO_2e in 2016 (per MassDEP[55] and calculation presented for "oil to gas heating conversion"). These emissions were multiplied by one minus the ratio of emissions from electricity used to power heat pumps to emissions from gas heating and central AC assuming 2019 gas system efficiencies (1 minus 0.3 per Lopez et al. 2019[56]).

- Costs: $13/MT CO_2e

  Residential heat pump adoption costs $648 more per home than a new gas furnace plus central AC over the 18-year lifetime of the equipment (per Lopez et al 2019[57]) without any rebates or financial incentives for either heat pumps or gas furnaces.

[53] MassDEP. December 2018. "CO2_FFC" tab.
[54] Lopez et al. 2019.
[55] MassDEP. December 2018. "CO2_FFC" tab.
[56] Lopez et al. 2019. p. 2
[57] Lopez et al. 2019. Ibid.

Commercial Thermal Electrification: Gas to Heat Pump

- Emission Reduction Potential: 4.7 MMT CO_2e

  The emission reduction potential of adopting heat pumps in place of commercial gas heating and central AC includes converting all oil *and* gas commercial heating to heat pumps. (The incremental emissions savings of switching from oil to gas heating is included as a separate measure: oil to gas heating conversion.) Massachusetts commercial gas heating (including oil systems assumed to have been converted to gas) emitted 6.6 MMT CO_2e in 2016 (per MassDEP[58] and calculation presented for "oil to gas heating conversion"). These emissions were multiplied by one minus the ratio of emissions from electricity used to power heat pumps to emissions from gas heating and central AC assuming 2019 gas system efficiencies (0.3 per Lopez et al. 2019[59]).

- Costs: $13/MT CO_2e

  In the absence of cost estimates specific to commercial heat pump applications, we assume the same per MT cost of emissions savings as that of residential systems.

Medium Solar

- Emission Reduction Potential: 0.9 MMT CO_2e

  Massachusetts emission reduction potential from medium photovoltaic solar installations (distributed solar at commercial and industrial sites) is identified in the avoided cost of Global Warming Solutions Act (GWSA) compliance supplement to the 2018 New England *Avoided Energy Supply Components* study.[60]

- Costs: $15/MT CO_2e

  The 2018 AESC's GWSA compliance supplement estimated a $15 per MT cost for medium solar, net of the expected wholesale cost of electricity.[61]

Hydroelectric Imports

- Emission Reduction Potential: 3.6 MMT CO_2e

  Massachusetts emission reduction potential from hydroelectric generation imported from Canada is identified in the avoided cost of Global Warming Solutions Act (GWSA) compliance supplement to the 2018 New England *Avoided Energy Supply Components* study as 25.1 MMT, or one new 8.3 TWh transmission line added each year between 2023 and 2030.[62] For this

[58] MassDEP. December 2018. "CO2_FFC" tab.
[59] Lopez et al. 2019.
[60] Knight et al. 2018. p.8.
[61] Ibid. p.8.
[62] Ibid. p.15.

assessment, this potential value is adjusted downward to one 8.3 TWh line per decade because just one such line has been more than a decade in the making. The assumption that one new line could be built per year in the 2020s is unsupported and seems overly optimistic.[63]

- Costs: \$25/MT CO_2e

  The 2018 AESC's GWSA compliance supplement estimated a \$25 per MT cost for hydroelectric imports, net of the expected wholesale cost of electricity.[64]

Offshore Wind

- Emission Reduction Potential: 34.5 MMT CO_2e

  Massachusetts emission reduction potential from offshore wind installations is identified in the avoided cost of Global Warming Solutions Act (GWSA) compliance supplement to the 2018 New England *Avoided Energy Supply Components* study.[65]

- Costs: \$30/MT CO_2e

  The 2018 AESC's GWSA compliance supplement estimated a \$30 per MT cost for offshore wind, net of the expected wholesale cost of electricity.[66]

Onshore Wind

- Emission Reduction Potential: 1.0 MMT CO_2e

  Massachusetts emission reduction potential from onshore wind installations is identified in the avoided cost of Global Warming Solutions Act (GWSA) compliance supplement to the 2018 New England *Avoided Energy Supply Components* study.[67]

- Costs: \$34/MT CO_2e

  The 2018 AESC's GWSA compliance supplement estimated a \$34 per MT cost for onshore wind, net of the expected wholesale cost of electricity.[68]

Small (Behind-the-Meter) Solar

- Emission Reduction Potential: 0.8 MMT CO_2e

  Massachusetts emission reduction potential from small photovoltaic solar installations (distributed solar at residential sites) is identified in the avoided cost of Global Warming

[63] Stanton. 2018. p.5.
[64] Ibid. p.5, 8
[65] Ibid. p.8.
[66] Ibid. p.8
[67] Ibid. p.8.
[68] Ibid. p.8

Applied Economics Clinic
Economic and Policy Analysis of Energy, Environment and Equity

Solutions Act (GWSA) compliance supplement to the 2018 New England *Avoided Energy Supply Components* study.[69]

- Costs: $44/MT CO_2e

The 2018 AESC's GWSA compliance supplement estimated a $44 per MT cost for residential solar, net of the expected wholesale cost of electricity.[70]

Passenger Car Electrification

- Emission Reduction Potential: 5.7 MMT CO_2e

Passenger car (light duty vehicle) electrification emission reduction potential is the Boston potential escalated to reflect the potential for the entire Commonwealth. Emission reductions from light duty vehicle electrification are taken from the 2019 Carbon Free Boston[71] study and assume that 2050 potentials are technically achievable by 2030.[72] Boston light duty vehicle miles travelled represents 5 percent of total Massachusetts light duty vehicle miles travelled (per the MAPC[73]). The Carbon Free Boston study did not examine the emissions or benefits impacts of off-peak charging, which have the potential to reduce the marginal abatement cost of this measure.[74]

- Costs: $50/MT CO_2e

Passenger car electrification costs are the Carbon Free Boston forecasted values per MT.[75] Costs to the consumer would be less depending on state and federal tax credits and other incentives. Recent reports of rapidly declining electric vehicle battery prices suggest that far lower 2050 passenger car electrification costs are possible.[76]

Measures not included

A few emissions abatement measures were not included in our Massachusetts MAC curve due to insufficient data, but are important to mention:

[69] Ibid. p.8.
[70] Ibid. p.8
[71] Boston GRC and Boston University ISE. 2019. *Carbon Free Boston Summary Report.* p.65.
[72] *Carbon Free Boston: Transportation Technical Report*, Figure 39.
[73] Metropolitan Area Planning Council (MAPC). 2009-2014 Municipal Vehicle Census Summary. Available at: https://www.mapc.org/learn/data/#vehiclecensus.
[74] *Carbon Free Boston: Transportation Technical Report*, p.47.
[75] Boston GRC and Boston University ISE. 2019. *Carbon Free Boston Summary Report.* p.65.
[76] Martin C. 2019. *Better Batterie: Bloomberg Quick Take*. The Washington Post. Available at: https://www.washingtonpost.com/business/energy/better-batteries/2019/10/11/155cf384-ec66-11e9-a329-7378fbfa1b63_story.html; Bullard N. 2019. *Electric Car Price Tag Shrinks Along With Battery Cost*. Bloomberg. Available at: https://www.bloomberg.com/opinion/articles/2019-04-12/electric-vehicle-battery-shrinks-and-so-does-the-total-cost.

- Transportation measures for Boston only;
- Historical abatement measures;
- Heavy-duty transportation; and
- Transportation Climate Initiative (TCI) "cap-and-invest" program.

Transportation measures for Boston only

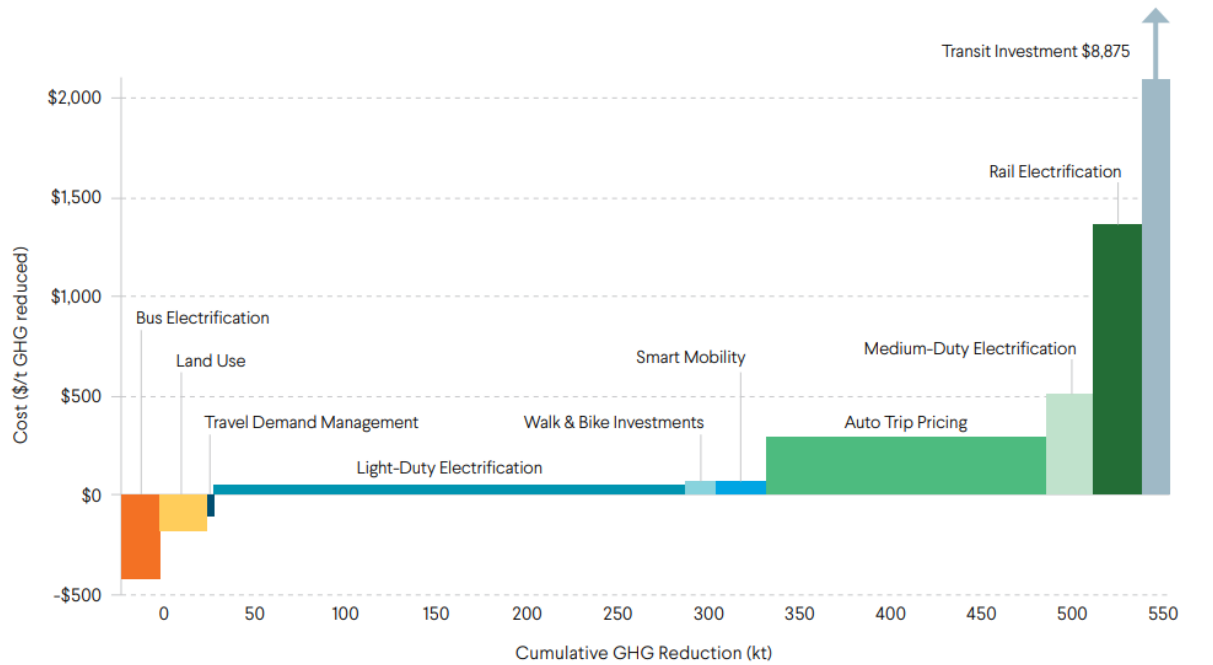
In 2016, Boston Mayor Walsh pledged to make the City carbon neutral by 2050[77] and asked the Boston Green Ribbon Commission (GRC) to establish a Working Group to support the City by developing strategies to reach that goal. GRC collaborated with the ISE at Boston University to develop Carbon Free Boston,[78] a report that lays out a framework to achieve carbon neutrality in 2050 including short, medium and longer-term actions the City can take to reduce greenhouse gas emissions from its transportation, buildings, energy and waste sectors.

In its transportation MAC curve (see Figure 5 below), Carbon Free Boston considered transportation measures for the City of Boston that are not applicable to the rest of Massachusetts and are modest in terms of their total emission savings. The electrification of passenger cars and buses is included in the MAC curve presented in this white paper. The remaining eight measures not included in our Massachusetts MAC are: auto trip pricing, land use, travel demand management, walk and bike investments, smart mobility, medium-duty electrification, rail electrification and transit investment. Taken together, the emission savings from these Boston-specific measures total 0.3 MMT CO_2e.

Of the eight transportation measures not considered in our MAC curve, land use and travel demand management have negative costs (meaning the strategy would save money). The remaining measures have a wide range of costs. Investments in walking, biking and smart mobility cost less than $70 per MT CO_2e and entail small emissions reductions. According to *Carbon Free Boston*, auto trip, or congestion, pricing has a cost of $281 per MT CO_2e with a greenhouse gas reduction potential of 0.2 MT CO_2e. Investment in new transit (which includes 42 new miles of rapid bus lanes and 35 new miles of urban rail) has the highest cost and a relatively small greenhouse gas reduction potential, but provide considerable societal benefits that are difficult to monetize and therefore were not included in the MAC curve estimations.

[77] Metropolitan Area Planning Council (MAPC). 2017. *Metro Mayors Climate Mitigation Commitment*. Available online: http://www.mapc.org/wp-content/uploads/2017/09/FINAL-Metropolitan-Mayors-Climate-Mitigation-Commitment.pdf.
[78] Boston GRC and Boston University ISE. 2019. *Carbon Free Boston Summary Report.*

Figure 5. Carbon Free Boston Summary Report MAC curve for transportation



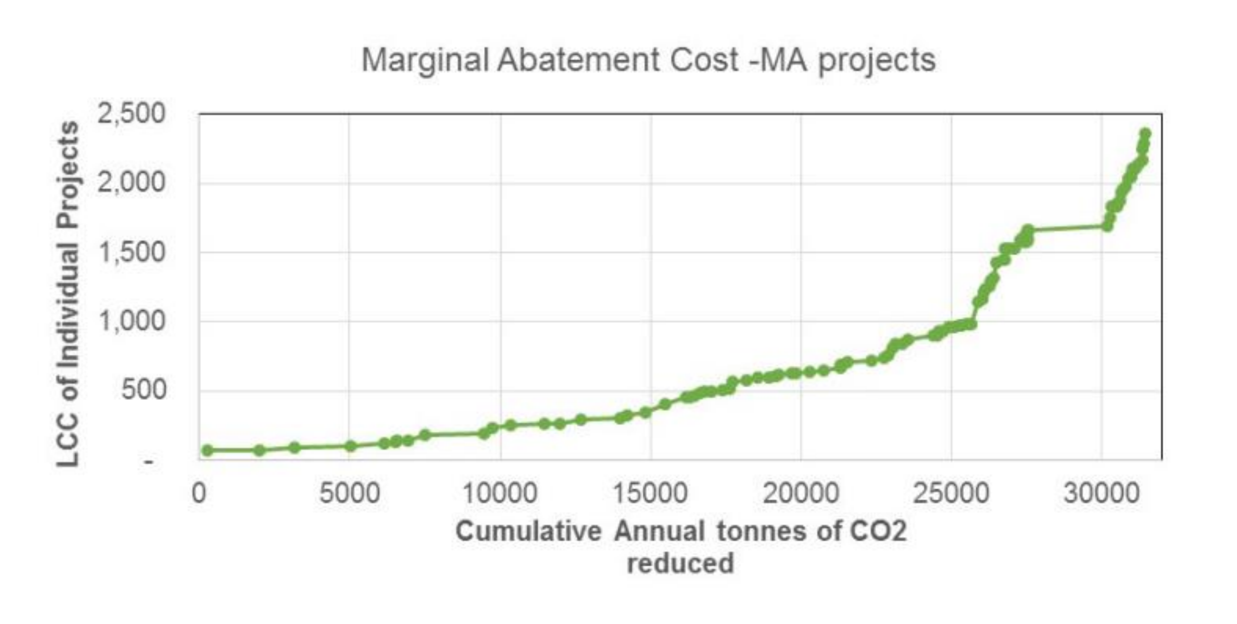
Source: Reproduced from Carbon Free Boston Summary Report, Figure 29, page 65. Note that the cost estimates do not include a full accounting of societal benefits.

Historical abatement measures

In 2017, a study to develop a metric for the cost of greenhouse gas abatement was undertaken as part of the MassDOT Research Program. Unlike most MAC analyses, the MassDOT study looked backwards in time (rather than forwards), analyzing almost 300 small-scale transportation projects that have been implemented throughout the Commonwealth in recent years (see Figure 6). It is important to note that the MAC for each project did not consider societal benefits beyond emissions reductions—each project's MAC was calculated by dividing the annual project costs by the annual emissions reduction.[79] In contrast to small-scale historical studies like this one, our MAC curve analysis looks forward in time at statewide emission reduction measures that would help Massachusetts comply with the state's GWSA emissions reduction targets.

[79] Baker and Khatani 2017.

Figure 6. Historical marginal abatement cost of Massachusetts transportation projects



Source: Reproduced from Baker and Khatani 2017. Figure 4.1.

In this study, researchers at the University of Massachusetts-Amherst found ten projects with marginal abatement costs of less than $200 per ton of CO_2e, which, taken together, saved 9,451 tons of CO_2e per year (see Table 2). All but two of these projects were traffic operational improvement projects. This result demonstrates the cost-effectiveness of small-scale transportation projects and—by extension—the potential for even greater cost savings if projects like these took place more widely and/or more comprehensively across the Commonwealth.

Table 2. List of Massachusetts transportation projects with MAC less than $200/tCO$_2$e

Project Title	Category	Total Project Cost ($)	Emissions Reduction (tonnes/yr)	Reported Cost Effectiveness ($/tCO$_2$)	LCC ($/tCO$_2$)
Oak Bluffs	Traffic Operations Projects	412,370	263	34	73
West Bridgewater	Traffic Operations Projects	2,805,960	1745	35	75
Northampton	Traffic Operations Projects	2,106,590	1140	41	86
Avon	Traffic Operations Projects	3,888,000	1886	45	96
Worcester	Traffic Operations Projects	2,902,792	1116	57	121
Easton Signalization & Geometric Improvements	Traffic Operations Projects	1,044,228	359	64	135
Cape Bike Shuttle	Transit	87,610	68	**118**	**137**
Easton Intersection Improvements	Traffic Operations Projects	1,062,986	359	65	138
Brockton	Traffic Operations Projects	2,160,432	556	86	181
Boylston Street	Complete Street Projects	8,214,319	1959	92	195

Source: Reproduced from Baker and Khatani 2017. Table 4.2.

Heavy-duty transportation

A 2017 study of the transition to zero-emission heavy-duty vehicles found that electric heavy-duty vehicles would cost about a quarter less than diesel vehicles in 2030.[80] The performance of diesel and electric heavy-duty vehicles may also be similar; the performance of Mercedes' Urban eTruck, for

[80] Moultak, M., Lutsey, N., and Hall, D. 2017. *Transitioning to Zero-Emission Heavy-Duty Freight Vehicles*. The International Council on Clean Transportation. Available online: https://www.theicct.org/sites/default/files/publications/Zero-emission-freight-trucks_ICCT-white-paper_26092017_vF.pdf.

example, is comparable to that of a similar size diesel truck.[81] Consumers may have cost-savings passed on to them from the transition to electric heavy-duty vehicles, as companies save because of the lower relative cost of electricity compared to gasoline; in 2016, Navidi et al. found that electrifying California's I-5 highway could save $598 million annually.[82]

Despite the similar cost and performance of electric and diesel trucks, installing new energy infrastructure for electric vehicles would be a large expense. A 2018 study found that the global fixed capital cost of 100 percent renewable medium and heavy-duty trucks would be around $9.4 trillion.[83]

The current recommendation for electrification of heavy-duty transport (i.e. large trucks) is to install overhead wires or underground energy delivery. Underground wireless power transfer (WPT) systems have more versatile charging capabilities and require less maintenance than catenary (overhead wire) systems but are much costlier to implement and sustain greater energy losses.[84] Because of the scale of inter-state commerce, however, it would not be practical for Massachusetts to adopt either charging system for heavy-duty transport unless there were a regional or national network.

Dynamic charging—charging while moving along a lane equipped with a WPT system—can reduce the cost of WPT systems by reducing the size the of battery pack. Other options for wireless charging include stationary charging, where the vehicle is parked, and opportunity charging, where the vehicle is stopped temporarily. [85]

TCI "cap-and-invest" program

The Transportation and Climate Initiative (TCI) is a regional coalition of twelve Northeast and Mid-Atlantic states and the District of Columbia working towards reducing carbon emissions from the transportation sector. States participating in the initiative include: Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Vermont, and Virginia.[86] In December 2018, nine TCI states and the District of Columbia announced their plan to design a regional market-based approach to reduce transportation pollution by the end of 2019.

---

[81] Edelstein, S. September 26, 2016. "Mercedes' Urban eTruck Concept Fully Revealed: Bodywork is Sleek, Futuristic." Digital Trends, Cars. Available at: https://www.digitaltrends.com/cars/mercedes-benz-urban-etruck-photos/.

[82] Navidi,T., Cao. Y., and Krein, P. 2016. "Analysis of Wireless Cantenary Power Systems for Electric Vehicle Range Extension on Rural Highways." *IEEE Xplore*. Available online: https://ieeexplore.ieee.org/abstract/document/7459224.

[83] (1) Value was converted from 2016$ to 2018$ using CPI inflation rate of 1.05 (original value: $900 million); (2) Garcia-Olivares, A., Sole, J., and Osychenko, O. 2018. "Transportation in a 100% Renewable Energy System." Energy Conversion and Management, 158: 266-285. Available online: https://reader.elsevier.com/reader/sd/pii/S0196890417312050?token=2A56C813E0AB6FDBC57ACB4EE4C3BDD07B5B1158207A0CA0B444B2B837E088892253748562181BF3F2FBF92A285A1E21. Table 4.

[84] Ibid.

[85] Lukic, S., and Pantic, Z. "Cutting the Cord: Static and Dynamic Inductive Wireless Charging of Electric Vehicles." *IEEE Xplore*. Available online: https://ieeexplore.ieee.org/abstract/document/6648485/authors#authors.

[86] TCI. (n.d.) "About us." Available online: https://www.transportationandclimate.org/content/about-us.

[87] Termed a "cap-and-invest" program, the policy would cap emissions from the transportation sector and require industry to purchase emission allowances at market rates. [88] Generated funds would then be invested in clean transportation in the region. Once the policy design process is completed, participating states can decide if they want to adopt and implement the policy.[89]

TCI's potential regional cap-and-invest program would place an enforceable limit on the carbon emissions from the combustion of transportation fuels, much like the policies that currently limit pollution in the power sector (e.g. the Regional Greenhouse Gas Initiative (RGGI)). Each year, the cap would decline to meet the region's climate targets.[90] Funds generated from the program would be reinvested into clean transportation solutions (e.g. expanded public transit, electrification of transit fleets, rebates for electric vehicles and improved transportation infrastructure).[91] It is estimated that the consumer cost of the program would be about $11 per metric ton[92] of CO_2e emitted. If implemented according to schedule, the program will be operational by 2021 and providing transportation investment funds to states by 2022.[93]

In Massachusetts, the Governor's Future of Transportation Commission estimated that the program could generate $150-500 million in revenue for the state and will cost drivers in the Commonwealth about $2 per month in increased gas prices.[94] The Future of Transportation Commission report does not include in its analysis reduction to greenhouse gas emissions in response to the higher prices for gasoline and diesel motor fuels.

---

[87] (1) Our Transportation Future. n.d. "About TCI." Available online: https://www.ourtransportationfuture.org/about_tci; (2) TCI. 2018. "Nine States and D.C to Design Regional Approach to Cap Greenhouse Gas Pollution from Transportation." Available online: https://www.transportationandclimate.org/nine-states-and-dc-design-regional-approach-cap-greenhouse-gas-pollution-transportation.

[88] Metzger, A. 2019. "Baker admin taking the lead on carbon pricing effort." CommonWealth Magazine. Available online: https://commonwealthmagazine.org/environment/baker-admin-taking-the-lead-on-carbon-pricing-effort/.

[89] (1) Our Transportation Future. n.d. "About TCI." Available online: https://www.ourtransportationfuture.org/about_tci; (2) TCI. 2018. "Nine States and D.C to Design Regional Approach to Cap Greenhouse Gas Pollution from Transportation." Available online: https://www.transportationandclimate.org/nine-states-and-dc-design-regional-approach-cap-greenhouse-gas-pollution-transportation.

[90] Ibid.

[91] (1) Our Transportation Future. n.d.; (2) TCI. 2018.

[92] Value converted from cents per gallon to dollars per MT of CO2 using EPA conversion factor: 8.887×10^{-3} metric tons CO2/gallon of gasoline. Original value: 10 cents per gallon.

[93] ecoRI News. 2019. "Regional Transportation Program Cuts Emissions Through Fees." Available online: https://www.ecori.org/climate-change/2019/5/20/regional-transportation-program-cuts-emissions-through-fees.

[94] Metzger. 2019.