energyfuturesgroup.com

Marginal Abatement Cost Curves

Examining the Mitigation Potential and Cost per Tonne of Emissions Reductions of Measures in the Vermont Pathways Analysis

Prepared by:

David G. Hill, Ph.D., EFG

Elizabeth Bourguet, EFG

Taylor Binnington, Stockholm Environment Institute

Shreekar Pradhan, Ph.D., Cadmus Group

September, 2022

Energy Futures Group, Inc

PO Box 587, Hinesburg, VT 05461 – USA | 802-482-5001 | 802-329-2143 | info@energyfuturesgroup.com

Contents

About the Authors

Energy Futures Group (EFG) is a clean energy consulting firm based in Hinesburg, Vermont and with offices in Boston and New York. EFG specializes in the design, implementation and evaluation of programs and policies to promote investments in energy efficiency, renewable energy, other distributed resources, and strategic electrification. EFG staff have worked on these issues on behalf of energy regulators, other government agencies, utilities and advocacy organizations across the United States, Canada, Europe, and China.

David Hill is a Managing Consultant who joined EFG in early 2020, after 22 years of employment with VEIC. He is known nationally for his advancement of sustainable energy program design and implementation support, scenario modeling for clean energy futures, and renewable energy policy.

Liz Bourguet is a Consultant at EFG who joined EFG in 2020 after graduating from the Yale School of Forestry and Environmental Studies with a Master of Environmental Management degree and who focuses on energy policy analysis and climate change mitigation strategies.

Taylor Binnington is a Scientist with SEI's Energy Modeling Program. He develops energy systems models to evaluate low-carbon pathways and assists analytical teams from government and civil society to develop their own low-emissions analyses and strategies.

Shreekar Pradhan is a Senior Specialist in Cadmus in Sustainability and Energy practices who joined Cadmus in 2022. Dr. Pradhan is an energy and environmental economist with more than 12 years of experience in the economic analysis of energy, climate, and other public policies and his work focuses on decarbonization at different layers–corporate, city, national, and global.

Acknowledgements

The Cadmus/EFG team would like to thank members of the Vermont Climate Council, its subcommittees and task leaders, members of the public, and the private and public sector employees of numerous organizations for their contributions and concern on the topic of climate change. This report complements the work conducted by our team as Technical Consultants to the Vermont Climate Council and the adoption by the Council of Vermont's Climate Action Plan in December of 2021. Any omissions or errors in this report are the responsibility of the EFG team authors.

Acronyms and Abbreviations

ANR	Vermont Agency of Natural Resources
ASHP	Air source heat pump
CAP	Climate action plan
CO2	Carbon dioxide
CO2E	Carbon dioxide equivalent
EAN	Energy Action Network
EFG	Energy Futures Group
EVT	Efficient Vermont
EV	Electric vehicle
GHG	Greenhouse gas
GSHP	Ground source heat pump
GWSA	Vermont Global Warming Solutions Act
HPWH	Heat pump water heater
ICE	Internal combustion engine
LEAP	Low Emissions Analysis Platform
MAC	Marginal abatement cost
MMTCO2E	Million metric tonnes of carbon dioxide equivalent
NYDEC	New York State Department of Environmental Conservation
PSD	Vermont Department of Public Service
PHEV	Plug-in hybrid electric vehicle
RNG	Renewable natural gas
SCC	Social cost of carbon
SDSC	Science and Data Subcommittee
SEI	Stockholm Environment Institute
VCC	Vermont Climate Council
VMT	Vehicle miles traveled

Executive Summary

In 2020, the Vermont Legislature passed Act 153, commonly referred to as the Vermont Global Warming Solutions Act (GWSA). The GWSA establishes requirements to reduce greenhouse gas emissions by not less than 26% from 2005 levels by 2025, by not less than 40% from 1990 levels by 2030, and by not less than 80% from 1990 levels by 2050.

Energy Futures Group (EFG) and the Stockholm Environment Institute (SEI) have collaborated as part of a team led by Cadmus Group LLC (Cadmus), providing modeling and analysis in support of the development of Vermont's Initial Climate Action Plan (CAP). Under contract with the Vermont Agency of Natural Resources (ANR), our team's role has been to provide analytic support and recommendations for the Vermont Climate Council (VCC) and its sub-committees. Our team produced the Vermont Pathways Analysis Report, which included detailed scenario analyses of pathways to meet the requirements of the GWSA. The VCC adopted Vermont's Initial CAP in December of 2021.[1]

The Pathways Analysis Report and Vermont's Initial CAP clearly indicate a full suite of activity and investments across all sectors are necessary to meet the GWSA requirements. Meeting the emission reduction requirements of the GWSA requires broad and deep changes across all sectors of Vermont's energy economy. There is not a single sector, a single strategy, or even a small subset of activities that alone can meet Vermont's emission reduction requirements.

Working as part of the Cadmus led team, EFG and SEI provided scenario modeling analysis for the CAP using the Low Emissions Analysis Platform (LEAP) model. The central mitigation scenario modeled in LEAP and described in the Pathways Analysis Report is comprised of a suite of 18 measures implemented between 2020 and 2050 that demonstrate Vermont's ability to meet the requirements of the GWSA in all time periods.

This report provides additional analysis and information on the emissions abatement potential and costs for each of the "measures" that contribute to meeting the emissions reduction requirements in the central mitigation scenario.

Each measure in the scenario modeling is an aggregate, representing many individual actions. For example, the measure Internal Combustion Engine Phase Out (ICE35) represents phasing

[1] https://anr.vermont.gov/content/vermont-climate-council-adopts-vermont-climate-action-plan.

out new sales of internal combustion engines for light duty vehicles by 2035. This single "measure" therefore represents thousands of individual electric or other advanced vehicle purchase decisions within the context of a regulatory requirement to phase out sales of internal combustion engine vehicles. Similarly, all the measures in the scenario modeling are composites of many individual actions and investments. Some of the measures include a mix of investments across different sectors. For example, non-energy measures include agricultural practices and reduction of industrial process emissions.

Since the state's goal is to examine each mitigation option in the context of a future scenario that meets Vermont's GWSA targets, we have evaluated the marginal cost per tonne of greenhouse gas (GHG) emissions reductions and emissions mitigation potential. We created scenarios with and without each measure and compared the total emissions reductions and costs in the following way:

A) Create a new scenario by removing one measure (called "measure X") from the "CAP Mitigation Scenario", to create a scenario called "CAP Mitigation Scenario minus Measure X".
B) Calculate cost and mitigation potential of measure X as the difference in cost and GHG emissions between "CAP Mitigation Scenario minus Measure X" and "CAP Mitigation Scenario".

To estimate the medium-term marginal abatement cost (MAC) curve, the analysis also "freezes" further implementation of each measure after 2030, while considering their ongoing costs and emissions mitigation, and evaluating those costs and reductions against a reference portfolio "baseline" that includes all other measures. This approach provides a useful high-level means for assessing the marginal abatement contribution and costs of emissions reductions for individual mitigation options.

Since measures in the portfolio are interactive, the method we adopted to create the marginal abatement cost curves partially isolates the impact and cost for each mitigation option while capturing the potential interactions of all other measures in the remaining portfolio. For example, weatherization reduces the energy load requirements for buildings thereby reducing the size and costs for space conditioning systems, and the need for new clean electricity generation. Weatherization also decreases the use of conventional fuels and thereby reduces the emissions reduction that would be realized by implementing an alternative cleaner heating system as a separate measure. The interaction of two abatement measures may create synergies or even a conflict or do nothing such that the resulting outcome of the two measures may be more or less than the sum or equal to the sum of the two outcomes. These interactions are captured in the scenario modeling. Thus, we exclude each measure from the rest of the measures in the portfolio to avoid interaction of the excluded measure while considering all other interactions, and this way we isolate the effect of the excluded measure. To create the marginal abatement cost curve, we repeat this process for each measure, and draw the curve by ordering the measures according to their marginal cost of abatement from the lowest to highest.

The MAC curves are useful to compare all measures on equivalent terms ($/tonne of CO2e), providing information on which measures have larger potential of abatement opportunities and each measure's relative cost per tonne of abatement.

Several other points to bear in mind with relation to the marginal abatement cost curves are:

- The full portfolio of measures included in Vermont's Initial CAP are highly cost effective from a societal perspective.[2]
- The marginal abatement cost curves can be useful to help rank and prioritize actions, but not necessarily to trim the total set of activities required, as excluding individual "higher-cost" measures from the portfolio risks not meeting requirements.
- Adoption and support for "higher-cost" measures may be necessary to lower their costs in the future. Past examples of where supporting "expensive" emerging clean energy technologies have led to sharp declines in costs include wind energy, solar energy, and lighting technologies.
- No regrets actions, those with negative net costs (net cost savings), will likely require policy and/or programmatic support before they are undertaken. They are measures that are not expected to occur in the baseline, and therefore it should not be assumed that they are "givens" that will occur without further support or catalyst.

Medium-Term Marginal Abatement Cost Curve

Figure ES-1 presents the medium-term MAC curve results. The marginal cost per metric tonne for each measure is represented on the vertical axis ($/tonne CO2e), with the cost value label appearing above (net costs) or below (net cost savings) each column segment in the chart. The

[2] See Vermont Pathways Analysis Report 2.0 February 11, 2022, p. 71. The mitigation scenario results in cumulative emissions reductions of 85 MMTCO2e by 2050 in comparison to the baseline with a discounted net present value of attaining these reductions of $6.4 billion (in 2019 dollars, at a 2% discount rate).

horizontal axis (and the width of each column in the chart) represents the cumulative emissions reduction (2020-2050) for each measure's implementation through 2030. The total cumulative emissions reduction represented on the horizontal axis in Figures ES-1 is 45.5 million metric tonnes CO2e (MMTCO2e).[3]

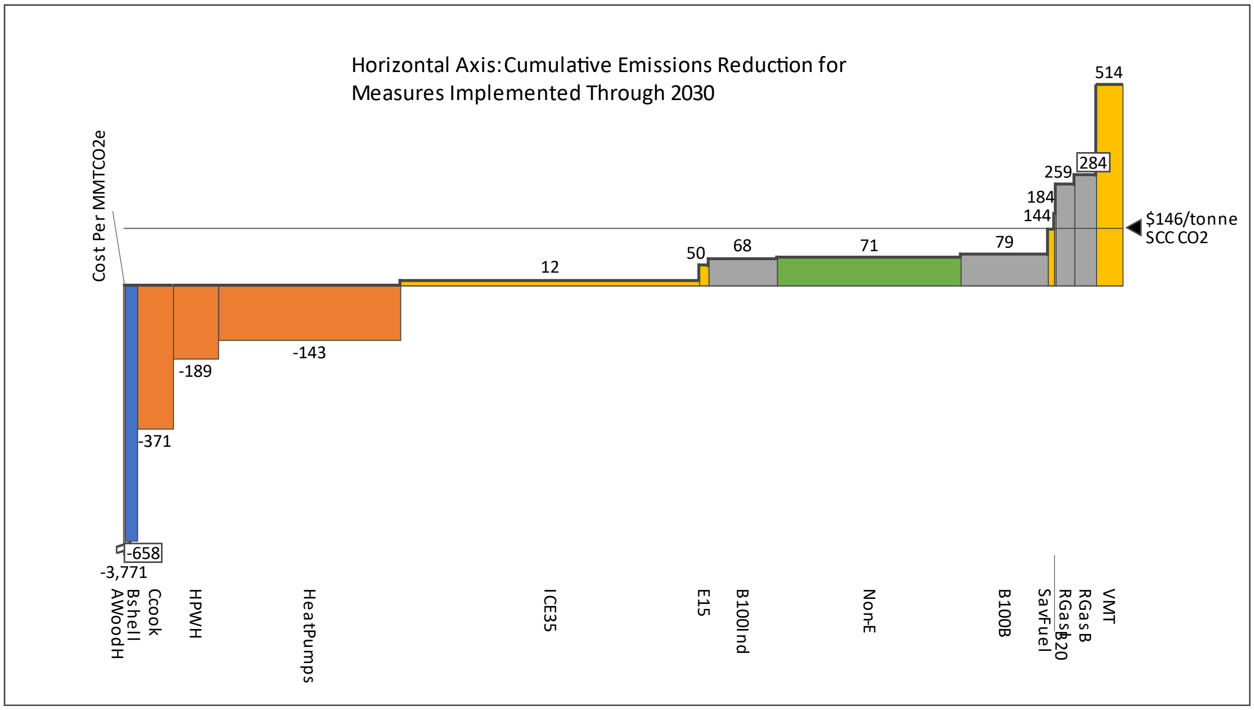


Figure ES1: MAC Curve of Measures Implemented Through 2030[4]

With respect to cost per tonne of avoided emissions, three broad measure groups are observable in Figure ES1. First are those with net negative costs (or net cost savings) on the left of the chart. Second is a group in the middle of the chart with net cost per tonne that is greater than $0 and less than the estimated social cost of carbon dioxide in 2030 of $146/tonne.[5] The

---

[3] Note that the emissions represented by the horizontal axes of the medium- and long-term MAC curves do not equal the total emissions reduction between the baseline and CAP mitigation portfolio. The latter, which does not exclude any measures, therefore has higher total cumulative emissions reductions than the horizontal axes for the medium- and long-term curves, which are constructed by excluding each individual measure from the portfolio.

[4] Appendices B and C includes tabular results for the 2030 (medium-term) and 2050 (long-term) marginal abatement cost curves presented in Figures ES-1 and ES-2.

[5] Appendix D includes estimated Social Cost of Greenhouse Gases adopted by the Vermont Climate Council. The value of $146/tonne is the levelized cost over the 2020-2050 horizon.

third group, to the right-hand side of the graph has marginal abatement costs greater than $146/tonne.

Five measures in the medium-term curve have net negative costs and therefore provide net savings. Three of these are electrification of end uses (clean cooking, heat pump water heaters, and heat pump space conditioning). The other two, advanced wood heating and building shell measures, are more expensive per tonne, and have smaller emissions reductions. In combination, these five measures with net costs savings represent 12.3 million tonnes of reduced emissions or 28% of the total cumulative reductions in the medium-term abatement curve.

There are five measures in the next group, with net costs between $0 and $146/tonne. In combination this group has the largest abatement potential, with 28.8 million tonnes of cumulative emissions reduction, representing 65% of the total medium-term abatement potential. This group includes the phase out of internal combustion engine vehicle sales by 2035, and ethanol 15% blending for gasoline, the adoption of B100 biodiesel in buildings and industry, and the non-energy measure group. When combined, the first two measure groups represent more than 92% of the emissions abatement potential.

The last group of five measures have costs greater than $146/tonne. Four of these are renewable fuels, and the fifth is reducing vehicle miles travelled through transportation demand management. These combine for 3.3 million tonnes of cumulative emissions reduction for the measure implementation through 2030, and this represents 7.5% of the medium-term abatement potential.

Long-Term Marginal Abatement Cost Curve

The long-term marginal abatement cost curve (Figure ES-2) represents impacts of measures implemented during the whole analysis period of 2020-2050. The same method of comparing the costs and emissions reductions for a scenario with each measure excluded to the costs and emissions for a full portfolio of measures was applied. Two additional measures, 100% renewable electricity by 2050 (REN100), and managed electric vehicle charging (MgEV), both of which have impacts that are largely present after 2030, were not included in the medium-term cost curve but appear in the long-term curve.

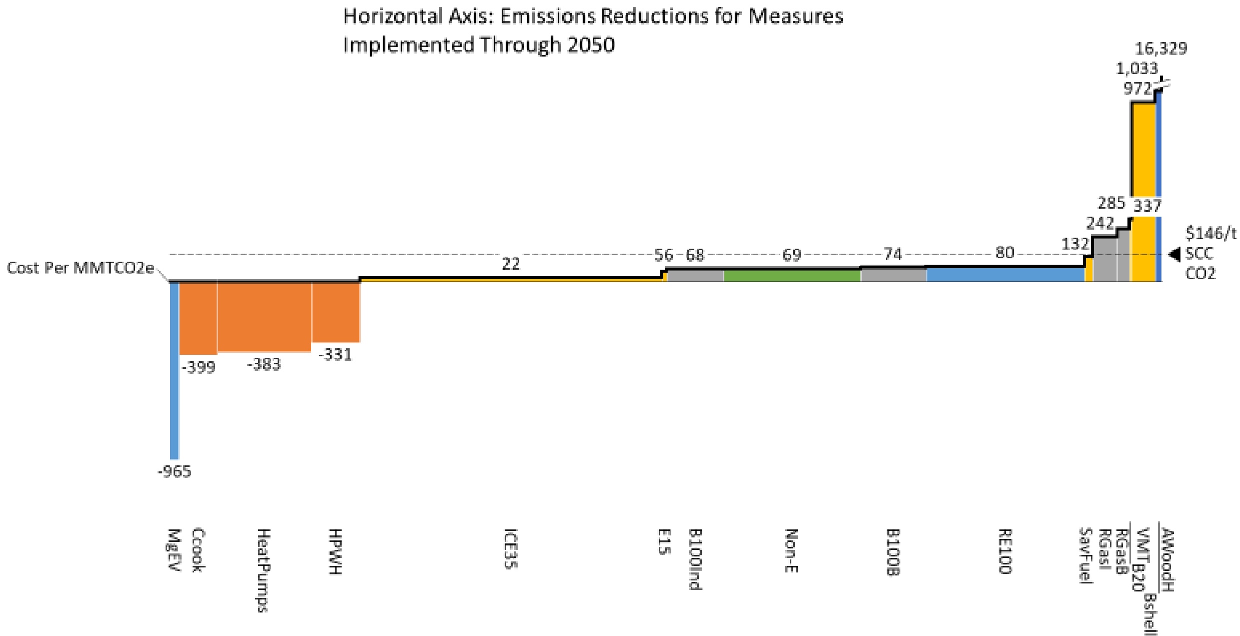


Figure ES2: MAC Curve of Measures Implemented Through 2050

With some exceptions, similar patterns to the medium-term MAC curve are observable in the long-term results. Four measures in the long-term MAC curve have negative net costs (net costs savings). Three of these are measures that electrify space conditioning, water heating and cooking. The fourth is managed electric vehicle charging. Combined these four measures account for 15.6 million tonnes of emissions reductions which is 19% of the total abatement of 81.35 million tonnes represented on the horizontal axis of the long-term MAC curve.[6]

The second group, with net costs between $0 and $146/tonne, is composed of seven measures with combined emissions reductions of 61 million tonnes, which is 74% of the total emissions reductions. Electric vehicles (ICE35), renewable electricity (RE100), and non-energy measures

[6] Note the long-term cumulative emissions reductions for the full portfolio, without any measures excluded, is higher (86.8 million metric tonnes CO2e) than the total represented by the horizontal axis of the long-term MAC curve, which is a representation of each measure's contribution calculated by comparing a portfolio with each measure excluded to the full portfolio.

(Non-E) are the three measures making the largest contributions to emissions reductions in this group.

The third group, to the right side of the chart, contains six measures with net costs greater than $146/tonne. Combined, these measures account for 5.6 million tonnes of emissions reduction, which is a relatively small (6.9%) share of the long-term abatement potential.

Two measures, advanced wood heating and building shell measures (weatherization) with net negative costs in the medium-term MAC curve, shift to the far right (most expensive) side of the long-term curve. This result occurs because over time, the fuels displaced by weatherization or advanced wood heating are increasingly non-fossil and therefore have less emissions reduction potential.

Marginal Abatement Cost Curves for Vermont's Initial Climate Action Plan

Background

In 2020, the Vermont Legislature passed Act 153, commonly referred to as the Vermont Global Warming Solutions Act (GWSA). The GWSA establishes requirements to reduce greenhouse gas emissions by not less than 26% from 2005 levels by 2025, by not less than 40% from 1990 levels by 2030, and by not less than 80% from 1990 levels by 2050. The GWSA also established the Vermont Climate Council (VCC) and directs the VCC to develop a Climate Action Plan (CAP) identifying strategies and programs to meet the GWSA requirements, with an initial plan due in December 2021, with updates due every four years. The VCC adopted Vermont's Initial CAP in 2021.[7]

Energy Futures Group (EFG) and the Stockholm Environment Institute (SEI) have collaborated as part of a team led by Cadmus Group LLC (Cadmus), providing modeling and analysis in support of the development of Vermont's Initial CAP. Our team's role has been to provide analytic support and recommendations for the VCC and its sub-committees. This report, following the VCC's adoption of Vermont's Initial CAP by nine months, provides additional analysis and details on the abatement potential and costs per tonne of emission reduction for the individual mitigation measures included in the Initial CAP. Achieving the emissions reductions dictated by the GWSA requires a complex blend of policy, regulatory, implementation, and investment activities along with adaptive management, monitoring, and revisions to the Initial CAP. Our team recognizes the ongoing, multi-decadal nature of the necessary activities, and we offer this report to help inform decision making by examining the scale and costs of individual mitigation measures included in the plan.

The team used the LEAP model to analyze alternative pathways for meeting the requirements of the GWSA. The emissions reductions by sector and time-period modeled in the mitigation scenario are illustrated in Figure 1.

[7] https://anr.vermont.gov/content/vermont-climate-council-adopts-vermont-climate-action-plan.

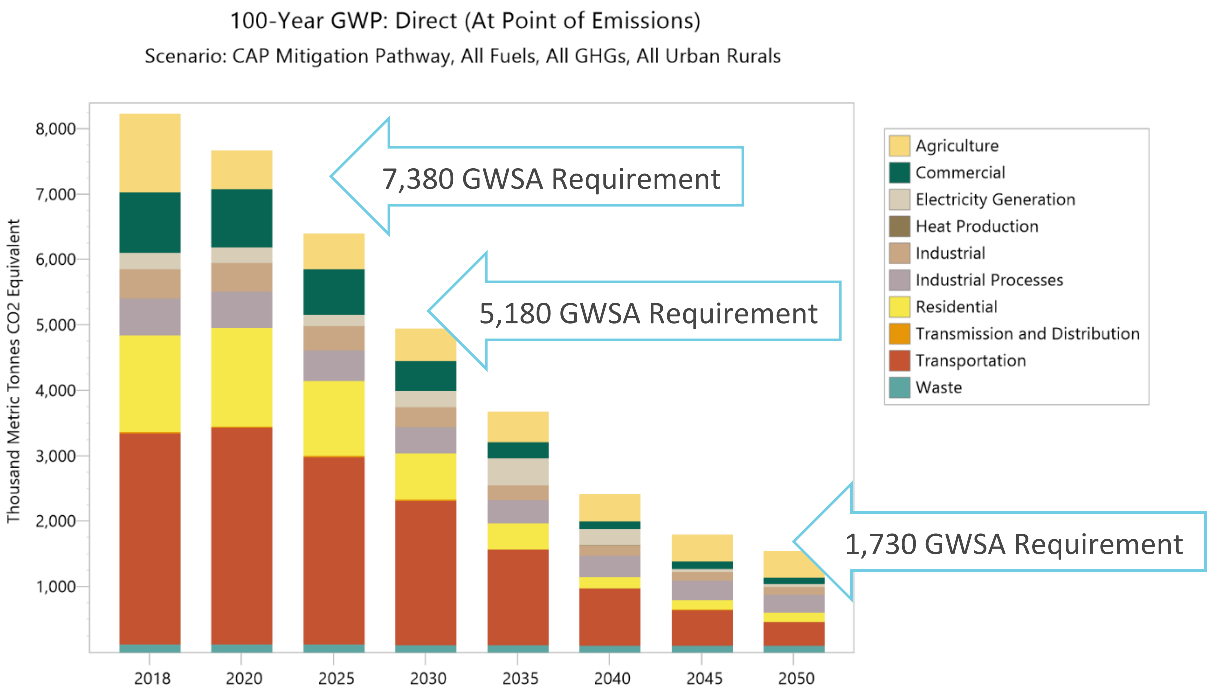


Figure 1. Mitigation Scenario Greenhouse Gas Emissions by Sector and GWSA Targets

The LEAP modeling of the mitigation scenario included 18 individual measures, each of which represents a collection of actions and investments within a particular category. The 18 measures, with their acronym, are briefly described in Table 1. Appendix A provides a more detailed description of each measure.

Table 1. Mitigation Option Measures in the Vermont CAP Analysis

Measure Name	Measure Acronym	Notes
Building Shell Improvements	BShell	Building weatherization, including the Weatherization at Scale Initiative, which weatherizes a total of 120,000 homes by 2030.
Clean Cooking	CCook	Electrification of stovetops and ovens in all buildings. All residential and commercial building cooking is shifted to electricity in 2035 in the mitigation scenario.
Heat Pump Water Heating	HPWH	Water heating needs met by heat pump water heaters (HPWH). By 2035, HPWHs meet all household and commercial water heating needs previously met by fossil fuels.
Heat Pump Residential Space Conditioning and	HeatPumps	Space heating needs are met by heat pumps. Residential and commercial heat pumps are combined in one scenario in the development of the MAC curve. By 2040 in the mitigation

		scenario, high-efficiency air- and ground-source heat pumps (ASHPs and GSHPs) supply 80% of home heating needs, except in rural single-family detached homes where heat pumps meet 70% of home heating needs by 2045. By 2040, air-source heat pumps heat 80% of commercial floorspace in the mitigation scenario.
Advanced Wood Heating	AWoodH	Advanced wood heating is comprised of high-efficiency wood or pellet stoves and advanced pellet boilers. By 2045, advanced pellet boilers replace 20% of propane and oil boilers. Residential wood or pellet stoves are 50%/80% "high-efficiency" by 2030/2050.
Commercial District Heating	CDistH	District heating is a system in which heat is provided to multiple buildings in a district from a central plant. The results from this measure are not included in the medium-term or long-term MAC curves.
Renewable Gas in Buildings	RGasB	Renewable natural gas (RNG) is biogas which comes from a range of sources and is used in place of fossil natural gas for residential and commercial buildings. 10%/20%/80% of fossil natural gas consumed for residential and commercial building uses is displaced by RNG by 2025/2030/2050, respectively.
Renewable Gas in Industry	RGasInd	Renewable natural gas (RNG) is biogas which comes from a range of sources and is used in place of fossil natural gas in the industrial sector. 10%/20%/80% of fossil natural gas consumed for industrial uses is displaced by RNG or biogas by 2025/2030/2050, respectively.
Internal Combustion Engine Phase Out	ICE35	A phase out of fossil fuel powered internal combustion engine vehicles and a shift towards electric vehicles. The mitigation scenario includes a phase out of all internal combustion engine vehicles by 2035.
E15 in Transportation	E15	Gasoline blended with 15% ethanol, a fuel produced from biomass, is used in transportation. The volume share of ethanol in gasoline in the mitigation scenario is 15% by 2040.
B100 in Buildings	B100B	B100 is pure biodiesel fuel used as building heating oil. By 2040, 100% of building heating oil is B100 in the mitigation scenario. Heating oil meets 0-10% of housing units' space heating energy needs in residential buildings in 2050, depending on the housing unit.
B100 in Industry	B100Ind	B100 is pure biodiesel fuel used in the industrial sector. By 2040, 100% of industrial diesel consumption is B100.
B20 in Transport	B20	Diesel fuel blended with 20% biodiesel used in transportation. The volume share of biodiesel in diesel in the mitigation scenario is 20% by 2050 in transportation.
VMT Reductions	VMT	A reduction in vehicle miles traveled (VMT), is a reduction in overall demand in the transportation sector. VMT across all vehicle classes and technologies is reduced 10% by 2050.
Sustainable Aviation Fuel	SavFuel	Sustainable aviation fuel is fuel produced from renewable biomass and waste resources to replace jet kerosene in air travel. Biofuels displace 50% of jet kerosene by 2050.

Renewable Electricity	REN100	The Renewable Energy Standard increases to 100% from 2032 to 2041. This measure is not included in the medium-term MAC curve because the difference from baseline occurs after 2030.
Managed EV Charging	MGEV	Managed electric vehicle (EV) charging is one load management tool that reduces demand on the electric grid during peak times. This measure is not included in the medium-term MAC curve.
Non-Energy Mitigation Options	Non-E	Non-energy mitigation options are sectors in Vermont that emit greenhouse gas emissions that are not attributed to energy use.

Approach to MAC Curve and Modeling Impacts of Individual Measures

The Vermont LEAP model includes many assumptions about the implementation costs of new mitigation measures and technologies.[8] These include capital costs, operation and maintenance, fuel costs, and other types of expenses. In the initial modeling, the capital cost for some technologies was annualized over a period of years (usually the expected lifetime of the technology), while for other measures, capital costs occur entirely during the first year that a new technology is introduced.

The MAC curve estimates are calculated using both a “long-term” time horizon and a “medium-term” time horizon. The long-term MAC curve includes costs and GHG abatement from all years in the model’s scenarios (2020-2050). The medium-term MAC curve includes costs and GHG abatement from all measures introduced from 2020-2030, as well as maintenance and fuel costs (including electric sector costs, which stand in for the cost of electricity) through the year 2050 but attributed only to those measures introduced through 2030. GHG abatement is calculated through 2050, but again only for those measures implemented through 2030. Creating the medium-term MAC curve requires a parallel set of scenarios in the Vermont LEAP model, each implementing an existing mitigation option through 2030, before holding its implementation level constant at 2030 levels thereafter.[9]

To create the medium- and long-term MAC curves SEI revised costs in the model to show non-annualized equipment costs for new measures and technologies in future years. This enables the model to generate investment cost needs for the model’s “CAP Mitigation Scenario” compared to the “Baseline Scenario”, in which no additional climate policies are put in place, for each year covered by the model. These investment costs include the full capital cost of a

[8] See Appendix A for a measure description table.

[9] For on-road vehicles, this would mean reverting to the baseline scenario’s new vehicle market share after 2030

technology the year it is introduced, rather than spreading that cost over several years. "Legacy" technologies like gas boilers (technologies that were in widespread use during the model's historical period) continue to be assigned annualized costs.[10]

Each column in the MAC curve reflects the cost per ton of GHG abatement (height of each column on the vertical axis) for reducing GHG emissions and the total mitigation potential (width of each column on the horizontal axis) for each "measure" in the model. Each measure's total cost is calculated by summing the total annual cost in each year of the analysis (2020-2030 or 2020-2050), with each year discounted to a common monetary year using a 2% discount rate. Total emissions reductions are calculated by summing the total avoided GHGs across the same years.

Both the cost and the avoided GHGs for each measure must be expressed relative to some alternative scenario that does not include that measure, and the choice of counterfactual scenario affects the resulting costs and mitigation potential. Since the state's goal is to examine each measure in the context of a future scenario that meets Vermont's GWSA targets, SEI evaluated each measure's cost-effectiveness and mitigation potential in the following way:

A) Create a new scenario by removing one measure (called "measure X") from the "CAP Mitigation Scenario", to create a scenario called "CAP Mitigation Scenario minus Measure X".
B) Calculate cost and mitigation potential of measure X as the difference in cost and GHG emissions between "CAP Mitigation Scenario minus Measure X" and "CAP Mitigation Scenario".

The sector and types of measures are indicated by colors for the individual columns.

- Building shell thermal improvements – dark blue
- Electrification for buildings (space conditioning, water heating, cooking) – orange

[10] The reason is threefold. First, the ages of these legacy devices are unknown, which means the year in which they are replaced (triggering an investment cost) is also unknown. Second, the total annual investment cost to replace retiring units within an existing established stock of devices would not be that different from the total annualized capital cost from all devices (not only those being replaced) in that year. Third, ANR and PSD have expressed interest in understanding the investment needs and timing for new technologies deployed as part of a GHG mitigation portfolio, but not the investment needs to continue purchasing "legacy" technologies.

- Transportation measures including electric vehicles, alternative fuels and transportation demand management – gold
- Renewable electricity – light blue
- Renewable gas, advanced wood heat, and non-transport biodiesel - gray
- Non-energy (agriculture, waste, and industrial processes) – green

Points to bear in mind with relation to the marginal abatement cost curves are:

- The full portfolio of measures included in Vermont's initial CAP are highly cost effective from a societal perspective.
- The marginal abatement cost curves can be useful to help rank and prioritize actions, but not necessarily to trim the total set of activities required, as excluding individual "higher-cost" measures from the portfolio risks not meeting requirements.
- Many measures are interactive with other measures in the portfolio.
- Adoption and support for "higher-cost" measures may be necessary to lower their costs in the future. Past examples of where supporting "expensive" emerging clean energy technologies have led to sharp declines in costs include wind energy, solar, lighting technologies.
- No regrets actions, those with negative net costs, will likely require policy and/or programmatic support before they are undertaken. They are measures that are not expected to occur in the baseline, and therefore it should not be assumed that negative net cost actions are a "given" that will occur without further support or catalyst.

Medium-Term Marginal Abatement Cost Curve Results

The medium-term MAC curve results are presented in Figure 2. The cost per metric tonne for each measure is represented on the vertical axis ($/tonne CO2e), with the cost value label appearing above or below each column segment in the chart. The horizontal axis (and the width of each column in the chart) represents the cumulative emissions reduction for each measure's implementation through 2030. The total cumulative emissions reduction represented in Figures 2 is 45.5 million metric tonnes CO2e (MMTCO2e).

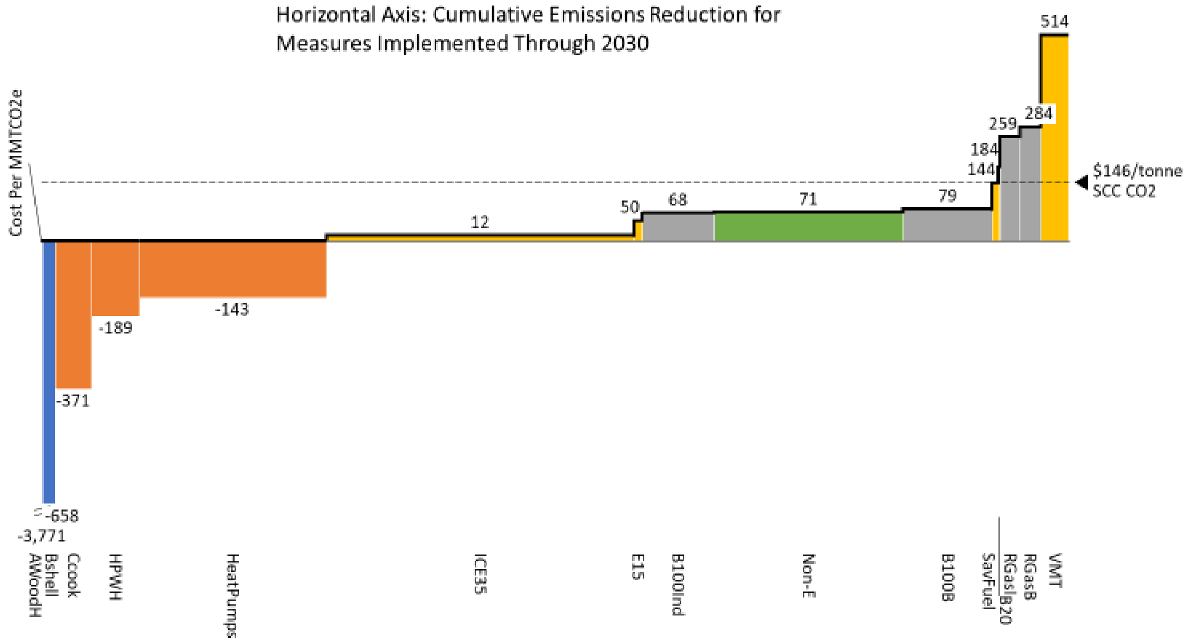


Figure 2: MAC Curve of Measures Implemented Through 2030[11]

Three measure groups are observable in Figure 2. First are those with net negative costs on the left of the chart. Second is a group in the middle of the chart with net cost per tonne greater than $0 and less than the estimated levelized social cost of carbon dioxide over 2020-2050 of $146/tonne. The third group, to the right-hand side of the graph has measure abatement costs greater than $146/tonne.

In the first group, there are five measures in the medium-term curve have net negative costs. Three of these are electrification (clean cooking, heat pump water heaters, and heat pump space conditioning). The other two, advanced wood heating and building shell measures, are more expensive per tonne, and have smaller emissions reductions. In combination, these five measures with net negative costs represent 12.3 million tonnes of reduced emissions or 28% of the total cumulative reductions in the medium-term abatement curve.

[11] Appendix A and B include tabular results for the 2030 (medium-term) and 2050 (long-term) marginal abatement cost curves presented in Figures 2 and 3.

There six measures in the second group, with net costs between $0 and $146/tonne. In combination this group has the largest abatement potential, with 29.0 million tonnes of cumulative emissions reduction, representing 65% of the total medium-term abatement potential. This group includes the phase out of internal combustion engine vehicle sales by 2035, and ethanol 15% blending for gasoline, the adoption of B100 biodiesel in buildings and industry, the non-energy measure group, and sustainable aviation fuel. When combined, the first two groups, with costs less than the social cost of carbon value of $146/tonne, represent more than 92% of the emissions abatement potential.

The last group of four measures have costs greater than $146/tonne. Three of these are renewable fuels, and the fourth is reducing vehicle miles travelled, through transportation demand management. These combine for 3.1 million tonnes of cumulative emissions reduction for the measure implementation through 2030, and this represents 6.9% of the medium-term abatement potential.

Long-term Marginal Abatement Cost Curve Results

The long-term marginal abatement cost curve (Figure 3) represents impacts of measures implemented during the whole analysis period of 2020-2050. The same method of comparing the costs and emissions reductions for a scenario with each measure excluded to the costs and emissions for a full portfolio of measures was applied. Two additional measures, 100% renewable electricity by 2050 (REN100), and managed electric vehicle charging (MgEV), both of which have impacts that are largely present after 2030, were not included in the medium-term cost curve appear in the long-term curve.

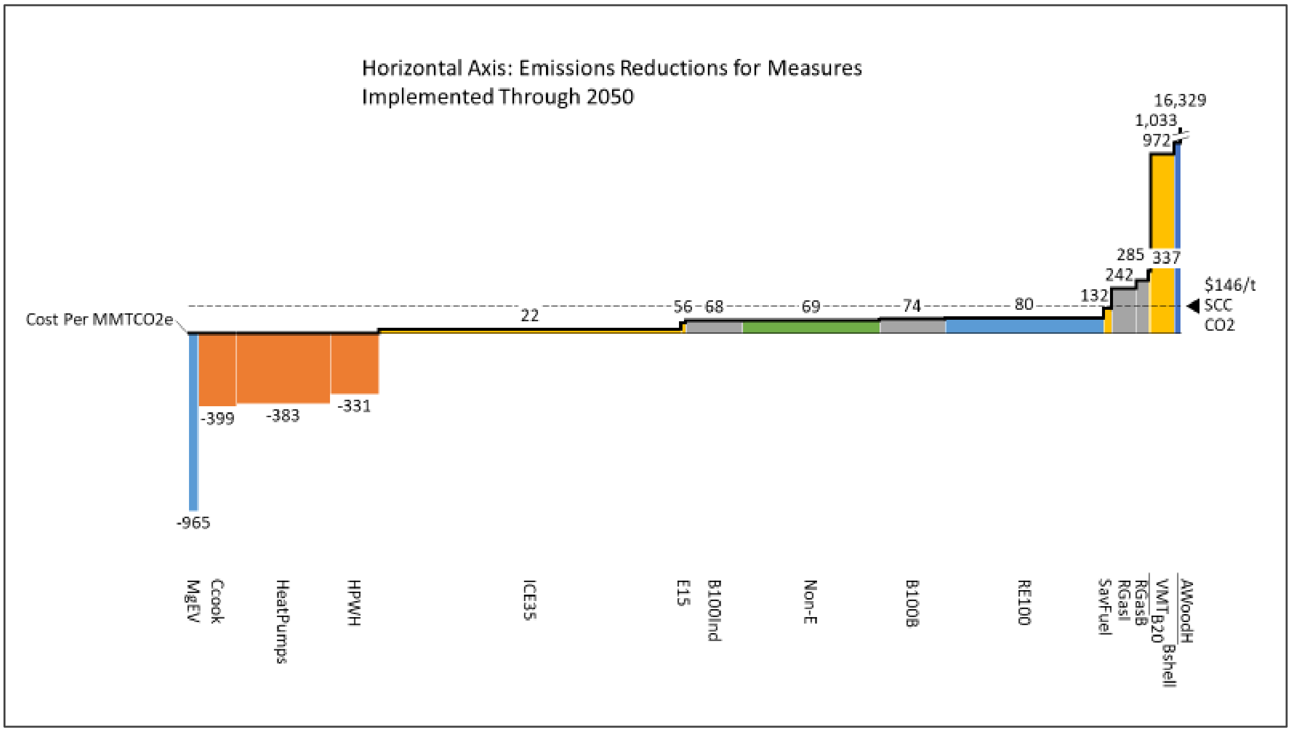


Figure 3: Long-Term MAC Curve of Measures Implemented Through 2050

With some exceptions, similar patterns to the medium-term MAC curve are observable in the long-term results. Four measures in the long-term MAC curve have negative net costs. Three of these are measures that electrify space conditioning, water heating and cooking. The fourth is managed electric vehicle charging. Combined these four measures account for 15.6 million tonnes of emissions reductions which is 19% of the total abatement of 81.35 million tonnes for the long-term MAC curve.

The second group, with net costs between $0 and $146/tonne, is composed of seven measures with combined emissions reductions of 61 million tonnes, which is 74% of the total emissions reductions. Electric vehicles (ICE35), renewable electricity (RE100), and non-energy measures (Non-E) are the three measures making the largest contributions to emissions reductions in this group.

The third group, to the right side of the chart, contains six measures with net costs greater than $146/tonne. Combined, these measures account for 5.6 million tonnes of emissions reduction, which is a relatively small (6.9%) share of the long-term abatement potential.

Two measures, advanced wood heating and building shell measures (weatherization) with net negative costs in the medium-term MAC curve, shift to the far right (most expensive) side of the long-term curve. This result occurs because over time, the fuels displaced by weatherization or advanced wood heating are increasingly non-fossil – whether clean electricity or other clean biofuels such as biodiesel or renewable gas.

Discussion and Conclusions

The medium-term (2030) and long-term (2050) MAC curve results presented in this report supplement the results of our team's previous work on the Vermont Pathways Analysis Report. These results should not be construed as representing the "cost-effectiveness" of each measure, but rather as a guide to the relative ranking for cost and mitigation potential for individual measures in an overall portfolio of measures, all of which are required to meet the GWSA requirements. Over these time horizons costs are also uncertain and could come down more rapidly or slower than anticipated based on technological advances, affecting relative placement of the measures along the curve. As reported in our earlier work, the total portfolio of measures included in the mitigation scenario provide significant economic benefits to the state, amounting to more than $6 billion dollars in present value net benefits.[12]

Neither the medium-term nor long-term MAC curves are predictions that all measures will be fully implemented. The results provide a strong indicator that it will be difficult to meet the GWSA requirements if measures or groups of measures are left out of the portfolio. The relative cost results can help inform decision making on the levels of public investment and support required to be on target to meet the GWSA requirements.

Policy, regulatory and programmatic decision-making and planning can be informed by the marginal abatement cost curves presented in this report. Additional considerations regarding equity, energy affordability and implementation logistics will also aid in determining the optimal sequencing and prioritizing investments and actions. The MAC curve results continue to underscore the overall economic benefits likely to accrue to the state from achieving the GWSA

[12] See Economic Results, Vermont Pathways Analysis 2.0, February 2021.

requirements, and that implementation of most, if not all, of the measures are required for success.

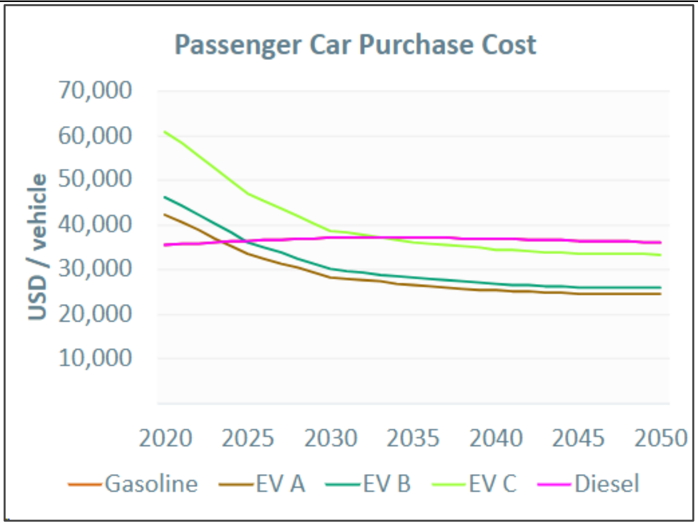
Appendices

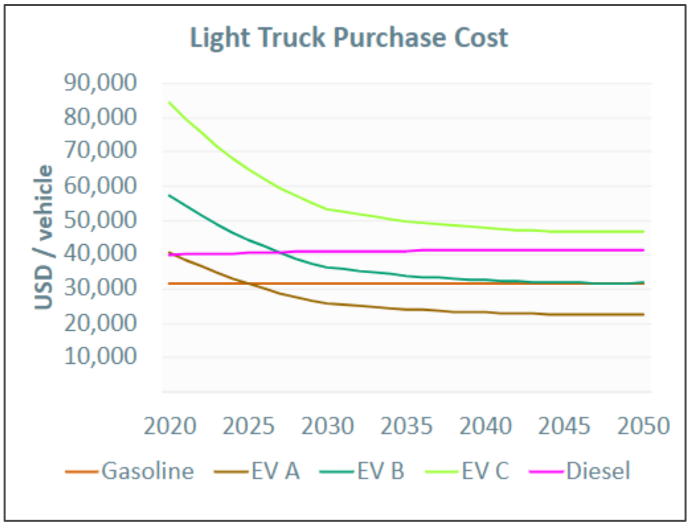
A. Measure Description Table

Mitigation Measure in CAP Mitigation Scenario	**Measure Acronym**	**Description**
Building Shell Improvements	BShell	The mitigation scenario includes the weatherization at scale initiative, which weatherizes an additional 90,000 housing residential building units by 2030 for a total of 120,000 homes weatherized by 2030. This includes 243k retrofits by 2050. Weatherization results in average useful energy savings of 20% and 38%, for single- and multi-family households respectively. Average weatherization retrofit cost $7,405/single-family household, $6,000/apartment (2-4 units), $3,000/apartment (5+ units).
Clean Cooking	CCook	Clean cooking means that stovetops and ovens have been electrified. All residential and commercial building cooking is shifted to electricity in 2035 in the mitigation scenario. Equipment cost difference between stove types assumed to be negligible; costs arise entirely from differences in fuel costs.
Heat Pump Water Heating	HPWH	Water heating needs met by heat pump water heaters shift demand away from fossil fuels. By 2035, heat pump water heating (HPWH) meet all household and commercial water heating needs previously met by fossil fuels. Residential high-efficiency HWHP installed cost of $2,475, lasting 13 years with annual maintenance of $20. Commercial HWHP serving 11,695 ft2 installed cost of $50,950, lasting 15 years with annual maintenance of $100.

Heat Pump Residential Space Conditioning and Heat Pump Commercial Space Conditioning	Heat Pump Space Heating	Space heating needs met by heat pumps shift demand away from fossil fuels. By 2040 in the mitigation scenario, high-efficiency air- and ground-source heat pumps (ASHPs and GSHPs) supply 80% of home heating needs, except in rural single-family detached homes where heat pumps meet 70% of home heating needs by 2045. By 2040, air-source heat pumps heat 80% of commercial floorspace in the mitigation scenario. Single- and two-head ASHP installed cost of \$6,100 and \$7,000 respectively, lasting 15 years with annual maintenance of \$72.5. Ducted ASHP installed cost of \$8,500, lasting 18 years with annual maintenance of \$72.5. GSHP installed cost of \$17,050, lasting 14 years with annual maintenance of \$75. Commercial heat pump serving 3000 ft^2 installed cost of \$7,550, lasting 21 years with annual maintenance of \$310.
Advanced Wood Heating	AWoodH	Advanced wood heating is comprised of high-efficiency wood or pellet stoves and advanced pellet boilers. By 2045, advanced pellet boilers replace 20% of residential and commercial propane and oil boilers. Residential wood or pellet stoves are 50%/80% “high-efficiency” by 2030/2050. Residential pellet boiler installed cost of \$20k, lasting 20 years with annual maintenance of \$250. Commercial pellet boiler installed cost of \$65k, lasting 20 years with annual maintenance of \$250, per 6900 ft2 commercial space. Ordinary residential wood/pellet stove installed cost of \$7,325/\$4,700, lasting 18 years with annual maintenance of \$198/\$260. Efficient residential wood/pellet stove installed cost of \$7,525/\$5,400, lasting 18 years with annual maintenance of \$198/\$260.
Commercial District Heating	CDistH	District heating is a system in which heat is provided to multiple buildings in a district from a central plant. In 2027, McNeil generating station captures 170,000 MMBTU/year waste heat for commercial sector use. Additional dedicated wood waste heat plants are added in 2030, 2035 and two in 2040, each producing 170,000 MMBTU/year. Heat delivered through district heating network costs \$17/MMBTU.
Renewable Gas in Buildings	RGasB	Renewable natural gas (RNG) is biogas which comes from a range of sources, including municipal solid waste landfills, digesters at wastewater treatment plants, livestock farms, food production facilities, and organic waste management operations, and is used in place of fossil natural gas (EPA). In the mitigation scenario, 10%/20%/80% of fossil natural gas consumed for residential and commercial building uses is displaced by

		RNG by 2025/2030/2050, respectively. Existing equipment assumed to operate using RNG without equipment additional cost.
Renewable Gas in Industry	RGasInd	Renewable natural gas (RNG) is biogas which comes from a range of sources, including municipal solid waste landfills, digesters at wastewater treatment plants, livestock farms, food production facilities, and organic waste management operations, and is used in place of fossil natural gas (EPA). In the mitigation scenario, 10%/20%/80% of fossil natural gas consumed for industrial uses is displaced by RNG or biogas by 2025/2030/2050, respectively. RNG costs $30/MMBTU. Existing equipment assumed to operate using RNG without equipment additional cost.
Phasing Out Internal Combustion Engines	ICE35	A phase out of fossil fuel powered internal combustion engine vehicles and a shift towards electric vehicles is a major strategy to reduce emissions in the transportation sector. The mitigation scenario includes a phase out of all internal combustion engine vehicles by 2035. Early gasoline-powered car and light truck sales shares approximately align with Advanced Clean Car II Standard. Individual technologies in each weight class are assigned separate costs.

<table>
<tr><td></td><td></td><td>


</td></tr>
<tr><td>E15 in Transport</td><td>E15</td><td>Gasoline blended with 15% ethanol, a fuel produced from biomass, is one strategy to reduce emissions from the transportation sector. The volume share of ethanol in gasoline in the mitigation scenario is 15% by 2040. Ethanol for blending costs $25.1/ MMBTU in 2019, rising to $44.9/MMBTU in 2050. Existing equipment assumed to operate using E15 without additional cost.</td></tr>
<tr><td>B20 in Transport</td><td>B20</td><td>Diesel fuel blended with 20% biodiesel, a fuel manufactured from vegetable oils, animal fats, or recycled restaurant grease (from AFDC), is one strategy to reduce emissions from transportation and buildings. The</td></tr>
</table>

		volume share of biodiesel in diesel in the mitigation scenario is 20% by 2050 in transportation.
VMT Reductions	VMT	A reduction in vehicle miles traveled (VMT), is a reduction in overall demand in the transportation sector, by reducing the need for individual vehicle trips, often through investments in public transit and land use policies. In the mitigation scenario, VMT across all vehicle classes and technologies is reduced 10% by 2050. A reduction of VMT by 10% is assumed to be achievable for $250 million/ year.
Sustainable Aviation Fuel	SavFuel	Sustainable aviation fuel is fuel produced from renewable biomass and waste resources to replace jet kerosene in air travel (EERE). In the mitigation scenario, drop-in biofuels displace 50% of jet kerosene by 2050. Drop-in aviation biofuel costs $37.3/ MMBTU. Existing aircraft assumed to operate using drop-in fuels without additional cost.
B100 in Buildings	B100B	B100 is pure biodiesel fuel. By 2040, 100% of building heating oil is B100 in the mitigation scenario. The capability to burn B100 requires upgrade cost of $1,045 per oil boiler or furnace, annualized over equipment's lifetime.
B100 in Industry	B100Ind	B100 is pure biodiesel fuel. By 2040, 100% of industrial diesel consumption isB100.
Renewable Electricity	REN100	A Renewable Energy Standard requires Vermont's distributed utilities to procure a certain percentage of their total retail electric sales from renewable energy (Vermont PUC). In the mitigation scenario, from 2032 to 2041, the Renewable Energy Standard increases to 100%, affecting the mix of capacity (MW) and energy (MWh). Existing Hydro-Quebec import contract is renewed after 2038. Cost is calculated internally within the model based on capital, operation & maintenance and fuel cost assumptions for electric generation technologies.
Managed EV Charging	MGEV	Managed electric vehicle (EV) charging is one load management tool that reduces demand on the electric grid during peak times. In the mitigation scenario, by 2040, 50% of all electric vehicles (including PHEVs) are charged slowly while plugged in, resulting in a flatter load profile. No additional costs are assumed.

Non-energy mitigation options	Non-E	Non-energy mitigation options are sectors in Vermont that emit greenhouse gas emissions that are not attributed to energy use. Non-energy mitigation options included in the mitigation scenario include emission reduction efforts in the following sectors: industrial processes; agriculture; land use, land use change and forestry (LULUCF); and waste management. Mitigation options in the agricultural sector include soil carbon sequestration, dietary changes to reduce enteric fermentation, and waste digesters to reduce emissions from manure management. Cost estimates for agricultural mitigation measures are not included.

B. Tables of Measure Cost and Abatement Potential Medium-term (2030)

Name of Scenario in LEAP	Measure Acronym	Cumulative Abatement Potential [MtCO2e] 2020-2050	Cumulative Discounted Cost [Million 2019 USD] 2020-2050	Average Cost per Metric Ton [USD/tCO2e]
Advanced Wood Heating	AWoodH	0.03	$ (124.34)	$ (3,771.68)
Renewable Electricity	RE100	-0.23	$ 443.91	n/a
Weatherization at Scale	Bshell	0.58	$ (380.80)	$ (658.44)
Fossil Cooking Phase Out	Ccook	1.57	$ (583.24)	$ (370.62)
Fossil H2O Heating Phase Out	HPWH	2.06	$ (388.16)	$ (188.79)
Heat Pump Space Heating	HeatPumps	8.10	$ (1,154.81)	$ (142.64)
ICE Sales_Phase Out	ICE35	13.31	$ 164.32	$ 12.34
E15 Ethanol	E15	0.36	$ 18.02	$ 50.04
B100 Industry	B100Ind	3.09	$ 210.55	$ 68.21
Non Energy Measures	Non-E	8.19	$ 578.69	$ 70.69
B100 Heating	B100B	3.86	$ 304.21	$ 78.84
Sustainable Aviation Fuel	SavFuel	0.26	$ 38.00	$ 144.17
B20 Biodiesel	B20	0.09	$ 16.32	$ 183.73
Renewable Industrial Gas	RGasI	0.85	$ 220.39	$ 258.95
Biogas	RGasB	0.92	$ 260.88	$ 283.94
District Heating	CDistH	-0.99	$ (362.02)	n/a
VMT Reductions	VMT	1.21	$ 620.48	$ 513.75
Managed EV Charging	MgEV	-0.16	$ (747.61)	n/a

Name of Scenario in LEAP	Measure Acronym and Category	Cumulative Abatement Potential [MtCO2e] 2020-2050	Cumulative Discounted Cost [Million 2019 USD] 2020-2050	Average Cost per Metric Ton [USD/tCO2e]
Advanced Wood Heating	AWoodH	0.03	$ (124.34)	$ (3,771.68)
Weatherization at Scale	Bshell	0.58	$ (380.80)	$ (658.44)
Fossil Cooking Phase Out	Ccook	1.57	$ (583.24)	$ (370.62)
Fossil H2O Heating Phase Out	HPWH	2.06	$ (388.16)	$ (188.79)
Heat Pump Space Heating	HeatPumps	8.10	$ (1,154.81)	$ (142.64)
ICE Sales_Phase Out	ICE35	13.31	$ 164.32	$ 12.34
E15 Ethanol	E15	0.36	$ 18.02	$ 50.04
B100 Industry	B100Ind	3.09	$ 210.55	$ 68.21
Non Energy Measures	Non-E	8.19	$ 578.69	$ 70.69
B100 Heating	B100B	3.86	$ 304.21	$ 78.84
Sustainable Aviation Fuel	SavFuel	0.26	$ 38.00	$ 144.17
B20 Biodiesel	B20	0.09	$ 16.32	$ 183.73
Renewable Industrial Gas	RGasI	0.85	$ 220.39	$ 258.95
Biogas	RGasB	0.92	$ 260.88	$ 283.94
VMT Reductions	VMT	1.21	$ 620.48	$ 513.75

C. Tables of Measure and Cost Abatement Potential Long-term (2050)

Name of Scenario in LEAP	Measure Acronym	Cumulative Abatement Potential [MtCO2e] 2020-2050	Cumulative Discounted Cost [Million 2019 USD] 2020-2050	Average Cost per Metric Ton [USD/tCO2e]
Managed EV Charging	MgEV	0.81	$ (779.49)	$ (965.96)
Fossil Cooking Phase Out	Ccook	3.11	$ (1,241.67)	$ (398.98)
Heat Pump Space Heating	HeatPumps	7.69	$ (2,949.23)	$ (383.40)
Fossil H2O Heating Phase Out	HPWH	4.05	$ (1,340.95)	$ (330.96)
District Heating	CDistH	-0.36	$ 53.21	n/a
ICE Sales_Phase Out	ICE35	24.69	$ 539.97	$ 21.87
E15 Ethanol	E15	0.46	$ 25.68	$ 56.26
B100 Industry	B100Ind	4.65	$ 314.92	$ 67.68
Non Energy Measures	Non-E	11.18	$ 775.65	$ 69.39
B100 Heating	B100B	5.41	$ 402.10	$ 74.30
Renewable Electricity	RE100	13.01	$ 1,041.03	$ 80.01
Sustainable Aviation Fuel	SavFuel	0.66	$ 87.00	$ 132.24
Renewable Industrial Gas	RGasI	1.99	$ 481.39	$ 242.26
Biogas	RGasB	1.02	$ 291.06	$ 285.26
B20 Biodiesel	B20	0.17	$ 56.61	$ 336.86
VMT Reductions	VMT	1.89	$ 1,838.00	$ 972.32
Weatherization at Scale	Bshell	0.55	$ 571.48	$ 1,033.99
Advanced Wood Heating	AWoodH	0.01	$ 106.92	$ 16,329.93

Name of Scenario in LEAP	Measure Acronym and Category	Cumulative Abatement Potential [MtCO2e] 2020-2050	Cumulative Discounted Cost [Million 2019 USD] 2020-2050	Average Cost per Metric Ton [USD/tCO2e]	Share of reduction	Weighted Average cost
Managed EV Charging	MgEV	0.81	$ (779.49)	$ (965.96)	0.99%	$ (9.58)
Fossil Cooking Phase Out	Ccook	3.11	$ (1,241.67)	$ (398.98)	3.83%	$ (15.26)
Heat Pump Space Heating	HeatPumps	7.69	$ (2,949.23)	$ (383.40)	9.46%	$ (36.25)
Fossil H2O Heating Phase Out	HPWH	4.05	$ (1,340.95)	$ (330.96)	4.98%	$ (16.48)
ICE Sales_Phase Out	ICE35	24.69	$ 539.97	$ 21.87	30.36%	$ 6.64
E15 Ethanol	E15	0.46	$ 25.68	$ 56.26	0.56%	$ 0.32
B100 Industry	B100Ind	4.65	$ 314.92	$ 67.68	5.72%	$ 3.87
Non Energy Measures	Non-E	11.18	$ 775.65	$ 69.39	13.74%	$ 9.53
B100 Heating	B100B	5.41	$ 402.10	$ 74.30	6.65%	$ 4.94
Renewable Electricity	RE100	13.01	$ 1,041.03	$ 80.01	15.99%	$ 12.80
Sustainable Aviation Fuel	SavFuel	0.66	$ 87.00	$ 132.24	0.81%	$ 1.07
Renewable Industrial Gas	RGasI	1.99	$ 481.39	$ 242.26	2.44%	$ 5.92
Biogas	RGasB	1.02	$ 291.06	$ 285.26	1.25%	$ 3.58
B20 Biodiesel	B20	0.17	$ 56.61	$ 336.86	0.21%	$ 0.70
VMT Reductions	VMT	1.89	$ 1,838.00	$ 972.32	2.32%	$ 22.59
Weatherization at Scale	Bshell	0.55	$ 571.48	$ 1,033.99	0.68%	$ 7.02
Advanced Wood Heating	AWoodH	0.01	$ 106.92	$ 16,329.93	0.01%	$ 1.31

D. New York Department of Environmental Conservation Social Cost of GHG Estimates

U.S Social Cost of Carbon Dioxide by Discount Rate, Adjusted for New York State (2020$ per metric ton of CO2)

	Recommended Range of Discount Rates			
Emissions Year	3% Average	2% Average (Central Rate)	1% Average	0% Average
2020	51	121	406	2,130
2021	52	123	409	2,125
2022	53	124	411	2,119
2023	54	126	414	2,114
2024	55	128	416	2,108
2025	56	129	418	2,103
2026	57	131	421	2,098
2027	59	132	423	2,093
2028	60	134	426	2,088
2029	61	136	428	2,083
2030	62	137	430	2,077
2031	63	139	433	2,072
2032	64	141	435	2,067
2033	65	142	437	2,061
2034	66	144	440	2,056
2035	67	146	442	2,050
2036	69	147	444	2,045
2037	70	149	446	2,040
2038	71	151	449	2,035
2039	72	152	451	2,030
2040	73	154	453	2,024
2041	74	156	456	2,020
2042	75	158	459	2,015
2043	77	160	461	2,011
2044	78	162	464	2,006
2045	79	164	467	2,002
2046	80	166	469	1,995
2047	81	167	471	1,989
2048	82	169	472	1,983
2049	84	170	474	1,976
2050	85	172	476	1,970

See DEC (2020) "Establishing a Value of Carbon"

Source: *Appendix: Value of Carbon,* New York Department of Environmental Conservation, revised June 2021. https://www.dec.ny.gov/docs/administration_pdf/vocapprev.pdf.