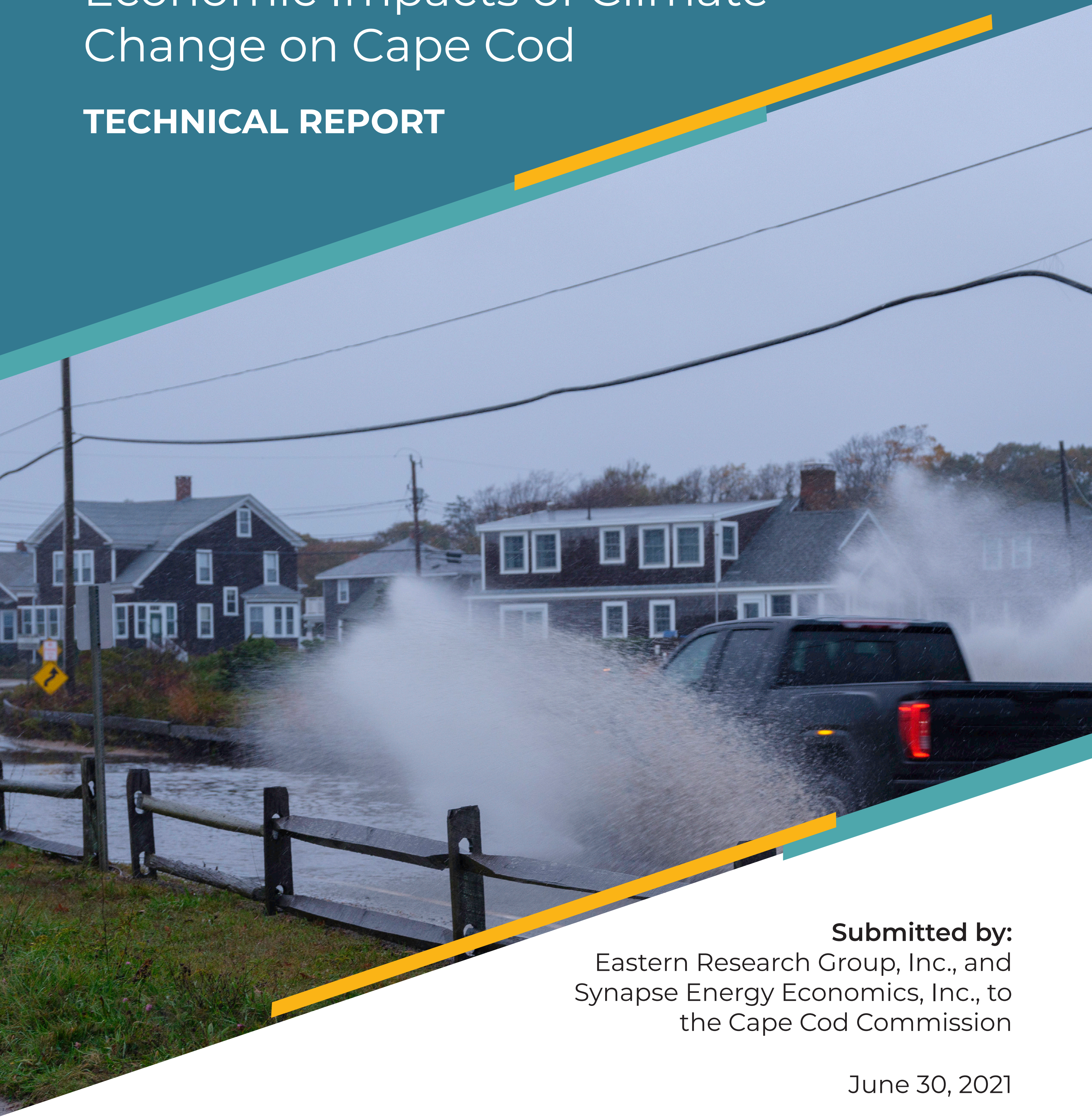
Economic Impacts of Climate Change on Cape Cod

TECHNICAL REPORT



Submitted by:
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the Cape Cod Commission

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Introduction

This report summarizes work by Eastern Research Group, Inc. (ERG), and Synapse Energy Economics, Inc., to inform the Cape Cod Commission as it develops the Cape Cod Climate Action Plan and potentially proposes amendments to the Regional Policy Plan by putting climate risks—and options to address those risks—into a monetary context. Climate change and continued reliance on fossil fuels will affect all sectors of Cape Cod's economy. Sea level rise (SLR) will increase instances of flooding and damage to coastal property and infrastructure. Warming ocean temperatures will alter fisheries and encourage harmful algal blooms. Burning of fossil fuels will continue to emit pollutants with adverse effects on public health. In response, we have assessed the impacts climate change may have on the region's economy, revenues, and investment decisions, evaluating the costs and benefits of key strategies to address climate change in the region.

This assessment is presented in three parts, which collectively make the case that without action on climate change, the impacts to Cape Cod's economy, communities, and resources will be severe. Each part is briefly described here and then detailed in subsequent sections of the report:

- **Part 1, Cost of Doing Nothing Analysis,** estimates losses that Cape Cod and its residents could incur without action to prevent or prepare for climate change. The cost of not adapting to a changing climate is large and will accelerate over time, with SLR and coastal flooding serving as the largest overall threats.
- **Part 2, Mitigation Scenarios and Scenario Metrics,** provides an energy use and emissions baseline based on current state and regional policies, as well as an assessment of four primary paths forward (or scenarios) for meeting the Cape's greenhouse gas (GHG) reduction goals (and key sectors for targeted mitigation) while continuing to meet energy needs. This analysis identifies key metrics to track the mitigation scenarios.
- **Part 3, Economic Analyses of Adaptation and Mitigation Strategies,** provides context for key strategies identified through the Cape Cod Climate Action Plan stakeholder engagement and planning process. We have provided costs and benefits or cost-effectiveness values for strategies to the extent possible.

Part 1. Cost of Doing Nothing Analysis

The "cost of doing nothing" refers to the estimated losses that Cape Cod and its residents could incur if the region does not adapt to climate change and make its own contributions to reducing GHG emissions. We primarily determined this cost based on damage incurred as a result of climate-related hazards, but we also included carbon sequestration losses associated with potential climate hazards.

This cost of doing nothing analysis serves several purposes. First, it helps the Commission set an economic baseline of the costs that the Cape Cod region could incur if it does not undertake adaptation or mitigation action. These are costs that can be avoided and can therefore be weighed against the costs of acting (implementing strategies developed by the Commission and regional stakeholders). Second, this analysis defines the benefits of adaptation and mitigation actions to provide perspective on those actions that have the greatest chance of reducing damages from climate change (i.e., actions with the greatest potential benefit). Thus, these cost of doing nothing estimates complement Part 3 of this report, which focuses on the costs and benefits and cost-effectiveness of various adaptation and mitigation strategies. Costs and benefit-cost information can support not only prioritizing, but also refining strategies—for example, identifying how and when density considerations may make it favorable to protect versus relocate housing.

Key Terms

Vulnerability: Degree to which climate change could reduce a value, identified by the colocation of a hazard and potential loss.

Loss: The actual reduction in value.

Hazard: The driving force that creates the reduction.

Exposure: The probability that the reduction will occur under any climate scenario.

Costs should not be the sole deciding factor in prioritizing mitigation and adaptation strategies but can provide an important perspective, along with considerations of equity in how different groups will share the risks and burdens related to climate change. It is important to keep in mind the limitations of each cost we evaluated, as this report focuses on those that are readily quantifiable.

To estimate the cost of doing nothing, we used geospatial analysis to determine the extent to which an economic layer (e.g., the value of housing, the value of ecosystems, number of jobs) is exposed to future climate impacts (e.g., SLR, storm surge). Where feasible, we incorporated the extent of damage (e.g., a depth-damage curve that considers how the depth of flooding is tied to damage, in addition to the extent of flooding), which allowed us to move from calculating the exposed value to a damage or loss. Where possible, we incorporated the probability of the hazard to move from the damage associated with an event to an expected annual loss over time, allowing us to better account for benefits and costs. To quantify the cost of lost carbon sequestration under the "do nothing" scenario, we used the social cost of carbon (SCC) approach (Interagency Working Group on Social Cost of Carbon, 2010).

Social Cost of Carbon

In juxtaposition to the price of purchasing carbon credits on the market, the social cost of carbon is a more accurate depiction of the cost to society. The social cost attempts to capture the impacts associated with releasing an additional metric ton of CO_2 into the atmosphere in terms of agricultural productivity, changes in energy costs, human health, and damages from increased flooding.

The analysis that follows is organized by climate hazard:

- Coastal hazards and SLR
- Severe precipitation events
- Cross-cutting climate hazards and impacts to industry
- Cross-cutting climate hazards and public health impacts

Coastal Hazards and Sea Level Rise

Our analysis applies the latest SLR projections for the state of Massachusetts (localized to the Cape Cod region) (Massachusetts Executive Office of Energy and Environmental Affairs, 2020) as shown in Table 1. The Resilient MA Action Team, an interagency steering committee responsible for implementation, monitoring, and maintenance of the State Hazard Mitigation and Climate Adaptation Plan, is applying these projections in its development of models and planning guidance. The Team selected a sea level rise scenario corresponding to the high emissions representative concentration pathway (RCP) 8.5 (Massachusetts Executive Office of Energy and Environmental Affairs, 2020).[1] We have selected the same scenario in this Cape Cod assessment. To identify projections specifically for the Cape Cod region, we used the average mean sea level predictions in the north and south of Massachusetts (as Cape Cod serves as the north-south dividing line in the modeling).

Throughout the geospatial analysis, we aligned the SLR projections (readily available for the decades bolded in Table 1) with the Cape Cod Commission's existing SLR inundation maps (produced in 1-foot increments above mean higher high water [MHHW][2] up to 6 feet as shown in the table's last column). To align the maps and the time-linked SLR projections, we converted the Commission's inundation maps to the North American Vertical Datum of 1988 (NAVD88) to match the water levels with the appropriate year of occurrence after running a regression model to interpolate the SLR level during the intervening (non-bolded) years. Table 1 shows the alignment between the SLR projections from the state (DeConto and Kopp, 2017) (gray columns) and the SLR inundation mapping from the Cape Cod Commission (white column).

Table 1. SLR projections for Cape Cod

Year of Occurrence	SLR (ft NAVD88)*	Cape Cod Commission SLR Map (ft above MHHW)**
2030	**1.20**	NA
2040	1.84	1
2050	**2.45**	NA
2054	2.84	2
2066	3.84	3
2070	**4.25**	NA
2076	4.84	4
2085	5.84	5
2093	6.84	6
2100	**7.70**	NA

* Relative to NAVD88; years outside of 2030, 2050, 2070, and 2100 were interpolated.

** Relative to MHHW (from Cape Cod Commission SLR inundation layers); these are six layers the Commission developed and used in prior work. We applied them in our analysis for consistency after mapping to an approximate year.

[1] An RCP greenhouse gas concentration trajectory adopted by the Intergovernmental Panel on Climate Change to describe different climate futures. RCP 8.5 is a high emissions future with very limited adoption of renewables.

[2] The average of the higher high tide of each tidal day observed over a 19-year period adopted by the National Ocean Service to obtain mean values for tidal datums.

Our analysis and modeling of projected SLR and storm damages consistently uses these state projections, focusing on impacts in the year 2030, 2050, and 2100 to the extent possible. For analyses that use the Commission's SLR inundation layers, we were unable to specifically focus on 2030, 2050, and 2100 (as the 1-foot increments do not exactly align) and instead focused on the closest year of occurrence, as shown on Table 1. The only flood-related analysis that did not use the Commission's SLR inundation layers was the estimate of damage to buildings from SLR and storm surge, for which we used the flood model within the Coastal Adaptation to Sea Level Rise Tool (COAST) to estimate the impacts.

Sea level rise and storm surge impacts to properties

Barnstable County has 560 miles of coastline, much of which contains residential, commercial, and public properties. Rising sea levels pose a threat to many of these properties in the next 80 years. Without adaptations in place, many properties could be lost to permanent flooding and many more could be exposed to storm surge damage. We analyzed the impact of SLR and storm surge on properties to estimate the value of this potential loss.

METHODS

We followed the method for monetizing impacts from coastal flooding and SLR established by NOAA in "What Will Adaptation Cost" (NOAA, 2013) for damages associated with certain levels of SLR and storm surge. We then supplemented the approach by creating 10,000 simulations to estimate the range or distribution in annual damages over time. Our specific process was as follows:

Single year damages: We used COAST (Blue Marble Geographics, 2020) to measure the impacts of SLR and storm tides on buildings in Barnstable County at several points between 2020 and 2100. The software uses two layers of data; an elevation map of the study area, typically from light detection and ranging (LiDAR) data; and an asset layer that includes building values in the study area. We also used SLR projections from the state (DeConto and Kopp, 2017) between 2020 and 2100 and storm tides from various return periods (one-year storm to 200-year storm).[3] Finally, we included a depth damage function (DDF) that estimates the percent damage to buildings based on relative water level from SLR and storm tides combined.

The COAST software models SLR and individual storms at different points in time, estimating the water level and measuring the damage to buildings based on the asset layer and the DDF. COAST estimates damage by combining SLR and storm tide but calculates damages from each risk differently—SLR damage is based on the total value of any building that is flooded while storm tide damage is based off the DDF.

Annual damage model: We used the damage results from the COAST model along with the SLR and storm tide data that we input into COAST to create a model of total storm damage between the years 2021 and 2100 based on one annual storm per year. We modeled a single

[3] The average number of years between storms of a certain size is the recurrence interval or return period (based on historical records and statistical techniques). The actual number of years between storms of any given size varies significantly because of the naturally changing climate.

storm per year based on the probabilities of various return periods and their associated storm tides, then added these values to the SLR to get the combined flood values for that year. To calculate damages each year, we took the damage from the total water level and subtracted the SLR damages from the previous year, because once SLR floods reaches a building, the owner is unlikely to rebuild, such that the area should not have additional damages associated with it. Conversely, with storm damage, the owner will often repair and have the potential for damage in the following years. We ran 10,000 simulations between 2021 and 2100 with a static SLR and a dynamic annual storm model; while we used the exact same SLR scenario, the storms were random and based only on their associated probabilities.

DATA

Single year damages: The Cape Cod Commission provided parcel-layer data that contained building values for commercial, residential, and public properties in Barnstable County. Table 2 shows SLR projections for the years 2030, 2050, 2070, and 2100 (latest projections from the state of Massachusetts). To run COAST, we performed a polynomial regression for these values and found a projected SLR of 0.717 feet NAVD88 for the year 2020. Table 3 shows return periods, storm tide values, and their associated probabilities taken from the U.S. Army Corps of Engineers (USACE) Sea-Level Curve Calculator (Version 2019.21) for the Woods Hole station. The LiDAR elevation data was taken from the U.S. Geological Survey (Andrews et al., 2018). We calculated the DDF by taking the average of the depth damage curves for all single-family residence types originally calculated by USACE (United States Army Corps of Engineers, 2003), which are shown in Table 4. We measured water levels relative to NAVD88.

Table 2. SLR projections by year

Year	SLR* (ft)
2030	1.20
2050	2.45
2070	4.25
2100	7.70

* Relative to NAVD88.

Table 3. Return periods with associated storm surge and probabilities

Return Period	Storm Surge* (ft)	Probability
1-year storm	2.26	1
5-year storm	3.89	0.2
10-year storm	4.51	0.1
20-year storm	5.22	0.05
50-year storm	6.34	0.02
100-year storm	7.37	0.01
200-year storm	8.50	0.005

* Relative to NAVD88.

Table 4. Depth damage function

Depth* (ft)	Damage Proportion
-2	0.0573
-1	0.099
0	0.153
1	0.209
2	0.2663
3	0.3243
4	0.3817
5	0.4377
6	0.4917
7	0.5425
8	0.5893
9	0.6318
10	0.6687
11	0.699
12	0.723
13	0.7413
14	0.7548
15	0.7642
16	0.7685

* Relative to NAVD88.

Annual damage model: For this model, we used the same SLR scenario (Table 2) and storm tide values (Table 3) that we used for the COAST software inputs. We ran a polynomial regression from the SLR data to obtain a continuous curve of SLR estimates for every year between 2021 and 2100. The COAST damage estimates were then used to estimate damage for all of Barnstable County based on water level. We ran a logistic model compared to the total value of buildings in Barnstable County to get a continuous curve of water level damage.[4]

Using the same sea level and storm tide data as the countywide analysis, we ran individual logistic models for the 15 towns in Barnstable County to estimate their damage functions based on the total building value in each town.

[4] COAST does not account for buildings that may already have adaptations to SLR. It considers any building that has been flooded due to SLR to be abandoned. For instance, we found a large amount of damage in the first year (2020) compared to the following years in our COAST simulations. For the 2020 scenarios, there was over $23 million in SLR damages, while the 2030 scenarios only had an additional $5 million in damages. We suspect that this is due to a structure getting flooded that would not actually be flooded, such as piers and lighthouses. These structures are made to exist near and on water, so the area might be flooded while the buildings or structures remain undamaged. However, while these damages might not occur in 2020 as we estimated through COAST, they could still be damaged later in the study period.

RESULTS

Single-event damages: ERG ran every combination of SLR and storm tide through COAST based on the years included in Table 2 (with the addition of 2020) and the return periods in Table 3. Table 5 shows the SLR and storm scenarios with individual and combined water levels, as well as estimated building damages from SLR alone and combined SLR and storm tide damages. Table 5 presents damages for storm tides by year for a given level of SLR. This is not the expected annual damage by year; rather, the table reflects what the damage would be for a single event. Further down in this section, we present the expected cumulative loss based on simulations, which are shown in Figure 2 and Table 6.

Damages from SLR are the cumulative amount from the beginning of our scenarios, while the combined damages are the damages from a storm tide (a single event) and SLR. For example, in the year 2030 scenarios in Table 5, just over $28.4 million in cumulative SLR damages are projected, which represents damage from the start of the scenarios in 2021 through 2030. To calculate the SLR damages that could occur between 2030 and 2050, we would then subtract the $28.4 million in damages that might occur through 2030 from the $70.5 million that might occur by 2050, resulting in around $42.1 million in additional SLR damage between 2030 and 2050. Additionally, the damage from storms alone is the SLR damage subtracted from the combination of SLR and storm tide for each scenario. The damage from each storm changes between years as a result of the different starting water levels due to SLR. For example, the 50-year storm floodplain in 2050 will be 1.25 feet higher than the 50-year storm floodplain in 2030 due to SLR.

Table 5. Damages from SLR and storm tide (damages are in millions of 2020$).

Year	Storm	SLR (ft)*	Storm Tide (ft)*	SLR and Storm Tide (ft)*	Cumulative Damage from SLR	Damage from Storm Tide and SLR
2020	1-year	0.717	2.26	2.977	$23.4	$37.6
2020	5-year	0.717	3.89	4.607	$23.4	$62.3
2020	10-year	0.717	4.51	5.227	$23.4	$86.0
2020	20-year	0.717	5.22	5.937	$23.4	$120.6
2020	50-year	0.717	6.34	7.057	$23.4	$217.9
2020	100-year	0.717	7.37	8.087	$23.4	$332.5
2020	200-year	0.717	8.5	9.217	$23.4	$586.5
2030	1-year	1.2	2.26	3.46	$28.4	$44.7
2030	5-year	1.2	3.89	5.09	$28.4	$81.0
2030	10-year	1.2	4.51	5.71	$28.4	$107.8
2030	20-year	1.2	5.22	6.42	$28.4	$150.8
2030	50-year	1.2	6.34	7.54	$28.4	$260.1
2030	100-year	1.2	7.37	8.57	$28.4	$405.4
2030	200-year	1.2	8.5	9.7	$28.4	$706.8
2050	1-year	2.45	2.26	4.71	$70.5	$95.3
2050	5-year	2.45	3.89	6.34	$70.5	$170.7
2050	10-year	2.45	4.51	6.96	$70.5	$224.5
2050	20-year	2.45	5.22	7.67	$70.5	$302.6
2050	50-year	2.45	6.34	8.79	$70.5	$454.8

Year	Storm	SLR (ft)*	Storm Tide (ft)*	SLR and Storm Tide (ft)*	Cumulative Damage from SLR	Damage from Storm Tide and SLR
2050	100-year	2.45	7.37	9.82	$70.5	$772.1
2050	200-year	2.45	8.5	10.95	$70.5	$1,097.9
2070	1-year	4.25	2.26	6.51	$150.9	$233.4
2070	5-year	4.25	3.89	8.14	$150.9	$399.5
2070	10-year	4.25	4.51	8.76	$150.9	$493.4
2070	20-year	4.25	5.22	9.47	$150.9	$691.4
2070	50-year	4.25	6.34	10.59	$150.9	$1,023.0
2070	100-year	4.25	7.37	11.62	$150.9	$1,372.2
2070	200-year	4.25	8.5	12.75	$150.9	$1,808.8
2100	1-year	7.7	2.26	9.96	$883.0	$1,280.6
2100	5-year	7.7	3.89	11.59	$883.0	$1,727.9
2100	10-year	7.7	4.51	12.21	$883.0	$1,917.2
2100	20-year	7.7	5.22	12.92	$883.0	$2,224.2
2100	50-year	7.7	6.34	14.04	$883.0	$2,635.6
2100	100-year	7.7	7.37	15.07	$883.0	$3,059.0
2100	200-year	7.7	8.5	16.2	$883.0	$3,540.3

* Relative to NAVD88.

Annual damage model: We ran the projected damages from our COAST model through our annual storm model (using Table 5 as an input, which shows damage by event). Figure 1 shows the cumulative damages from 10,000 simulations of the annual storm model, while Figure 2A and B show the median damage (white line) and 80 percent confidence interval (CI) (shaded region) for cumulative damages over time (Figure 2A) and for new annual damages (Figure 2B).

Figure 1 and Figure 2A show that the cumulative projected damages to the region between 2021 and 2100 will be $15.3 billion (80 percent CI: $13.4–$17.8 billion).[5] From 2021 through 2030, the median cumulative projected damages to the region totaled $0.64 billion (80 percent CI: $0.49–$0.94 billion). Figure 2B shows the median annual projected damage was $56.5 million (80 percent CI: $32.8– 130.1 million) in 2030, $84.6 million (80 percent CI: $50.4–$195.8 million) in 2050, and $429.9 million (80 percent CI: $259.4–$966.0) in 2100.

[5] This uses the single event totals from Table 5 and the probability of these events as inputs into the monte carlo simulation. The $15.3 billion is the median value of the output.

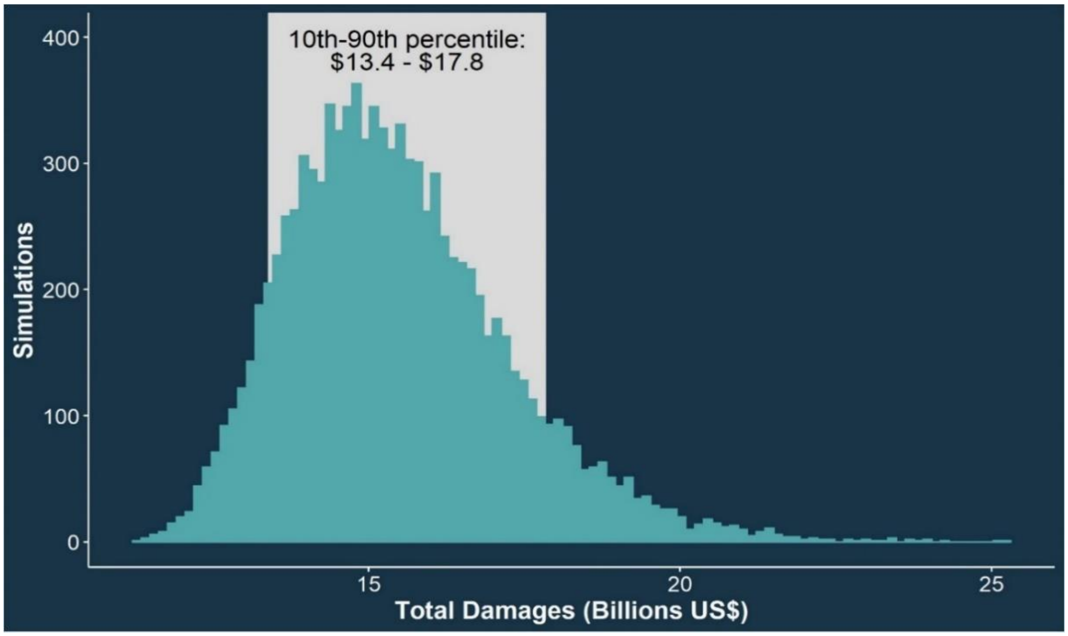

Figure 1. Cumulative damages (in billions of US$) for all of Barnstable County between 2021 and 2100.

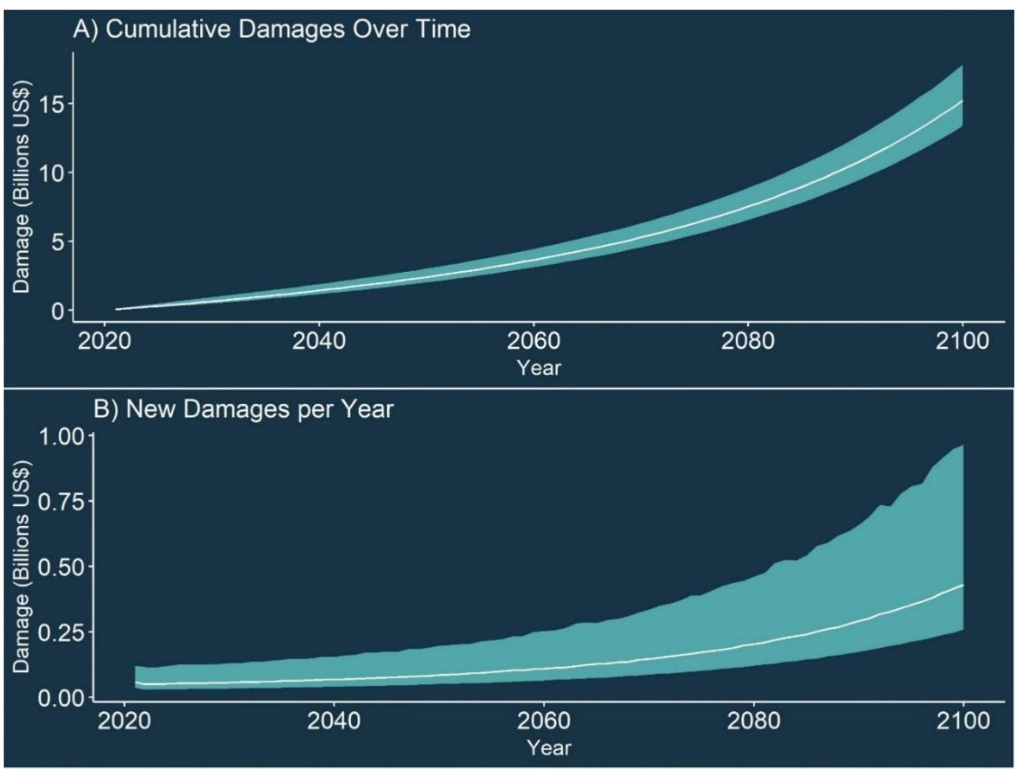

Figure 2. (A) Damages over time for all of Barnstable County. (B) New damages per year.

Table 6 shows the results from our town analyses, separated over three time periods. These estimates show damages for each individual time period and do not include damages accrued leading up to that time period. For example, the total damage for the town of Bourne was $54.6 million in 2021–2030 and $140.67 million in 2031–2050. But the combined total damage for Bourne between 2021 and 2050 was $195.27 million ($54.6 million + $140.67 million). Notably, the length of the time periods are not equal, so the average total damages should be compared between towns (horizontally), while the annual damages (in parentheses) can all be compared (vertically).

Table 6. Cumulative damage by town (average across simulations expressed in millions of 2020$).

Town	Cumulative Damage 2021–2030 (Annual $ Damage)	Cumulative Damage 2031–2050 (Annual $ Damage)	Cumulative Damage 2051–2100 (Annual $ Damage)	Cumulative $ Damage by Town 2021–2100
Barnstable	120.66 (12.07)	295.99 (14.8)	1,695.71 (33.91)	2,112.36
Bourne	54.6 (5.46)	140.67 (7.03)	971.69 (19.43)	1,166.96
Brewster	0.83 (0.08)	2.27 (0.11)	19.74 (0.39)	22.84
Chatham	46.22 (4.62)	114.35 (5.72)	678.21 (13.56)	838.78
Dennis	47.99 (4.8)	128.06 (6.4)	1,024.05 (20.48)	1,200.1
Eastham	7.05 (0.7)	18.56 (0.93)	141.92 (2.84)	167.53
Falmouth	159.08 (15.91)	416.15 (20.81)	3,054.28 (61.09)	3,629.51
Harwich	13.72 (1.37)	38.25 (1.91)	368.11 (7.36)	420.08
Mashpee	40.08 (4.01)	104.51 (5.23)	762.78 (15.26)	907.37
Orleans	11.52 (1.15)	29.05 (1.45)	186.74 (3.73)	227.31
Provincetown	39.68 (3.97)	114.43 (5.72)	1,245.2 (24.9)	1,399.31
Sandwich	21.26 (2.13)	53.9 (2.69)	353 (7.06)	428.16
Truro	7.67 (0.77)	21.78 (1.09)	225.2 (4.5)	254.65
Wellfleet	30.58 (3.06)	72.92 (3.65)	374.25 (7.49)	477.75
Yarmouth	85.02 (8.5)	224.81 (11.24)	1,720.95 (34.42)	2,030.78
Totals	**685.96 (68.6)**	**1,775.7 (88.78)**	**12,821.83 (256.44)**	**15,283.49**

Total land value affected: The analysis above calculates damages to buildings. We performed a supplementary analysis to estimate the total value of land affected from permanent inundation at several points in time using the 1- to 6-foot SLR inundation ArcGIS layers from the Cape Cod Commission's Open Data Hub.

Table 7 presents the results. Total land value represents the total value of all parcels either partially or completely flooded. Proportional land value is the value of land flooded, calculated by the fraction of the property flooded multiplied by the property's land value.

Table 7. Total land value affected by SLR (in millions of 2020$).

SLR* (ft)	Total Land Value Affected (Million $)	Proportional Land Value Affected (Million $)
1	$10,039	$1,585
2	$11,002	$2,087
3	$12,007	$2,708
4	$12,942	$3,465
5	$13,783	$4,350
6	$14,538	$5,269

* Relative to MHHW; relative to NAVD88 would be 0.84 feet higher.

LIMITATIONS AND FUTURE ANALYSIS

Single year damages: COAST is a bathtub model, meaning that it only measures damage due to inundation and not due to water movement and velocity. We used property values from 2020 and made no adjustments over time, so we did not discount the value of buildings, nor did we escalate the price of buildings over time. We used the value of the home to estimate the cost of repairing the house, although these values may not always align.

Annual damage model: Our model assumes a single storm in a year, though multiple may occur. We also assumed that buildings flooded from SLR are abandoned while buildings flooded from storm tides are repaired.

Property value: COAST uses the building value to estimate damages. It does not account for the total value of the land that the building is on. We performed a supplementary analysis to estimate the total value of land affected by flooding at several points of SLR.

Sea level rise impacts to tax revenue

For each time period, we estimated the loss in tax revenue resulting from SLR-driven flooding of properties on Cape Cod. Our estimates account for properties that are projected to be flooded in a given year, properties that are projected to be isolated in a given year, properties that are within a quarter mile of flooded roads, and properties that are projected to flood in the next time period. We conducted this analysis at the county, town, and community activity center (CAC) level using a methodology similar to a study by McAlpine and Porter (2018).

Community Activity Centers

The 2018 Cape Cod Regional Policy Plan defines community activity centers as areas that have a concentration of business activity, community activity, and a compact built environment. The vision for these areas is to accommodate mixed use and multifamily residential development in a walkable, vibrant area; to preserve historic buildings; and to provide diverse services, shopping, recreation, civic spaces, housing, and job opportunities at a scale of growth and development desired by the community, with adequate infrastructure and pedestrian amenities to support development.

METHODS

Our methodology grouped property devaluation due to flooding into four groups:

- **Properties that are likely to be flooded in the specified year.** Properties that were more than 50 percent flooded were assumed to lose all their value. Before this point, we assumed that lost acreage was equivalent to lost value, such that property devaluation would be proportionate to how much of the property was flooded (e.g., at 23 percent inundation, the property will lose 23 percent of its value).[6]
- **Properties that are likely to be isolated in the specified year.** Properties that will be isolated as a result of flooding of all access to the property were assumed to lose all their value.[7]
- **Properties that are within a quarter mile of flooded roads.** Our analysis excludes properties that were already flooded or isolated in the given year. McAlpine and Porter (2018) found that property values within a quarter mile of flooded roads in Miami (or within a quarter mile of roads that will be flooded in about the next 15 years) increased at a rate of $3.71/square foot/year less than other properties not impacted. We adjusted that value to be proportionate to the average property value in Barnstable County and converted it to 2020 dollars. We then applied the resulting property value penalty of $3.63/square foot/year to affected properties. We intersected SLR layers and NAVTEQ road layers from the Cape Cod Commission's Open Data Hub to conduct this analysis. Because of the limited number of flood layers (six) and complexity of analysis needed to look at roads that will be flooded in the next 15 years, we only looked at roads that are currently flooded; these results thus slightly underestimate the impact from this loss.
- **Properties that are likely to be flooded in the next 15 years or so.** This analysis focuses on properties that will be flooded and includes those that were near flooded roads; any additional penalty was considered additive. McAlpine and Porter (2018) found that properties that will be flooded in the next 15 years in Miami grew in value at a rate of $3.08/square foot/year less than properties that will not be impacted. We adjusted that value to be proportionate to the average property price in Barnstable County and converted it to 2020 dollars. We then applied a property value penalty of $3.01/square foot/year in the first year that a property was included in the next zone likely to be flooded. Next, we multiplied by the number of years between time steps if the property remained in this zone at the next time step.[4]

If a property was devalued more than it was worth, we set the property value loss to be the value of the property. Our analysis examined the following years, which relate to the year each SLR increase is projected to occur:

- 2025: Assumed no flooding or isolated properties but penalized properties that will flood with 1 foot MHHW of SLR in 2040 (15 years later) plus 1 foot for highest astronomical tide (HAT) to align with the method in the McAlpine and Porter study.

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[6] We used SLR layers from the Cape Cod Commission's Open Data Hub and Commission-provided parcel data for Cape Cod to conduct this analysis.

[7] We used isolated homes layers provided by the Cape Cod Commission.

- 2040: Assumed 1 foot MHHW of SLR and associated isolation of properties. Penalized properties that will flood with 3 feet MHHW of SLR in 2054 plus HAT.
- 2054: Assumed 2 foot MHHW of SLR and associated isolation of properties. Penalized properties that will flood with 4 feet of SLR in 2076 plus HAT.
- 2076: Assumed 4 feet of SLR and associated isolation of properties. Penalized properties that will flood with 6 feet MHHW of SLR plus HAT.

We multiplied each property's total loss in value per year by the 2020 tax rate of the town (Table 8).[8] To determine the tax revenue loss for every year from 2021 to 2100, we did a linear interpolation between years and extrapolated out to 2021 and to 2100.

Table 8. Tax rate (2020) by town

Town	Tax Rate per 1,000$ of Value
Barnstable	8.51
Bourne	10.74
Brewster	8.62
Chatham	4.82
Dennis	6.1
Eastham	8.72
Falmouth	8.59
Harwich	8.73
Mashpee	8.96
Orleans	7.56
Provincetown	6.32
Sandwich	14.31
Truro	7.07
Wellfleet	7.48
Yarmouth	10

RESULTS

We determined total tax revenue loss by county, town, and CAC. By 2030, Cape Cod is expected to lose a total of almost $200 million in tax revenue relative to no SLR occurring. The towns of Barnstable and Falmouth are expected to experience the highest loss in tax revenue relative to no SLR occurring (Table 9 and Figure 3).

[8] This analysis used the "natural" tax rates for all towns, which do not reflect higher residential tax rates in four towns that have year-round residential tax exemptions (Barnstable, Provincetown, Truro, and Wellfleet). Limited information on properties subject to such exemptions prevented using those higher tax rates in the analysis and results in a more conservative estimate of the potential lost tax revenue.

Table 9. Total lost tax revenue in millions of 2020$ per time period by town.

Town	2021 to 2030	2031 to 2050	2051 to 2100	Total
Barnstable	37.94	203.07	1187.48	1428.48
Bourne	20.53	97.34	617.92	735.79
Brewster	4.89	16.82	101.31	123.02
Chatham	9.48	74.89	459.04	543.41
Dennis	11.72	71.62	464.42	547.75
Eastham	7.09	37.30	236.77	281.16
Falmouth	26.75	158.71	1115.16	1,300.63
Harwich	7.30	50.73	368.23	426.26
Mashpee	8.35	57.02	403.61	468.98
Orleans	12.95	58.64	372.48	444.06
Provincetown	2.96	34.45	336.69	374.10
Sandwich	13.34	74.93	359.16	447.43
Truro	9.83	51.89	282.08	343.81
Wellfleet	11.54	59.92	314.85	386.31
Yarmouth	14.82	88.70	636.29	739.81
Totals	**199.48**	**1,136.03**	**7,255.48**	**8,590.99**
Annual Average	**13.30**	**81.14**	**329.79**	**108.75**

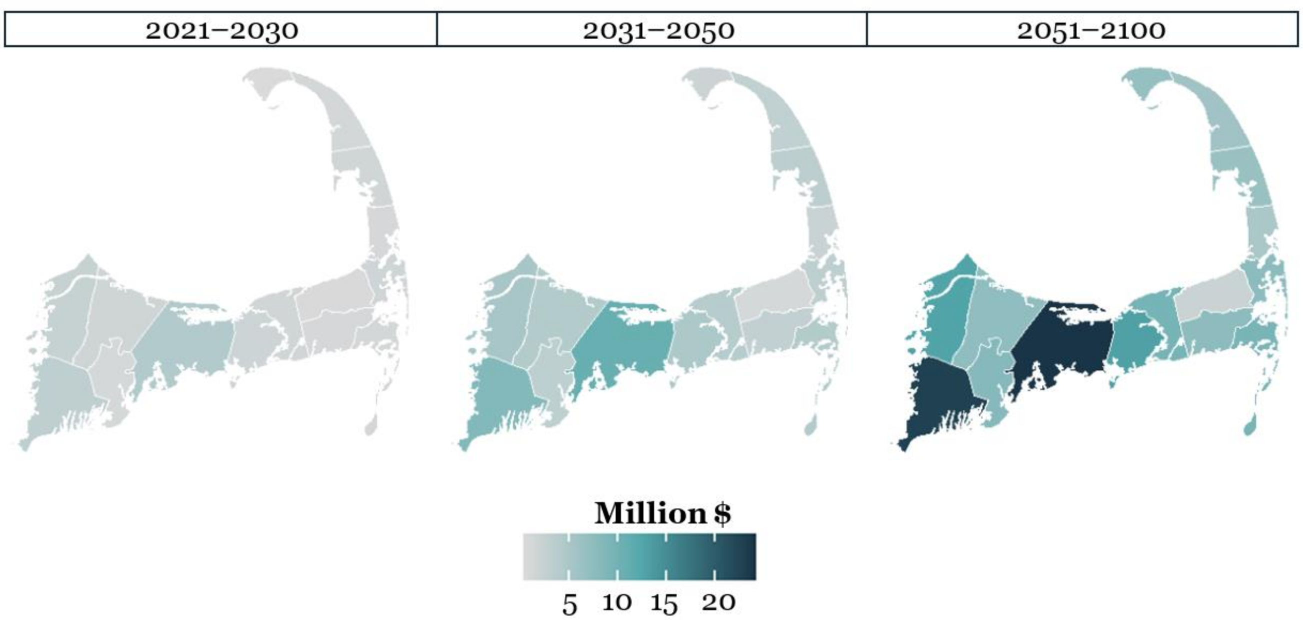


Figure 3. Average annual lost tax revenue from SLR, driven by property value loss by town in each period.

CACs are expected to lose on average about $0.8, $5, and $24 million per year in tax revenue from 2021 to 2030, 2031 to 2050, and 2051 to 2100 respectively (Table 10). Buzzards Bay, Provincetown, Woods Hole, Hyannis, and Wellfleet CACs are expected to suffer the greatest loss in tax revenue (Figure 4).

Table 10. Total lost tax revenue in millions of 2020$ per time period by CAC.

CAC Name	2021 to 2030	2031 to 2050	2051 to 2100	Total
Barnstable Village	0.70	3.01	13.34	17.05
Buzzards Bay	0.14	0.89	11.72	12.74
Chatham	0.51	5.16	32.86	38.54
Dennis	0.21	1.07	5.48	6.76
Dennis Port	0.15	0.95	4.23	5.33
Falmouth	0.71	2.92	17.72	21.35
Harwich Port	0.30	2.76	19.13	22.20
Hyannis	1.11	5.88	39.13	46.12
Orleans	0.36	1.32	7.41	9.09
Osterville	1.03	4.89	26.17	32.09
Provincetown	1.74	19.33	212.30	233.37
Sandwich	1.06	4.72	25.43	31.21
South Yarmouth	0.38	2.09	16.93	19.39
Wellfleet	2.08	9.47	34.66	46.21
West Dennis	0.81	3.63	16.00	20.44
Woods Hole	0.74	7.03	46.58	54.36
Total	**12.02**	**75.12**	**529.11**	**616.24**
Annual Average	**0.80**	**5.37**	**24.05**	**7.80**

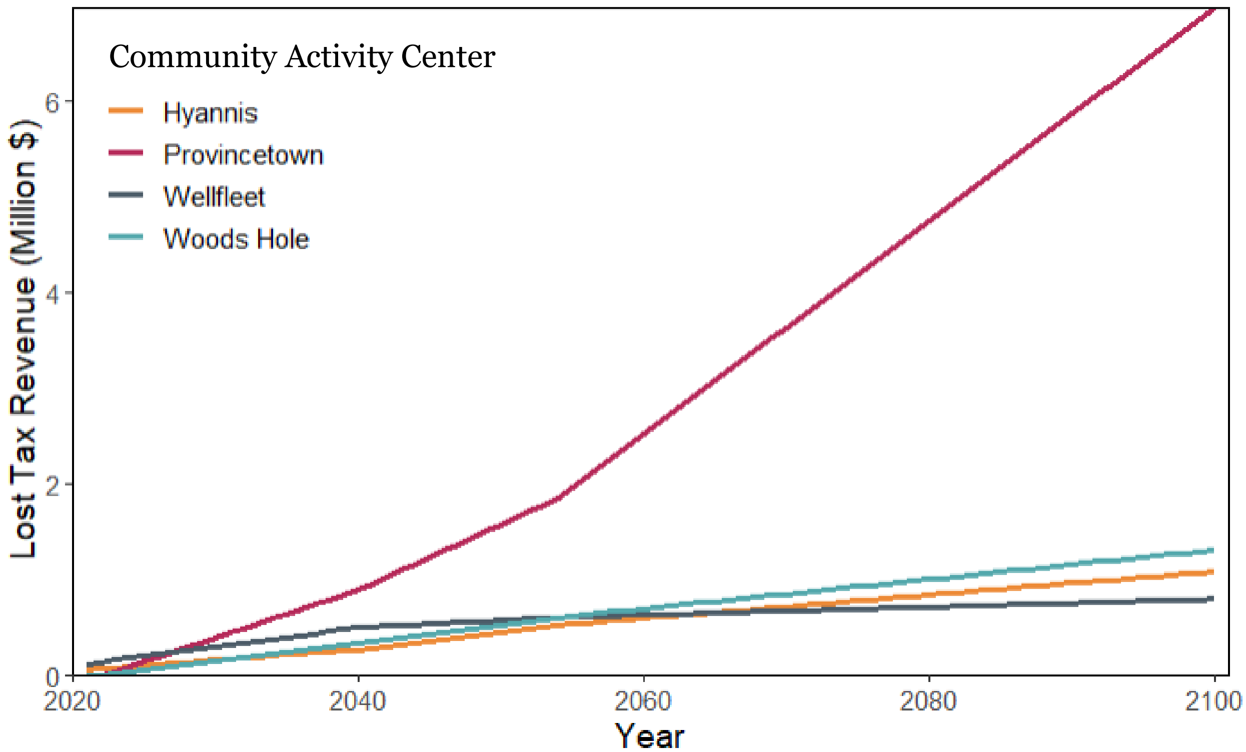


Figure 4. Projected tax revenue loss from SLR in each year from 2021 to 2100 at the top four most impacted CACs.

LIMITATIONS AND FUTURE ANALYSIS

This study provided a basic estimate of tax revenue loss due to SLR on Cape Cod. However, further analyses could strengthen our model's robustness. First, this analysis likely underestimates tax revenue loss, especially later into the 21st century. We did not penalize properties that will be near a flooded road or isolated in the next time period (as was done in the study we based this analysis on) because we had a limited number of flood layers; thus, we slightly underestimated the losses from this impact. Due to data availability, we also used property value loss per square foot estimates from a model that was trained on Miami-specific property transaction data (McAlpine & Porter, 2018). Although we adjusted these values to be proportionate to the average property value in Barnstable County, more accurate property value loss estimates would likely result from using property transaction data specific to Cape Cod.

Sea level rise impacts to jobs

Many Cape Cod businesses are located along the shoreline, and as sea levels continue to rise, jobs will likely be displaced over time. Businesses would therefore need to relocate to less vulnerable locations before SLR impacts them. The addition of storm surge on top of these already rising seas could also expose businesses to more frequent flood damage and interruption in the absence of adaptation strategies.

METHODS

To assess when and where SLR could impact businesses, we conducted a GIS-based SLR exposure analysis of businesses in Barnstable County. Our analysis evaluated flooding at several points of time using 1–6 feet of SLR layers from the Cape Cod Commission's Open Data Hub. Business and accompanying jobs data were obtained from ESRI Business Analyst, which provides point-based business information according to latitude and longitude.[9] We counted businesses at addresses with coordinates that will be flooded.

Businesses were grouped into industries by their North American Industry Classification System (NAICS) codes, a business classification system. We analyzed all affected businesses as well as affected businesses that are part of Cape Cod's maritime economy, known as its blue economy. The blue economy is a significant economic driver for the Cape Cod Region, representing 12 percent of jobs and 11 percent of gross revenue (Cape Cod Blue Economy Project, 2019). Appendix A includes a list of industries and their associated NAICS codes that are part of the Cape's blue economy.

For each business type, we calculated wages per employee to evaluate the economic impact of flooded businesses in Barnstable County. Our calculation used annual average employment level data and total annual wages for the year 2019 from the Bureau of Labor Statistics' Quarterly Census of Employment and Wages (QCEW) for all 6-digit NAICS codes of interest. For those 6-digit NAICS codes that were not present in the QCEW data, we used employment and wage data for a 5-digit NAICS code and assumed that the 6-digit NAICS code has the same wages-to-employee ratio. If a 5-digit NAICS code was not present, we used 4-digit and then 3-digit codes; in a few cases, we used 2-digit NAICS codes for this same approximation. We then adjusted wage data for inflation using the Bureau of Economic Analysis (BEA) GDP Price Deflator and divided by the number of employees in each industry employment level to get a final ratio.

RESULTS

Jobs and businesses along the coast and in some inland areas on Cape Cod are at risk from SLR. Cape Cod's blue economy is particularly vulnerable because of the density of businesses located along the coast. About 58 percent of businesses and 78 percent of jobs affected by just 1 foot of SLR are part of the Cape's blue economy (Table 11). For example, we found that most of the establishments located along Commercial Street, Provincetown's main and most well-known street, will be flooded with 1 to 2 feet of SLR (Figure 5). Of all industries impacted by SLR on Cape Cod, the restaurant industry is projected to lose the highest number of total jobs. This is especially impactful as the hospitality industry is a significant economic driver in the region. Water passenger transportation is also projected to lose a high number of jobs; however, the industry is more likely to adapt to SLR than restaurants.

[9] To perform a reasonableness test on the ESRI Business Analyst data, ERG compared Barnstable County data to the Bureau of Labor Statistics' (BLS') Quarterly Census of Employment and Wages (QCEW) data set. ESRI Business Analyst showed 58,040 jobs and QCEW showed 56,720 jobs. The number of establishments was 7,086 in ESRI Business Analyst and 6,374 in QCEW. This is likely due to ESRI Business Analyst catching some smaller firms that the BLS methodology did not catch. Overall, this analysis gave us confidence in the ESRI Business Analyst point-based data.

Table 11 and Table 12 show how each SLR scenario impacts Cape Cod's businesses and blue economy. Clearly, flooding risk may lead to the greatest loss of tourism jobs, which include tour operators, boat dealers, marinas, RV parks, accommodations, and food services.

Table 11. Number of businesses, jobs, and estimated wages affected by each additional foot of SLR.

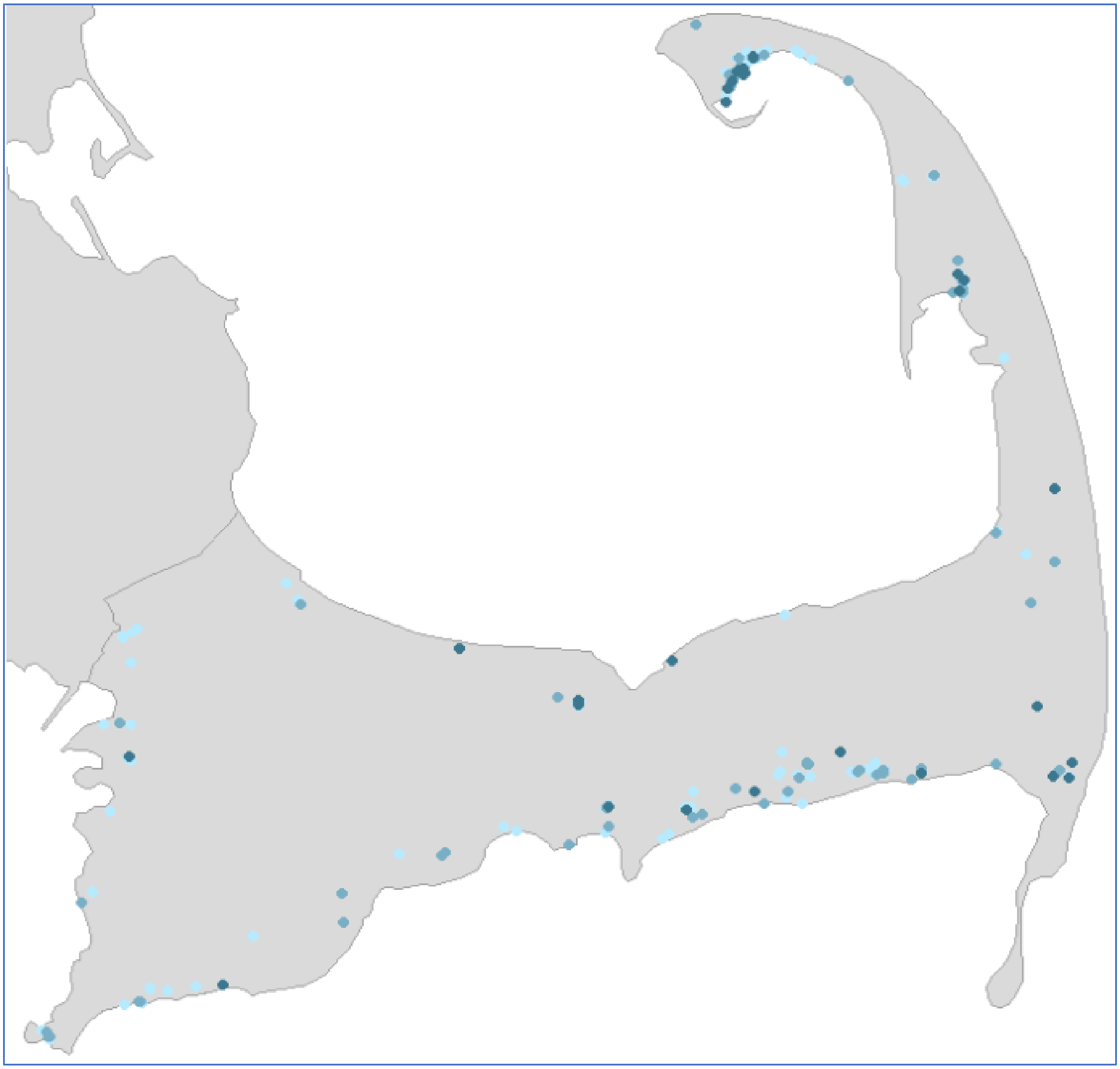
Year	SLR (ft)*	Businesses Affected	Jobs Affected	Wages Affected (Millions 2020$)
2040	1	26	293	$11.39
2054	2	45	415	$15.98
2066	3	78	695	$29.80
2076	4	151	1,602	$65.95
2085	5	275	4,592	$175.71
2093	6	371	6,612	$270.70

* Relative to MHHW; relative to NAVD88 would be 0.84 feet higher.

Table 12. Blue economy businesses, jobs, and wages affected by SLR.

Year	SLR (ft)*	Businesses Affected	Jobs Affected	Wages Affected (Millions 2020$)
2040	1	15	229	$8.04
2054	2	22	299	$10.30
2066	3	38	504	$21.54
2076	4	71	1,030	$39.63
2085	5	118	2,007	$72.57
2093	6	165	2,548	$92.13

* Relative to MHHW; relative to NAVD88 would be 0.84 feet higher.



Establishments affected beginning at:

1–2 ft of SLR (2040–2054) 3–4 ft of SLR (2066–2076) 5–6 ft of SLR (2085–2093)

Figure 5. Locations of all establishments affected by 1 to 6 feet of SLR. Darker colors indicate businesses that will be flooded sooner (with lower levels of SLR) and lighter colors indicate businesses that will be flooded later (with higher levels of SLR). Some businesses are located very close to each other, so some overlap in the points may occur.

LIMITATIONS AND FUTURE ANALYSIS

This analysis of exposed businesses underestimates the total impact of flooding because it does not consider changes in access to these establishments due to SLR. Even if the business location is dry, the business might still experience losses if all access points to the site are flooded. Additionally, while the business location itself may be dry, the area it operates in could be flooded. For example, an ecotourism business with headquarters in an unflooded location could still lose business if the outdoor expedition space it operates in is flooded. Future analyses could look at access to businesses as well as flooding impacts on a business level to account for differences at headquarters and the operating region. Additionally, this analysis only considers impacts to businesses from SLR-induced flooding. Storm surge damage can also impact company revenue and job stability for months, even if businesses recover from individual storms.

Sea level rise impacts to beach tourism

Cape Cod is a vacation spot for many people in New England and beyond, with millions of beach visitors every year. These beaches, however, could be significantly impacted by SLR. As sea levels rise, the beaches could narrow and become more crowded, leading beachgoers to value their experience less and potentially resulting in decreased beach visitation. Ultimately, SLR impacts to beaches could negatively affect Cape Cod's economy.

METHODS

To analyze the economic impacts of lost tourism, we relied on data that Opaluch and Hwang (2018) provided to the Cape Cod Commission in a technical memorandum. The memorandum includes annual estimates of the number of beach visitors, the associated economic value of each user-day, and the value per meter of beach width for three shoreline categories—National Seashore, town beaches, and other seashore (Opaluch & Hwang, 2018). Opaluch and Hwang used readily available studies conducted at sites similar to Cape Cod to estimate these values. We converted all values to 2020$ using the BEA's GDP Price Deflator.

Our analysis focused on Cape Cod National Seashore beach visitation because it represents the most complete and reliable data reported by Opaluch and Hwang (2018). There are 64 kilometers (40 miles) of Cape Cod National Seashore.[10] We calculated the current annual value of beach recreation on Cape Cod using the Opaluch and Hwang (2018) estimates of annual National Seashore beach use (5.5 million user-days) and the associated user-day value ($44.82/user-day). The economic impact of SLR on beach visitation is based solely on SLR impact to the Cape Cod National Seashore.

Due to geospatial data limitations, we used the best readily available data to estimate beach loss. The beaches for which geospatial data were available were barrier beaches and public or semi-public beaches. We estimated the average width of beach lost for each foot of SLR based on barrier beaches that are also considered public or semi-public beaches. Table 13 provides the average beach width lost for each foot of SLR (rounded to the nearest meter) and the year that it

[10] https://www.nationalparks.org/explore-parks/cape-cod-national-seashore

is projected to occur (as we outlined in Table 1). The annual rate of beach loss was then estimated and applied to National Seashore data.

Table 13. Average beach width (public or semi-public barrier beaches) lost to SLR.

SLR* (ft)	Year of Occurrence	Average Beach Width Lost (m)
1	2040	15
2	2054	18
3	2066	21
4	2076	25
5	2085	28
6	2093	30

* Relative to MHHW.

Applying Opaluch and Hwang's (2018) estimates of beach use and user-day value (Table 14) and our estimates of the average beach width lost due to SLR (Table 13), we calculated the lost value associated with each foot of SLR using the following equation:

*Lost Value = User-Days per Meter * Average Value per User-Day per Meter of Width * Width of Beach Lost * Length of Shoreline Impacted*

Table 14. National Seashore beach use and user-day value (Source: Opaluch and Hwang, 2018).

Shoreline Category	Annual User-Days per Meter (days/m)	Average Value per User-Day per Meter of Width (2020$/day/m)	Length of Shoreline (m)
National Seashore	70.28	$1.39	64,000

To calculate the annual economic value lost as sea levels continue to rise through the foreseeable future, we estimated the annual beach width lost to be 0.30 meters/year, assuming a linear beach width loss rate from 2040 to 2093 (Table 13). We estimated the annual lost value due to SLR impacts on beach width by multiplying the values in Table 14 by the estimated annual beach width lost (0.30 meters/year).

RESULTS

Cape Cod's economy currently benefits significantly from beach recreation, but SLR will likely have a large impact on the available beach area and ultimately decrease the value of Cape Cod beaches. The annual value of beach recreation on Cape Cod is currently estimated to be over $246.5 million when considering National Seashore beaches (Table 15).[11] This value is associated with the non-market economic benefit derived from the average value a visitor places on a beach day—it does not measure the economic impact to (or influx in) revenue as a result of beach width. However, as beaches are a major driver of tourism to the Cape, the economic impact of disappearing beach width could be many times larger than the lost economic value.

[11] Estimates of annual user-days and user-day values presented in Table 15 are taken from Opaluch and Hwang (2018).

Table 15. Current annual value of beach recreation on Cape Cod.

Shoreline Category	Annual User-Days	User-Day Values (2020$/Day)	Annual Value (2020$)
National Seashore	5,500,000	$44.82	$246,510,000

As sea levels rise, the beaches will narrow. With less beach area available, the economic value from beach recreation will decrease. One foot of SLR is projected to have an annual impact of $93.8 million on the Cape Cod economy.[12] As sea levels rise beyond 1 foot, the annual lost value will continue to increase significantly. Table 16 provides the average beach width lost for each foot of SLR and the annual lost value that results from this lost beach width.[13]

Table 16. Annual lost economic value from average beach width lost due to SLR.

SLR* (ft)	Year of Occurrence	Average Beach Width Lost (m)	Annual Lost Value (2020$)[14]
1	2040	15	$93,800,000
2	2054	18	$112,550,000
3	2066	21	$131,300,000
4	2076	25	$156,300,000
5	2085	28	$175,050,000
6	2093	30	$187,550,000

* Relative to MHHW.

We estimate the annual lost economic value due to SLR to be $1.90 million per year, assuming that SLR causes a beach width loss 0.30 meters/year.[15] This results in a total lost value of $9.65 billion from 2021 to 2100. Table 17 provides the economic value lost due to SLR impacts on beach width.

Table 17. Economic value lost due to SLR impacts on beach width.

Years	Cumulative Lost Value (2020$)	Average Lost Value (2020$)
2021–2030	$541,980,000	$54,198,000
2031–2050	$1,653,720,000	$82,686,000
2051–2100	$7,457,900,000	$149,158,000
Total (2021–2100)	**$9,653,600,000**	**$120,670,000**

[12] This estimate, and all other value estimates in this section, only consider National Seashore beaches. The annual lost value associated with each foot of SLR was calculated using the equation outlined in the methods section. For example, the annual lost value from 1 foot of SLR was calculated as 70.28 days/m * $1.39/day/m * 64 km * 15m = $93.8 million.

[13] The average beach width lost was multiplied by the values in Table 14 to determine the annual lost value.

[14] Based on average beach width lost (m).

[15] The rate of beach width loss was estimated assuming a constant rate of loss from the beach width lost presented in Table 13.

LIMITATIONS AND FUTURE ANALYSIS

This analysis assumes that the annual user-days per meter and the average value per user-day per meter of beach width will remain the same through 2100. This means that although beach width decreases year after year due to SLR, the beach visitors would place the same value on each meter of beach width, regardless of how large or small the beach actually is. In reality, a beach that is only 1 meter wide will likely not provide the same economic value as a beach that is 10 meters wide. Our analysis does not consider the increase in economic loss as a beach becomes too narrow for visitors to enjoy.

Due to data limitations, we used barrier beaches that are also public or semi-public to determine the average width of beach lost for each foot of SLR.[16] We then assumed that the average width lost on these beaches would be similar to the width lost along the 64 kilometers of National Seashore. After making this assumption, we only used National Seashore values to estimate the economic impact of SLR on these beaches. We did not apply National Seashore user-day values or any other values to barrier beaches.

By only considering barrier beaches that are also public or semi-public beaches, we ensure that the width of beach loss is only based on barrier beaches that have recreation value. Many public beaches, however, are *not* considered barrier beaches. For example, many of the beaches facing Cape Cod Bay are not classified as barrier beaches. Therefore, our analysis of the average beach width lost for each foot of SLR is based on significantly fewer beaches than are accessible on Cape Cod. These estimates are applied over the full 64 kilometers of National Seashore on Cape Cod and are therefore appropriate for our purposes here. Additional research on beach visitation is needed for non-National Seashore beaches to estimate economic losses at town beaches.

Another limitation of this analysis is that it assumes that no beach migration will occur as sea levels rise. This assumption is valid in areas that have developed land or uplands that prevent beach migration from occurring. Beaches may migrate inland if there is low-lying, undeveloped land inland of the beach area. The site-specific nature of this analysis requires more resources than were available for this work, but future analyses should consider whether some beaches will not narrow due to their ability to migrate inland.

Our estimates only consider the economic impact from lost beach visitation and do not consider the lost economic value from visitor spending. For example, beach visitors may spend money at a local ice cream shop, souvenir store, or a nearby hotel. The economic impact of this additional spending is not considered in our analysis. Future analyses should quantify the total economic impact of beach visitors to fully understand how beach loss will impact the Cape Cod economy.

Sea level rise impacts to salt marshes and eelgrass ecosystem services

Salt marshes and eelgrass are complex ecosystems that support the wellbeing of communities and wildlife throughout the Cape. They regulate the environment around them, providing cleaner water, mitigating GHGs through carbon storage, and supporting local fisheries by providing important forage and nursey habitat for many species. To understand the potential

[16] Ideally, the analysis would estimate the average width of beach lost for each foot of SLR based on National Seashore beaches, not barrier beaches that are also public or semi-public.

loss if no action is taken to protect these ecosystems, we conducted a SLR inundation exposure analysis on salt marshes in Barnstable County and valued three ecosystem services that they currently provide: nitrogen removal, carbon sequestration, and commercial fishing.

METHODS

We used ArcGIS for the SLR inundation exposure analysis, applying salt marsh and 2018 SLR layers from the Cape Cod Commission's Open Data Hub. For each increment of SLR, we calculated the acreage of salt marsh that would be under water at mean sea level. Table 18 presents the acres of salt marsh impacted by SLR. Salt marshes are naturally low lying, so most acreage is lost within the first foot of SLR.

This analysis is limited by the ability to predict marsh migration. Salt marshes migrate horizontally over time and can adjust vertically through peat accumulation and sediment deposition. Many marshes worldwide have insufficient accretion rates to keep pace with changing sea levels, with predictions of 60 to 90 percent of salt marshes worldwide unable to keep pace with SLR by the end of the century (Crosby et al., 2016). Marshes experiencing higher rates of local SLR are less likely to keep pace (Crosby et al., 2016). Rates of SLR around Cape Cod currently exceed the pace of elevation gain, and a study of salt marsh conditions (Smith, 2017) found that the migration of individual marshes in the Cape Cod National Seashore respond quite differently depending on a range of topography and land use. Steep slopes of elevation, the loss of barrier beaches, and structures such as roads and parking lots can limit marsh expansion. More frequent and intense storms can bring in additional sediment to increase accretion.

Smith (2017) estimated that high marsh areas on Cape Cod could experience 90 to 100 percent marsh loss with just over 1.5 feet of SLR, as low marsh migrates into high marsh and high marsh is unable to migrate higher. Three feet of SLR could lead to a 30 percent loss of total marsh (Smith, 2017). The many factors influencing marsh migration make it difficult to efficiently model at a countywide scale. Even salt marshes with rates currently keeping pace with SLR are likely to be outpaced by 2100, and the losses in the following analyses will occur at a later date. Our simplified analysis represents a worst-case scenario, assuming that all salt marsh is unable to keep pace with SLR and that salt marsh drowns within 1 foot of SLR relative to MHHW, losing almost 700 acres a year.

Using the benefit transfer method, we calculated the ecosystem service values of nitrogen removal, carbon sequestration, and biomass contributions to commercial fisheries for the area of salt marsh lost. Benefit transfer takes values from a "study site" and applies them to a "policy site" where estimates are not available. In this case, the policy site is Barnstable County. This method saves time and resources when information on the policy site is not available by assuming an economic value from a study site with similar characteristics.

Table 18. Acres of salt marsh impacted by SLR.

SLR* (ft)	Acres of Salt Marsh Impacted	Year
1	13891	2040
2	13892	2054
3	13892	2066

SLR* (ft)	Acres of Salt Marsh Impacted	Year
4	13892	2076
5	13892	2085
6	13892	2093

* Relative to MHHW.

Nitrogen removal: Salt marshes remove excess nitrogen from runoff, reducing expenditures for treating wastewater while helping to maintain water quality. The Cape Cod Commission's Technologies Matrix estimates that the annual cost for a conventional wastewater treatment plant to treat nitrogen is $130 per kilogram (*Technologies Matrix | Cape Cod Commission*, n.d.). We used that value to estimate the value of nitrogen removal that the salt marsh provides.

According to Drake et al. (2015), salt marshes in New England remove between 4.7 and 8.5 grams of nitrogen per meter per year. We applied those values to estimate the low and high range of nitrogen removed, as well as the annual amount of nitrogen removed by the marsh area that would be inundated by SLR.

Carbon sequestration: Carbon sequestration can be valued using the SCC approach, a method that many federal agencies use to value the climate impacts of a rulemaking.

While the SCC is a comprehensive estimate of damages, it is limited by a lack of precise information on the nature of some damages. The SCC increases each year because future emissions are expected to cause larger incremental damages as greater climatic change leads to more stressors on natural and economic systems. The EPA discounted the future impacts at 5, 3, and 2.5 percent, and developed a fourth set of costs at the 95th percentile outcome and 3 percent discount rate to account for high-risk climate scenarios (Interagency Working Group on Social Cost of Carbon, 2010). We extrapolated the SCC to 2100, using the 3 percent (to select the middle value in the range) and 95th percentile SCC to estimate a range of carbon sequestration values. The extrapolated values assume the economic and climatic trends modeled out to 2050 remain the same until 2100 (Table 19).

Table 19. Social cost of carbon (in 2020$).

Year	3% Discount Rate	High Impact (95th Percentile)
2020	$50.31	$149.05
2030	$61.63	$186.11
2050	$84.27	$260.23
2070	$106.91	$334.35
2100	$140.87	$445.53

Carbon sequestration rates vary due to a number of environmental factors that impact accretion rates. Drake et al. (2015) found that sequestration rates in New England salt marshes range from 74 to 126 grams of carbon (gC)/m^2/year. We used those rates to estimate low and high burial rates of carbon, then converted gC to carbon dioxide (CO_2) equivalents using the ratio of the mass of a CO_2 molecule to a carbon molecule (44/12). Next, we multiplied CO_2 equivalents by the SCC and established a baseline of current carbon sequestration to ultimately calculate the loss of carbon sequestration for every year from 2040 to 2100.

Commercial fisheries: Salt marshes support commercial fisheries by providing a food source and nursey grounds for fish species. We used the trophic transfer method to calculate the value of commercial species biomass that an acre of salt marsh provides. Trophic transfer involves identifying the primary productivity of an ecosystem and determining the amount of productivity that is lost at each successive trophic level up to the point where the trophic level reflects a marketable commodity (Kneib, 2003; McCay & Rowe, 2003).

This value was then multiplied by the acres lost to SLR to determine the loss of the ecosystem service (i.e., total commercial fish species biomass). We started with a primary productivity rate of New England marsh grasses of 500 grams of dry weight per square meter per year ($g/DW/m^2/yr$) and a benthic microalgal production rate of 106 $g/DW/m^2/yr$ (McCay & Rowe, 2003). At the commercial species trophic level, 0.16 percent of total primary and benthic microalgal production remains (Kneib, 2003). We assumed dry weight is 22 percent of wet weight.[17] Using these values, salt marshes generate 17.8 kilograms of wet weight per acre per year of commercial fish.

To place a value on commercial fish, we downloaded total landings in Massachusetts from the National Marine Fisheries Database for 2015–2019 for 11 of the 13 main fisheries on Cape Cod.[18] We used the average percentage of landings of each species to calculate a weighted average price, resulting in a value of $5.95 per pound.

Eelgrass: Our valuation of the ecosystem services that the current extent of eelgrass provides (i.e., nitrogen removal, carbon sequestration and commercial fisheries) draws on the same methods described above for salt marshes, but applying values relevant to eelgrass.

RESULTS

Salt marshes: Using the acres of flooded salt marsh from Table 18, we calculated the value of the ecosystem services lost for nitrogen removal, carbon sequestration, and commercial fish biomass. In a scenario where marsh accretion cannot keep up with SLR, all of the marsh will drown with 1 foot of increase, which we estimate will occur in 2040. Table 20 presents the annual values of the lost services for 2040; carbon sequestration was valued using the SCC with a discount of 3 percent. Under a high-impact climate scenario, the value of carbon sequestration increases to $3.4 to $5.8 million in 2040.

Table 21 summarizes the total loss of ecosystem services through 2100, at which point billions in carbon sequestration, nitrogen filtration, and commercial fishery revenue could be lost. Even if some salt marsh migrates to keep pace with SLR, small losses in habitat or changes in water quality could lead to changes in fishery stocks and economic losses.

[17] This is the percentage used in the trophic studies we reviewed.

[18] Data were not available for two species: Monkfish and Black Sea Bass.

Table 20. Annual value lost in salt marsh ecosystem services from SLR for 2040 (in millions of 2020$).

Acres	Value of Nitrogen Removal (Low)	Value of Nitrogen Removal (High)	Value of Carbon Sequestration (Low Burial)	Value of Carbon Sequestration (High Burial)	Value to Commercial Fisheries
13,891	$34.3	$62.0	$0.9	$1.6	$3.3

Table 21. Value lost in ecosystem services through 2100 (in millions of 2020$).

Year	Value of Nitrogen Removal (Low Burial)	Value of Nitrogen Removal (High Burial)	Value of Carbon Sequestration (Low Burial)	Value of Carbon Sequestration (High Burial)	Value to Commercial Fisheries
2041–2050	$343	$620.2	$12.1	$20.6	$32.9
2051–2070	$685.9	$1,240.5	$29.3	$49.9	$65.7
2071–2100	$1028.9	$1,860.7	$57	$97	$98.7

Eelgrass: There are 12,562 acres of eelgrass habitat along the coast of Barnstable County (*Eelgrass | Northeast Ocean Data Portal*, 2018). Eelgrass beds provide many of the vital ecosystem services that salt marshes do. These vital habitats are sensitive to changes in the physical environment, including temperature, light availability, and pollution. Many efforts have been made to improve water quality and restore eelgrass beds in Massachusetts. While eelgrass meadows will likely tolerate SLR, they are particularly vulnerable to increasing water temperature, which is the most important limiting range factor (Carr et al., 2012). Eelgrass habitats can rapidly decline once temperatures reach a certain threshold. Eelgrass in 27° C water (typical temperate range is 5° to 25° C) showed a decrease in biomass growth ranging from 40 to 80 percent (Kim et al., 2020). Frequent die-offs are predicted in water above 30° C (Carr et al., 2012).

A combination of stressors, including poor water quality, are responsible for the current decline of eelgrass beds. In the future, warming ocean temperatures will increase changes in nutrient circulation and events of hypoxia, leading to greater eelgrass losses and impacting the vital ecosystem services they provide.

We estimated the value of current eelgrass ecosystem services (i.e., nitrogen removal, carbon sequestration, and commercial fisheries) using the same methods we applied in the context of salt marshes, instead using values relevant to eelgrass.

Cole and Moksnes (2016) estimate that eelgrass removes nitrogen at a rate of 12.3 kilograms per hectare per year, which is equivalent to 67 pounds per acre per year. Current eelgrass extent removes 841,740 pounds of nitrogen per year, valued at $500,485,380.

Carbon sequestration rates among eelgrass beds vary spatially and temporally and are influenced by multiple environmental conditions. A study of New England salt marshes and eelgrass beds found carbon sequestration rates of eelgrasses ranged from 41 to 170 $gC/m^2/year$

(Drake et al., 2015). We used this range to estimate a low and high burial rate, then converted gC to CO_2 equivalents and multiplied by the SCC to estimate the current value of carbon sequestration by eelgrass beds.

We used the same method of trophic transfer to estimate the contribution of commercial revenue provided by eelgrass beds. The studies we reviewed found a benthic faunal production rate (175 g/DW/m^2/year) as the starting point, with 4 percent of productivity reaching a marketable trophic level (Kneib, 2003; McCay & Rowe, 2003). This works out to 128.8 kilograms of wet weight per acre per year. We used the same average price per pound of $5.95. Eelgrass therefore currently contributes $21,209,640 in revenue to commercial fisheries. Table 22 summarizes the ecosystem services that eelgrass provides. The value of carbon sequestration is presented using the SCC with a 3 percent discount rate for the year 2020. Under a high-impact climate scenario, that value increases to $2.4 to $5.9 million for 2020.

Table 22. Current value of ecosystem services provided by eelgrass beds annually (in millions of 2020$).

Acres	Value of Nitrogen Removal	Value of Carbon Sequestration (Low Burial)	Value of Carbon Sequestration (High Burial)	Value to Commercial Fisheries
12,562	$49.5	$.38	$1.6	$21.5

A global assessment of over 200 studies found an average loss of 110 km^2 per year since 1980 (Waycott et al., 2009). A Massachusetts Division of Marine Fisheries study found that eelgrass beds are losing density and declining in acreage at increasingly faster rates, with an average loss of 132 acres a year from 1951 to 2014 across three sites in Duxbury, Kingston, and Plymouth Bays (Ford & Carr, 2016). More recent rates suggest even faster declines, with an average loss of 467 acres a year from 2012 to 2014 (Ford & Carr, 2016). If the eelgrass around Barnstable County declined at the average rate of other habitats off the coast of Massachusetts, the region would lose over $2.67 million in ecosystem services a year.

LIMITATIONS AND FUTURE ANALYSIS

The accuracy of the benefit transfer method is limited by the similarities between the study site and policy site and will become less accurate as these sites deviate spatially and temporally. Our analysis used studies from the region, but even sites within New England have a range of ecosystem functions. Our analysis does not account for marsh migration, which varies for each site depending on elevation, land use, and sediment sources. Some marsh migration is likely to occur; more site-specific analysis is needed to determine which areas meet the conditions necessary. Not all climate change impacts to salt marshes are understood. Our analysis assumes ecosystem services would continue to function normally if not for SLR. However, habitat fragmentation and changes in temperature and weather could further reduce the ecosystem service values even if adaptations for SLR are put in place.

Sea level rise impacts to roads

SLR-induced flooding of roads could impact many assets along the coast. For example, property values and tax revenue (as captured in the property value section above) could decrease; drive times could increase because drivers have to take longer, alternative routes that have more congestion; emergency response times might increase; evacuation routes could be impacted; and roads could be damaged and lost.

This analysis assessed how many miles of road SLR will inundate over time. We quantified the damage to the road based on the estimated cost of building the road. The cost to keep the road functioning after SLR would be much higher and would require either 1) raising the road or 2) re-paving the road and implementing other strategies to keep the water out. Because of a lack of data and resources, we did not quantify the value of increased drive times, increased emergency response times, or evacuation route impacts.

METHODS

We primarily used GIS-based SLR data layers from the Cape Cod Commission's Open Data Hub to determine the miles of roads that would be exposed to 1 to 6 feet of SLR in Barnstable County. We also calculated the miles of road isolated using data available from the hub.

RESULTS

While SLR could flood many miles of road, each foot of SLR could isolate two to seven times more miles of roads from 2040 to 2093 (Table 23). Isolated roads could also impede access to properties that are not flooded.

Table 23. Miles of road impacted by SLR on Cape Cod.

Year	SLR* (ft)	Miles of Road Flooded	Damage to Roads Flooded (Millions 2020$)	Miles of Road Isolated
2040	1	13.7	$95.9	48.9
2054	2	30.9	$216.3	82.9
2066	3	62.3	$436.1	158.0
2076	4	107.7	$753.9	268.9
2085	5	158.4	$1,108.80	338.2
2093	6	211.6	$1,481.20	706.7

* Relative to MHHW (from Cape Cod Commission SLR inundation layers); relative to NAVD88 would be 0.84 ft higher.

LIMITATIONS AND FUTURE ANALYSIS

This analysis only accounts for the miles of road lost and costs associated with rebuilding the road as is, thus underestimating the damage. It provides a starting point by helping us see the size of the infrastructure investment that could be lost without action. Rebuilding in a manner that would prevent the roadway from flooding would require raising the road (many times more expensive than building at grade) or rebuilding the road in place while also implementing coastal armoring/natural infrastructure to keep the roadway dry. This does not consider other costs associated with tax revenue loss, lost time from traffic being forced to take alternative routes, slower emergency response times, or impacted evacuation routes.

Coastal erosion impacts to properties, tax revenue, and jobs

Cape Cod's beaches are naturally dynamic. In recent years, the rate of shoreline change has increased due to SLR as well as development and other human activities that interrupt sediment transport. The 2015 *Report of the Massachusetts Coastal Erosion Commission* puts the town of Yarmouth on the list of top 20 communities facing accelerated erosion rates, specifically 8.70 feet per year in Yarmouth between 1970 and 2009 (*Report of the Massachusetts Coastal Erosion Commission Volume 1: Findings and Recommendations*, 2015). This increase in erosion puts Cape Cod communities at an increased risk for habitat loss, property loss, and infrastructure damage by multiplying the effects from SLR and storm surge (Roberts et al., 2015).

Anecdotally, some beachside homeowners are combatting beach and dune erosion by investing in coconut fiber rolls that can be buried in sandy slopes in front of homes to hold the sand in place (at a cost of $200 to $2,000 per square foot of installation every five years[19]) (Deconto et al., 2019). Given the steps landowners are taking to protect their properties from erosion, including burying fiber rolls, stabilizing dunes, and building seawalls, it is undoubtedly important to understand the economic impacts of erosion on the Cape.

LIMITATIONS AND FUTURE ANALYSIS

Long- and short-term historic erosion and accretion rates are available for the Cape from the U.S. Geological Survey, Massachusetts Coastal Zone Management Agency, and Massachusetts Coastal Erosion Commission. In developing the Cape Cod Coastal Planner, an online decision-support tool, the Cape Cod Commission projected these erosion rates forward 40 years to estimate future impacts. While this future projection is helpful for planning purposes, it is challenging to estimate damages without "double counting" because erosion is closely linked to SLR and storm surge impacts. In a future analysis, we recommend integrating SLR, storm surge, and erosion projections to support a combined analysis of economic impacts.

Severe Precipitation Events

In addition to storm surge and coastal flooding, Cape Cod deals with flooding from extreme precipitation events. These events may or may not accompany high surge and surf. Precipitation-based flooding is due to an influx of rain at a faster rate and volume than infiltration and stormwater and drainage systems can accommodate. These flood events may extend far inland and lead to a range of problems for communities, including but not limited to flooded roads, properties, and other infrastructure, as well as water quality issues as pollutants are mobilized.

[19] Costs in 2019$.

Given the challenges of projecting localized precipitation and calculating how new precipitation patterns will impact on-the-ground infiltration and flood patterns, one of our best starting points for looking at rain-induced flooding is the FEMA floodplain. On Cape Cod, 15,000 single-family homes are located within FEMA's special flood hazard area (see Figure 6), which is defined by an area's susceptibility to flooding during a 1 percent annual chance flood event. This flood hazard can be associated with creek or coastal flooding or flood-related erosion hazards and may include additional effects of storm waves. Homeowners in this flood hazard area with mortgages from government-backed lenders are required to have flood insurance (Flood Insurance | FEMA.Gov, n.d.).

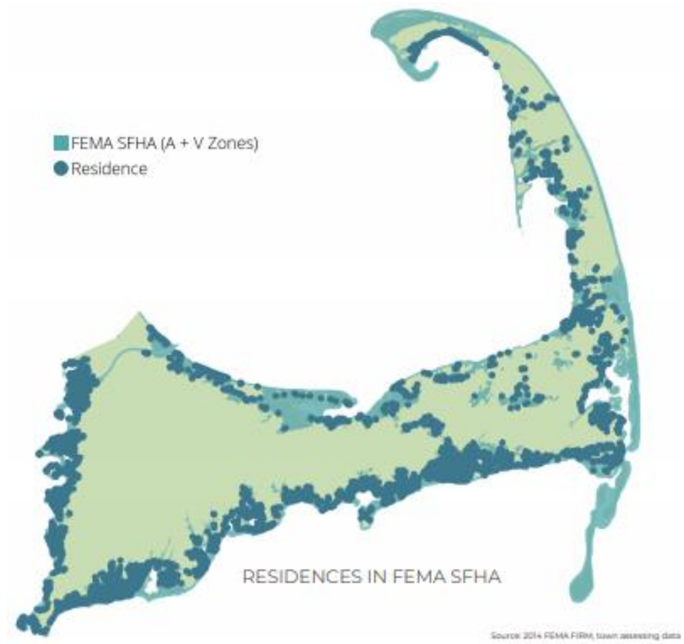


Figure 6. Residences in the FEMA special flood hazard area (credit: Cape Cod Commission).

Our earlier discussion of SLR and storm surge impacts to properties considers the effects of a 1 percent annual chance coastal storm surge. Using the data currently available, we cannot readily quantify potential damages from a severe rainstorm (causing overland and creek flooding) as distinct from a flood event driven by storm surge.

FUTURE ANALYSES

Moving forward, we recommend evaluating precipitation-based flooding as distinct from storm surge-driven flooding to avoid accounting for surge impacts twice.

Cross-Cutting Climate Hazards and Impacts to Industry

Impacts of climate change to fisheries and aquaculture

Fisheries and aquaculture are important parts of Barnstable County's economy and heritage. They support local seafood processing businesses, markets, and restaurants. Additionally, fresh seafood and healthy fisheries support tourism and recreational fishing off the Cape. Rising ocean temperatures and increasing ocean acidification threaten to change the health, distribution, and population of these fisheries, making this economic sector particularly vulnerable. Approximately half of commercial, forage, and protected fish and invertebrate species in the Northeast are expected to be negatively affected by ocean warming and acidification by 2050 (USGCRP, 2018). These impacts will ripple through the ecosystem, affecting valuable and iconic fisheries including Atlantic cod, Atlantic sea scallops, and American lobster.

METHODS

In this section, we present the data available for Barnstable County fisheries and aquaculture and summarize the predicted climate change impacts on major fisheries for the county to show the risk to the industry if no action is taken.

RESULTS

In 2017, Barnstable County had 1,175 people working in fishing, aquaculture, seafood processing, and seafood markets, over 822 of whom were self-employed (*ENOW*, 2020). The industry contributed $14.9 million in local wages and $34.2 million in regional gross domestic product (*ENOW*, 2020). Climate changes put this multimillion-dollar sector of the economy at risk, threatening the livelihoods of over a thousand county residents.

The main fisheries of Cape Cod are presented in Table 24, with landing data from 2014 (more recent data at the county level was not available). We calculated an estimated value for each species using the state average price per pound paid to fishermen according to the National Marine Fisheries Service (NMFS). The value used is the price paid to fishermen at the first time of sale. The regional landing data come from the Cape Cod Commercial Fishermen's Alliance. The landings for scallops and mussels include shell weight, and NMFS data are given in pounds of meat per dollar. Although, we were not able to estimate the value of all species in Table 24, the Cape Cod Commercial Fishermen's Alliance finds the sea scallop fishery to generate over $5 million worth of revenue for the region each year.

Table 24. Landings in Barnstable, Dukes, and Nantucket counties.

Species	Landings* (Pounds)	Average Price per Pound	Value (2020$)
Skate	9,000,000	$0.38	$3,428,998
Dogfish	6,312,441	$0.23	$1,483,242
Sea scallops**	5,317,258	$13.93	-
Mussels**	5,138,648	$0.85	-
Lobster	3,564,209	$4.88	$17,397,938
Conch**	1,771,671	$4.98	-
Bay scallops**	830,535	$16.17	-
Striped bass	741,231	$4.64	$3,441,043
Monkfish	739,164	NA	-
Bluefish	373,446	$1.15	$430,931
Atlantic cod	170,150	$1.91	$324,754
Black sea bass	161,195	$3.57	$575,195
Bluefin tuna	118,200	$6.66	$787,355

* Landings are from Barnstable, Dukes, and Nantucket counties, circa 2014.
** Species landings include shell weight, while price per pound is from weight of meat per pound.

Many of these fisheries are at risk of climate change impacts. Scallops and lobsters are particularly vulnerable to ocean acidification and warming ocean temperatures. In 2019, Cape

Cod fishermen experienced a large lobster die-off because warmer surface water prevented water from mixing vertically. This stratification led to an accumulation of nutrients and organic matter that depleted the dissolved oxygen as they decayed. Without the mixing of oxygen-rich surface water with water at lower levels, many benthic-dwelling organisms, including lobster, died of hypoxia.

Ocean temperatures are rising at an increasingly faster rate in the Northeast compared to other regions in the United States. From 2007 to 2016, regional waters increased by 0.25° F a year, which is four times faster than the long-term trend (NAC, 2018). Sea surface temperatures along the Northeast continental shelf warmed three times faster in the last 30 years than the global average. This warming has already impacted marine ecosystems and fisheries by shifting characteristics of phytoplankton blooms and the timing of fish and invertebrate reproduction (USGCRP, 2018). Many fish and invertebrates in the region have been moving northward. Figure 7 displays trends of key New England fisheries and their northward migration based on their latitudinal centers of biomass. The majority of American lobster are now found in waters north of Cape Cod (at 41.67° N) and will continue moving farther north as waters warm. These changes will impact fisheries by increasing the distance fishermen travel and expenses such as equipment and fuel. But warming waters may also introduce new target species as fish from farther south migrate north.

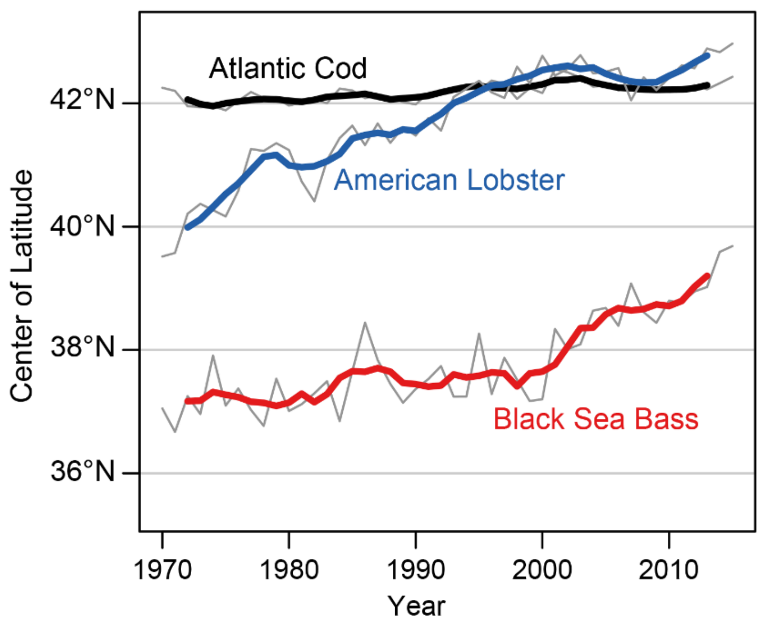


Figure 7. Migration of key fisheries (Source of graph: National Climate Assessment, 2018).

Ocean acidification also threatens local fisheries, particularly lobster and other shellfish. Since the preindustrial era, sea surface pH has dropped 0.1 pH units, resulting in a 26 percent increase in acidity in the last 150 years (Cooley & Doney, 2009). Ocean acidification, a consequence of rising anthropogenic CO_2 emissions, is poised to change marine ecosystems profoundly by increasing dissolved CO_2 and decreasing ocean pH, carbonate ion concentration, and calcium carbonate mineral saturation worldwide. These conditions hinder many marine plants and animals from growing calcium carbonate shells and skeletons. The first direct impacts on humans may be through declining harvests and fishery revenues from shellfish, their predators, and coral reef habitats. Using a case study of U.S. commercial fishery revenues, we began to constrain the economic effects of ocean acidification over the next 50 years by applying atmospheric CO_2 trajectories and laboratory studies of their effects, focusing especially on mollusks.

In 2007, the $3.8 billion U.S. annual domestic ex-vessel commercial harvest ultimately contributed $34 billion to the U.S. gross national product. Mollusks contributed 19 percent, or $748 million, of the ex-vessel revenues that year. Substantial revenue declines, job losses, and indirect economic costs could occur if ocean acidification broadly damages marine habitats, alters marine resource availability, and disrupts other ecosystem services. We reviewed the implications for marine resource management and marine-resource-dependent communities, many of which already possess little economic resilience (Feely et al., 2009). Ocean pH is predicted to decline another 0.2 to 0.3 pH units by 2100. Higher acidity increases the energy mollusks need to form shells as they grow, taking away energy from other functions such as reproduction and immunity. The impacts of acidification alone could cause U.S. commercial shellfisheries to lose hundreds of billions of dollars in revenue by 2070.

These impacts might hit Barnstable County's top fisheries hard. Atlantic bay scallops have already experienced declines in growth, survival, and development due to ocean acidification (Rheuban et al., 2018). As the ocean continues to acidify, the biomass of sea scallops is predicted to decline by 50 percent by 2100 (Rheuban et al., 2018). Lobsters living in acidified ocean water exhibit significantly smaller growth, take longer to reach each molt stage of development, and have reduced survival rates (Keppel et al., 2012).

The loss of eelgrass and salt marsh habitats might also impact local fisheries, as they are key places for many species to nurse and forage. Changes to a few species can ripple throughout the marine ecosystem and impact commercial species that are not directly affected by climate change. While fisheries may adapt by targeting new species as current fisheries decline, the economy might still experience negative impacts. Lobster and scallops are some of the highest value species for fishermen in Barnstable County, and the loss of these fisheries could result in reliance on lower value catch. Changing to different fisheries could require new investments in equipment to comply with industry standards, and lower value species could require more time and effort to replace revenue lost by affected species.

AQUACULTURE

Warming and more acidic waters might also impact the growing aquaculture industry. In 2019, there were 265 licensed growers and 676.6 acres permitted for aquaculture cultivation in

Barnstable County (Kennedy et al., 2020). This represents over half of the aquaculture acreage in Massachusetts.

Oysters represent more than 95 percent of all aquaculture-raised products in Massachusetts (Kennedy et al., 2020). Oyster landings for Barnstable, Dukes, and Nantucket counties increased by 10,000,000 pieces from 2014 to 2018, bringing in an additional $5.5 million in revenue (Kennedy et al., 2020). Table 25 presents the 2019 landings and value of oysters in Barnstable County (Kennedy et al., 2020). Over $17 million of oysters were grown in Barnstable, a value similar to that of American lobster caught in the county.

Table 25. 2019 Aquaculture landings for oysters in Barnstable County.

Town/Region	Pieces	Reported Value
Barnstable	13,388,942	$7,358,572
Bourne/Falmouth	1,024,211	$563,867
Brewster	586,945	$336,143
Chatham	830,078	$490,699
Dennis	2,328,009	$1,278,132
Eastham	952,324	$505,712
Mashpee	326,051	$187,631
Orleans	1,128,850	$648,828
Provincetown/Truro	146,783	$88,321
Wellfleet	10,089,940	$5,437,374
Yarmouth	907,110	$498,202
Total	**31,709,243**	**$17,393,481**

Like sea scallops, oysters and clams are vulnerable to ocean acidification. The increased frequency and intensity of storms damage equipment and infrastructure necessary for growing oysters, increasing capital costs for growers. Increasing temperatures also make oysters and other shellfish more vulnerable to diseases and parasites that kill them in early life stages. Paralytic shellfish poisoning (PSP), a biotoxin caused by toxic algae that infects oysters during harmful algal blooms, threatens oysters and public health. Outbreaks of PSP can cause temporary or permanent closures of aquaculture operations, resulting in revenue losses to growers. Increasing ocean temperatures are predicted to increase algal bloom events and thus are likely to increase the occurrence of PSP outbreaks.

LIMITATIONS AND FUTURE ANALYSIS

Our assessment provides an overview of what is at risk; it does not project economic losses in Barnstable County. The data available included landings from Dukes and Nantucket counties, in addition to Barnstable County landings. Multiple years of data at this level were not available, and we were unable to assess and compare current trends in landing data with climate trends. Species have varying levels of vulnerability and adaptability to climate change. Future analysis could examine species-level impacts and responses to ocean warming and acidification.

Impacts of climate change to agriculture

The most economically valuable crop in Massachusetts is the cranberry, and Cape Cod's natural environment has historically provided ideal conditions for cranberries to grow (*USDA 2019 State Agriculture Overview for Massachusetts*, 2020). They are native to the region and represent an important part of Cape Cod's history, culture, and economy. In 2019, Massachusetts was responsible for over a quarter of the United States' cranberry production, and most of this production is concentrated in the Cape Cod region (New England Agricultural Statistics Service, 2020). Cranberries have about a $1.4 billion economic impact on Massachusetts, providing over 2,100 full-time equivalent jobs within the state and an additional 4,800 jobs in the support and processing sector of cranberry production (MA Department of Agricultural Resources, 2016). The vitality of the industry is at risk due to a variety of economic and environmental pressures (MA Department of Agricultural Resources, 2016).

METHODS

We primarily conducted a SLR flooding vulnerability analysis on cranberry bogs on Cape Cod. We obtained data on active cranberry bogs as of May 2013 and SLR layers from the Cape Cod Commission's Open Data Hub. Table 26 presents the acres of bogs impacted for each foot of SLR and the year in which the SLR is expected to occur.

Table 26. Acres of Cape Cod cranberry bogs impacted by SLR.

Year	SLR* (ft)	Number of Cranberry Bogs Impacted	Acres of Bogs Impacted
2040	1	11	146.3
2054	2	13	161.2
2066	3	19	196.6
2076	4	28	295.5
2085	5	31	316.8
2093	6	34	410.1

* Relative to MHHW.

To determine the annual rate of bog loss due to SLR, we first calculated the annual rate of loss between 2020 and 2039 to be 5.94 acres/year, assuming the acres of bogs are lost at a constant rate. We then used a polynomial regression to estimate the annual rate of bog loss from 2040 to 2100.

Cranberry yield per acre (barrels/acre) and the price per barrel were obtained from the U.S. Department of Agriculture (New England Agricultural Statistics Service, 2020). Based on data from 2015 to 2019, the average yield for Massachusetts cranberries was 172.3 barrels/acre, and the average price per barrel was $29.98. We calculated the revenue per acre of cranberry bog by multiplying the yield per acre by the price per barrel (Table 27).

Table 27. Massachusetts cranberry yield per acre and price per barrel (Source: New England Agricultural Statistics Service, 2020).

Year	Yield (Barrels) per Acre	Price per Barrel (2020$)[20]	Revenue per Acre (2020$)
2015	177.3	$32.80	$5,815
2016	174.3	$30.70	$5,351
2017	154.0	$31.50	$4,851
2018	180.4	$27.10	$4,889
2019	175.6	$27.80	$4,882
Average (2015–2019)	**172.3**	**$29.98**	**$5,166**

RESULTS

Cranberry production is vulnerable to climate change impacts in many ways. Cranberries require cool temperatures when maturing, cold winters (about 62 days below 45° F), and boggy habitats. Climate change projections indicate that the Northeast may experience milder and shorter winters, hotter summers, and increased precipitation. Milder winters may not only impact the cranberry's cold winter requirements, but also allow cranberry pests to thrive and reduce harvest yields. Additionally, hotter summers may increase heat stress on the plants, and increased precipitation may lead to poor pollination and higher rates of plant infection (Armstrong, 2016).

As of May 2013, 127 cranberry bogs covered 1,218.3 acres on Cape Cod. These cranberry bogs collectively produce $6.3 million in revenue per year based on a revenue of $5,166 per acre. However, 9 to 34 percent of Cape Cod's cranberry bogs could be impacted by 1 to 6 ft of SLR.

Using the $5,166/acre value, we estimate that 1 foot of SLR will impact roughly 150 acres of Cape Cod cranberry bogs, resulting in a lost economic value of $755,800. As sea levels continue to rise beyond 1 foot, more and more cranberry bogs will be impacted, resulting in greater and greater economic losses (Table 28). Figure 8 shows the bogs that each increasing foot of SLR will impact. Darker colors indicate the bogs that will be flooded sooner (with lower levels of SLR) and lighter colors indicate bogs that will be flooded later (with higher levels of SLR). Point size indicates the bog size in acres. Figure 8 only shows impacted bogs, which represent about one-third of all bogs in the region.

Table 28. SLR impact on cranberry production on Cape Cod.

Year	SLR* (ft)	Number of Cranberry Bogs Impacted	Acres of Bogs Impacted	Lost Revenue ($)
2040	1	11	146.3	$755,800
2054	2	13	161.2	$832,800
2066	3	19	196.6	$1,015,700
2076	4	28	295.5	$1,526,600
2085	5	31	316.8	$1,636,600
2093	6	34	410.1	$2,118,600

* Relative to MHHW.

[20] The source does not provide the dollar year. We assume that the values are in 2020$, the same year that the source was published.

By 2100, Cape Cod may experience a loss of $79.2 million due to SLR impacts on cranberry bogs. This analysis assumes a linear rate of bog loss between 2021 and 2039 and uses the results of a polynomial regression to estimate the annual rate of bog loss between 2040 and 2100. Table 29 provides the projected economic value lost due to SLR impacts on Cape Cod cranberry bogs.

Table 29. Economic value lost due to SLR impacts on Cape Cod cranberry bogs.

Years	Average Annual Loss (2020$)	Cumulative Lost Value (2020$)
2021–2030	$168,800	$1,688,000
2031–2050	$556,100	$11,121,000
2051–2100	$1,327,700	$66,385,000
Total (2021–2100)	**$989,900**	**$79,194,000**

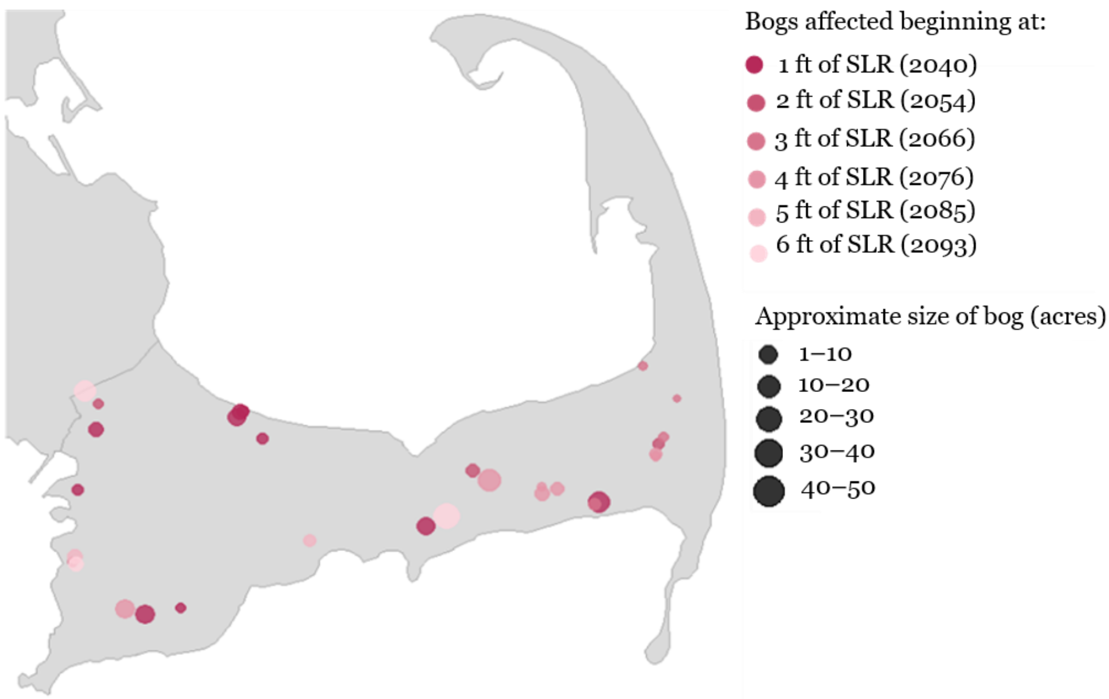


Figure 8. Cape Cod cranberry bogs affected by SLR.

LIMITATIONS AND FUTURE ANALYSIS

This analysis likely underestimates the impact of SLR on Cape Cod's agricultural sector, focusing only on the impact to cranberry bog production and not any jobs lost because of the decrease in cranberry bogs. Future analyses should account for these potential lost jobs—including those impacted down the supply chain in the manufacturing/processing of cranberry-related goods—and the ripple effect through the rest of the Massachusetts economy. The cumulative economic impact from lost cranberry bogs, including from job losses, is likely to significantly impact Cape Cod and Massachusetts at large.

Cranberry bogs have been identified as potentially ideal sites for wetland restoration projects (MA Division of Ecological Restoration, 2018). Many of the cranberry bogs on Cape Cod were previously undisturbed wetland bogs (MA Department of Agricultural Resources, 2016). Restoring the cranberry bogs to their original wetland state can provide many benefits, such as increasing habitat for wildlife, fish, and shellfish; providing flood and erosion protection; improving surface water quality by filtering pollutants; and providing recreation areas (OW US EPA, 2015). Wetland restoration can also help address a variety of the climate change problems that Cape Cod is facing. In Part 3 of this report, we look at the nitrogen removal benefits of converting bogs to their original wetland ecosystems. Future analyses should look at the additional tradeoffs associated with converting cranberry bogs to wetlands.

Cross-Cutting Climate Hazards and Public Health Impacts

Impact of criteria pollutants on public health

Criteria pollutants—including particulate matter ($PM_{2.5}$), nitrous oxides (NO_x), and sulfur dioxide (SO_2)—are emitted from vehicle tailpipes, onsite building energy (e.g., propane, fuel oil, natural gas), and power plants, among other sources. Barnstable County residents and visitors are experiencing and will likely continue to experience negative health impacts from tailpipe and onsite building emissions of these criteria pollutants. Power plants that serve Barnstable County might also cause health impacts, including asthma, cancer, and sometimes death, to people throughout the region who are located near the plants.

METHODS

Part 2 of this report includes results that show emissions of criteria pollutants for the sustained policy case (baseline) and four decarbonization scenarios. Part 3 demonstrates the approximate economic loss (in terms of health impacts) of the sustained policy case compared to decarbonization scenarios in the transportation, building energy, and electricity sectors.

Impact of extreme heat on public health

Extreme weather events caused by climate change can cause a host of physical and mental public health issues. Of growing concern in the Northeast are heat-related illnesses and deaths caused by increasing temperatures. Populations most vulnerable to heat-related morbidity include the elderly and people who live alone.

METHODS

We estimated health care costs of current high heat days by connecting statewide costs of emergency department visits and national costs for heat-related hospital stays with heat illness tracking data for Barnstable County (*Heat Stress Hospitalization | MEPHT*, 2020). We considered these costs in light of projected five- to eight-fold increases in high heat index days (over 90° F) per year by midcentury (over historic numbers) (Dahl et al., 2019).

RESULTS

The Health Care Cost Institute compiled a national data set of emergency department visits (broken down by state) from 2009 to 2015 to track changing and generally increasing costs of emergency department visits (Health Care Cost Institute, 2015.). The procedure codes tracked are key components of an emergency room visit and basic evaluation. As such, these costs capture the base cost of visiting the emergency department for heat illness (even though heat illness is not the focus of the data). For Massachusetts, these costs increase each year, with the average price per claim reaching $565 by 2015 ($612 in 2020$). If we assume that emergency room visits for the approximately 36 annual heat illness patients in Barnstable County (an average annual case count from 2010 to 2016; *Heat Stress Hospitalization | MEPHT*, 2020) cost at least $612 per visit, the annual cost of these emergency room visits amounts to approximately $22,032 today.

The average cost per heat-related hospital stay is estimated at $6,717 in 2020$ (converted from 2005$). Applying this cost to the approximately three annual hospitalizations in Barnstable County (an average annual heat hospitalization count from 2010 to 2016; *Heat Stress Hospitalization | MEPHT*, 2020) puts the cost of today's heat-related hospitalizations at about $20,152. Hospitalizations and emergency department visits combined cost about $42,200 per year.

Incidences of illness and treatment costs are both relatively low but will rise with a growing number of extreme heat days. Historically (1971–2000), Barnstable County has experienced an average of two high heat index days (over 90° F) per year. By midcentury (2036–2065), the county is expected to experience an average of 11 to 17 annual high heat days (the range is based on the extent to which the globe cuts emissions). By late-century (2070–2099), the county is expected to experience 17 to 45 annual high heat days (Dahl et al., 2019). We expect heat illness cases to grow under these changing conditions.

LIMITATIONS AND FUTURE ANALYSIS

The hospital and emergency department costs above are a small component of public health costs related to extreme heat. Future analyses should evaluate impacts to mental health as well as outdoor worker safety and the related economic consequences of altering work schedules to avoid high heat times.

Impact of vector-borne diseases on public health

Like much of New England, Cape Cod is expected to experience an increased prevalence of Lyme disease and West Nile virus (OAR US EPA, 2016). Escalating Lyme infection rates are particularly concerning, with disease symptoms that can include arthritis, Bell's palsy and other cranial nerve palsies, meningitis, and carditis. These symptoms lead to costly medical treatments, income loss, and lower quality of life. While West Nile virus is less common, increasing cases are also concerning because the virus can be fatal in rare cases.[21] While

[21] https://www.cdc.gov/westnile/index.html

warming winters contribute to increased incidence of these vector-borne diseases, a variety of landscaping and development practices also contribute to this increase.

METHODS

Given the complex factors impacting Lyme and West Nile virus infection rates, we cannot project future infections in Barnstable County. Rather, we can draw on existing literature on the cost to treat patients and number of infections in the region to estimate the current costs of treating infections in Barnstable County. We will provide qualitative discussions of the latest literature on how a changing climate is expected to impact disease prevalence.

RESULTS

Lyme disease: In 2019, there were 107 emergency department visits due to tick-borne disease in Barnstable County (*Monthly Tickborne Disease Reports | Mass.Gov*, 2020). While these visits may have resulted in a diagnosis of Lyme disease, babesiosis, or anaplasmosis, Lyme makes up the majority of diagnoses in the state.

A 2006 study in Maryland estimates that a Lyme disease patient (whether early or late stage) incurs an annual average of $4,273 in direct medical costs plus $7,485 (2019$) in indirect medical costs, nonmedical costs, and productivity losses (Zhang et al., 2006). These direct medical costs are supported by a national-level study in 2015 that estimates Lyme disease is associated with $3,200 (2019$ adapted from 2015$) in higher total annual health care costs (Adrion et al., 2015). If we apply costs from the Maryland study, we can assume that Lyme disease costs are $4,273 for direct medical costs plus $7,485 for indirect costs for a total annual cost of almost $12,209 (2019$). If we assume that 107 tick-borne disease visits last year were diagnosed as Lyme disease, the total cost associated with infections from that year is approximately $1.7 million.

West Nile virus: Barnstable County has recorded no cases of West Nile virus for eight of the past 10 years. In 2017 and 2018, the county recorded between one and 10 cases each year (*ArboNET Disease Maps*, 2020). Additional research is needed to estimate the costs of treating those patients.

LIMITATION AND FUTURE ANALYSIS

We recommend further investigating the costs of treating and managing these diseases, especially an expanded literature review on the costs to treat West Nile (as this was beyond the scope of this study). These cost analyses can be improved as data tracking on current cases of Lyme in Barnstable County improves, especially as some Lyme cases do not result in an emergency department visit. They can also be improved as future projections of the prevalence of these diseases improve.

Part 2. Mitigation Scenarios and Scenario Metrics

We provided energy sector modeling services in support of the Cape Cod Commission's efforts to explore the economic impacts of climate change. Energy sector modeling focused on an exploration of several GHG emissions mitigation scenarios. We performed modeling for three primary energy sectors: transportation, buildings, and electricity because these were the primary contributors to GHG emissions in the Cape Cod GHG emissions inventory, which each included a sustained policy scenario (i.e., we continue to operate business as usual according to any policies in place at the time of this analysis), as well as four decarbonization scenarios to reduce emissions across these three sectors.

For this analysis, we developed scenarios in an effort to meet Massachusetts's goal to reduce GHG emissions by at least 85 percent below 1990 levels by 2050. At the time of this analysis, the state also adopted a 2030 target of 50 percent below 1990 levels, which we aligned with in this analysis. It is widely acknowledged in the literature that meeting these aggressive GHG targets requires deep decarbonization across all sectors.[22] The pathway to decarbonization requires fuel-switching from petroleum-based fuels and natural gas used in the transportation and buildings sectors to clean renewable electricity. Thus, the focus of our energy sector modeling was the transition to an electric grid with low and zero carbon emissions generation sources and beneficial electrification of the transportation and buildings sectors.

Methods

We used the following modeling tools for the three energy sectors:

EV-REDI for the transportation sector: EV-REDI is a custom-built stock-flow model for modeling multiple impacts of transportation electrification for individual states. EV-REDI contains data on vehicle sales, stock, efficiencies, CO_2 emissions, and criteria pollutant emissions. It allows modelers to quickly develop different projections of electrification and emissions for light- (e.g., passenger vehicles), medium- (e.g., class 6 trucks), and heavy-duty vehicles (e.g., tractor trailers used for long-haul travel), and other parts of the transportation sector. EV-REDI can also be used to evaluate the emissions impacts of light-duty vehicle adoption trajectories, as well as the emissions impacts of non-light-duty vehicles.

The Buildings Decarbonization Calculator (BDC) for the buildings sector: The BDC is a custom-built calculator for modeling the evolution of building energy consumption for space and water heating in the residential and commercial sectors. The model calculates the impact of changes in the market share of heating system technology on both total heating system stock and energy consumption by fuel type. It accounts for the expected lifetimes of space and water heating technologies, the efficiencies of systems installed each year, and changes in the total number of households and commercial buildings over time.

Independent System Operator (ISO) of New England forecasts for the electricity sector: This modeling uses existing forecasts for the electricity sector produced by ISO New England, which is responsible for operation of the bulk transmission system across all New England states, operation of wholesale energy markets, and system planning. As part of the system planning function, ISO New England produces electricity forecasts for each New England state. We used the forecast for Massachusetts to calculate an average compound annual

[22] See, for example, The Brattle Group. September 2019. *Achieving 80% GHG Reduction in New England by 2050: Why the region needs to keep its foot on the clean energy accelerator*. Available at https://brattlefiles.blob.core.windows.net/files/17233_achieving_80_percent_ghg_reduction_in_new_england_by_20150_september_2019.pdf.

growth rate (CAGR) for electric sales. The CAGR was applied to Barnstable County's 2017 electricity consumption used for the 2017 Cape Cod GHG emissions inventory. GHG emissions were based on New England-wide average per MWh. The baseline trajectory for electric sector GHG emissions assumes Massachusetts meets its existing regulatory goal of supplying 80 percent of all electricity in 2050 with zero-carbon renewable sources of generation.

We performed energy sector modeling sequentially, starting first with the transportation and buildings sectors. These models provide annual fuel use, including electricity consumption for electric vehicle (EV) charging and heat pumps in buildings. We then added the incremental annual electricity consumption associated with newly electrified end uses to ISO New England's baseline electricity consumption forecasts to calculate total projected electric load in Barnstable County.

Non-energy emissions in Barnstable County account for 5.3 percent of total emissions. This category includes GHG emissions from industrial processes, agriculture, and waste emissions. Unlike the energy emissions, the non-energy emissions were not modeled in-depth. Waste emissions were assumed to change proportionally with population over time and agriculture emissions were held constant. Industrial process emissions were assumed to decline over time due to the expectation that new regulations will limit the use of high global warming potential gases for industrial processes.

We began the modeling by developing a baseline from which we evaluated alternative decarbonization scenarios. The baseline modeling in each sector adopted a sustained policy approach, which assumes that the current policy goals are met, thus representing a snapshot in time given the current policy context.[23]

In collaboration with the Cape Cod Commission, we developed four decarbonization scenarios to explore pathways to achieve proportional emissions reductions in the county to align with Massachusetts's GHG targets. Transportation sector decarbonization scenarios included varying degrees of vehicle fleet electrification and reductions in vehicle miles traveled (VMT). The building sector decarbonization scenarios included varying degrees of heating systems electrification and building efficiency gains. The four decarbonization scenarios are the following:

- **SER1**—The state-level emissions reduction baseline scenario determines the level of beneficial electrification necessary given baseline energy efficiency gains to meet Massachusetts's GHG emissions reduction goals.
- **CEN**—The carbon emissions neutrality reduction scenario determines the level of beneficial electrification necessary given baseline energy efficiency gains to meet the goal of carbon neutrality by 2050.While all three "SER" scenarios are strictly based on emissions reductions from 1990 emissions levels, this scenario is a slightly more aggressive decarbonization scenario (approximately a 90 percent reduction from 1990 levels) where all remaining emissions are offset by sequestration. This scenario assumes

[23] For details on all assumptions used in the sustained policy and decarbonization scenarios, please see the interim deliverable Barnstable, MA: Final GHG Mitigation Modeling Scenarios and Priority Metrics slide deck dated November 18, 2020.

sequestration increases from 9 percent in 2017 to around 12 percent of 2017 emissions levels by 2050 (as given in the Cape Cod GHG Inventory).

- **SER2**—The state-level emissions reduction aggressive efficiency scenario determines the level of beneficial electrification necessary assuming aggressive efficiency efforts to meet Massachusetts's GHG emissions reduction goals. These efforts include targeted programs and policies on Cape Cod to aggressively reduce VMT and improve the energy performance of homes and businesses through weatherization.
- **SER3**—The state-level emissions reduction year-round residency sensitivity scenario determines the level of beneficial electrification necessary assuming 50 percent of seasonal residents convert to year-round residents relative to historic patterns, while meeting Massachusetts's GHG emissions reduction goals.

MODELING ASSUMPTIONS FOR TRANSPORTATION SECTOR

Table 30 lists the assumptions for the transportation sector modeling for the sustained policy baseline and the four decarbonization scenarios. We provide more detailed metrics for each scenario in Appendix C of this report.

Table 30. Modeling assumptions for transportation sector.

Scenario	Description
Sustained Policy (SP): Continue with electrification and efficiency measures in place	• 7% of light-duty vehicle (LDV) sales are electric by 2025 and 24% by 2030.[24] • Modest heavy-duty vehicle (HDV) sales are electric by 2030 (6% of medium-duty, 4% of heavy-duty, 24% of buses). • VMT per LDV remains constant through 2050. • VMT per HDV remains constant. • Fuel efficiency reaches 44 MPG for new cars and 32 MPG for new light trucks by 2030.
SER1 Aggressive electrification	• Aggressive LDV electrification (69,000 by 2030, 214,000 by 2050; 93% of sales in 2030, 100% of sales in 2050). • Aggressive HDV electrification (48% of sales in 2030, 100% of sales in 2050). • VMT per LDV remains constant through 2050. • VMT per HDV remains constant. • Fuel efficiency reaches 44 MPG for new cars and 32 MPG for new light trucks by 2030.
CEN Aggressive electrification	• Aggressive LDV electrification (69,000 by 2030, 214,000 by 2050; 93% of sales in 2030, 100% of sales in 2050). • Aggressive HDV electrification (48% of sales in 2030, 100% of sales in 2050). • VMT per LDV declines 2.5% by 2030 and 7.5% by 2050. • VMT per HDV remains constant.

[24] Our EV adoption forecasts for the sustained policies scenario came from Bloomberg New Energy Finance's 2020 EV Outlook ("BNEF EVO Report 2020 | BloombergNEF | Bloomberg Finance LP," n.d.).We used their national forecast of EV market share of new sales for light-, medium-, and heavy-duty vehicles.

Scenario	Description
	• Fuel efficiency reaches 44 MPG for new cars and 32 MPG for new light trucks by 2030. • Non-motor vehicle emissions (primarily from boats and aircraft) decline 48% by 2050, instead of remaining constant as in the other scenarios.
SER2: Aggressive efficiency with electrification	• Somewhat slower EV adoption relative to SER 1 (39,000 by 2030, 200,000 by 2050; 63% of sales in 2030, 100% of sales in 2050). • VMT per LDV declines 15% by 2030 and 25% by 2050. • VMT per HDV remains constant. • Fuel efficiency reaches 44 MPG for new cars and 32 MPG for new light trucks by 2030.
SER3: Increased year-round population	• Aggressive LDV electrification (70,000 by 2030, 283,000 by 2050; 85% of sales in 2030, 100% of sales in 2050). • Aggressive HDV electrification (44% of sales in 2030, 100% of sales in 2050). • VMT per LDV declines 9% by 2030 and 15% by 2050. • VMT per HDV remains constant. • Fuel efficiency reaches 44 MPG for new cars and 32 MPG for new light trucks by 2030. • Number of registered vehicles increases assuming 50% of part-time residents become full-year residents.

The following set of figures graphically depict key inputs into each transportation modeling scenario. Figure 9 presents the percent of light-duty EVs on the road over time for each scenario, and Figure 10 presents the percent of heavy-duty EVs on the road over time for each scenario. Note that in the figures below, a dashed line means two scenarios share the same trajectory.

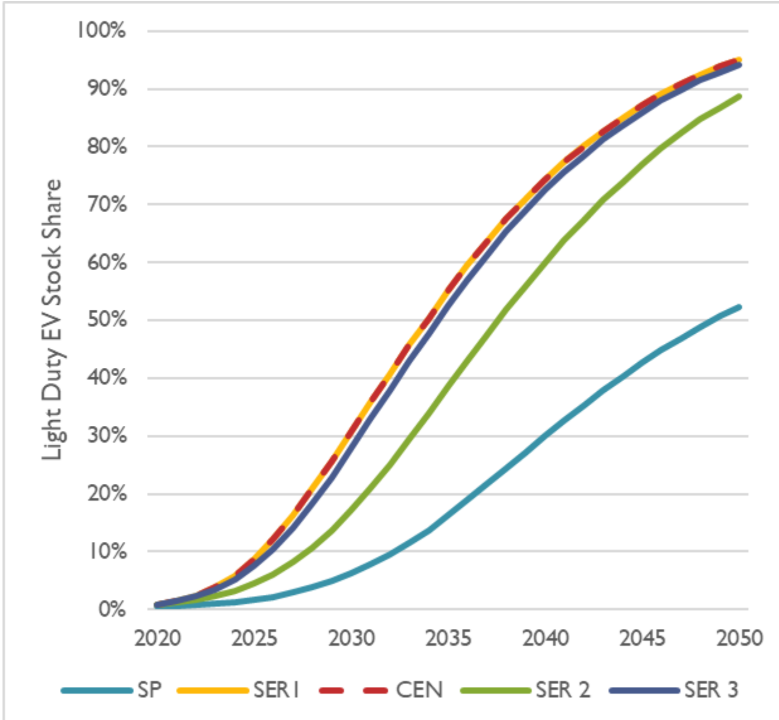


Figure 9. Percent of light-duty EVs over time by scenario.

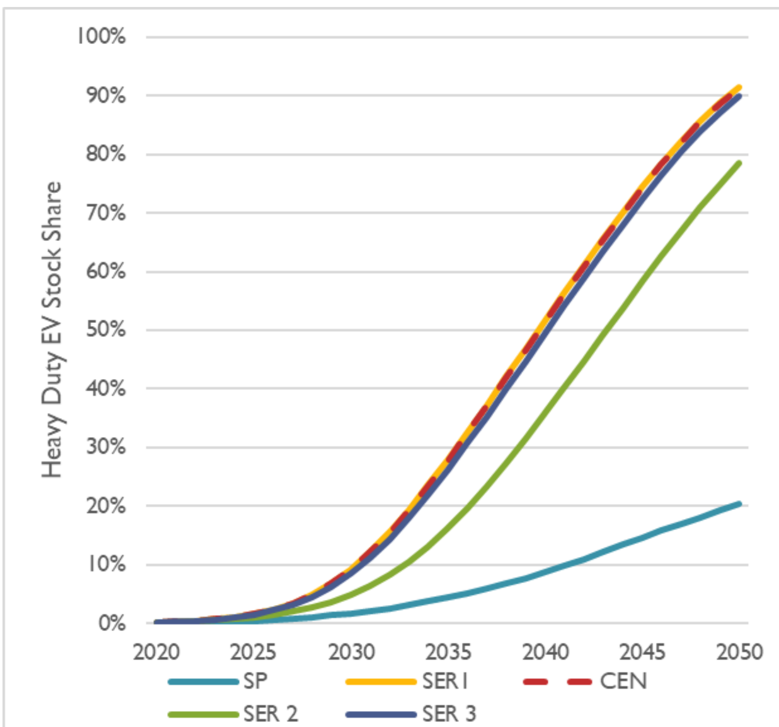


Figure 10. Percent of heavy-duty EVs over time by scenario.

Figure 11 and Figure 12 present the total light-duty EV stock and heavy-duty EV stock in Barnstable County, respectively, over time and by scenario.

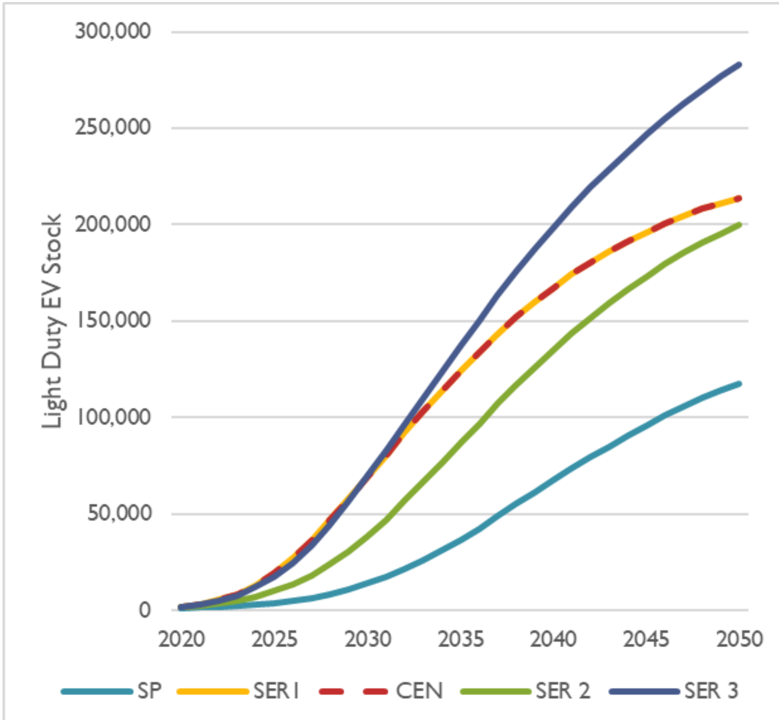


Figure 11. Total light-duty EV stock over time.

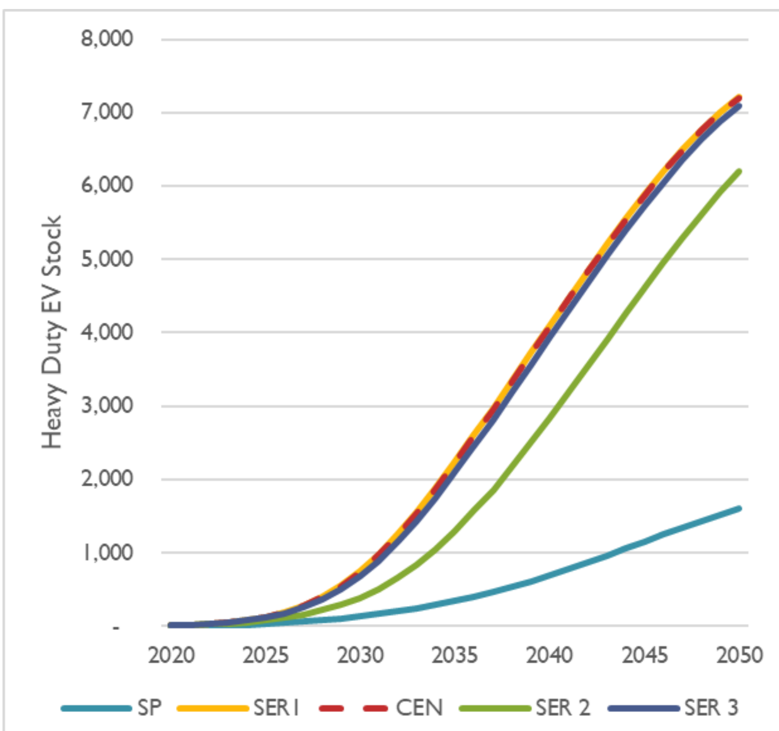


Figure 12. Total heavy-duty EV stock over time.

Figure 13 and Figure 14 depict the percent of new car sales by year that are light-duty EVs and heavy-duty EVs in Barnstable County, respectively.

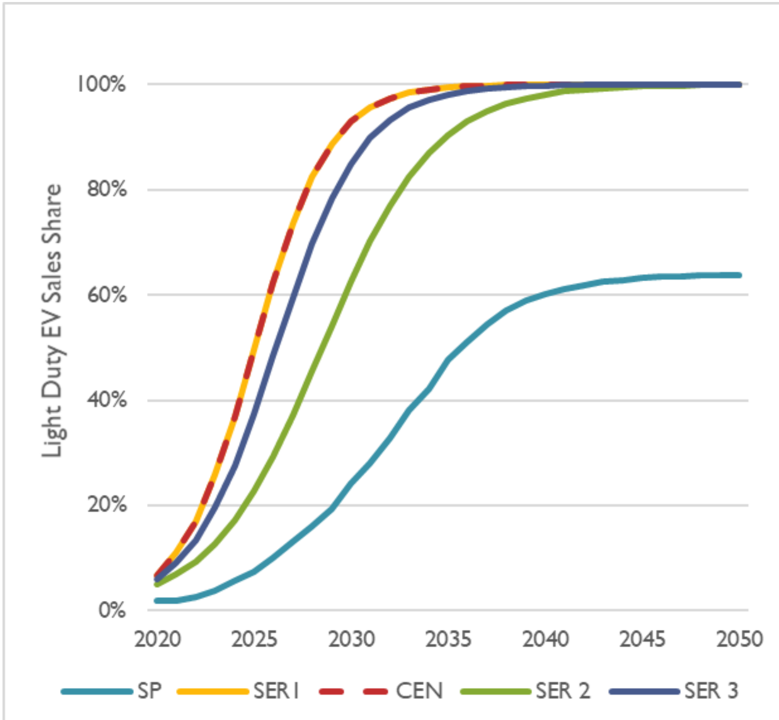


Figure 13. Percent of new light-duty vehicle sales that are EVs.

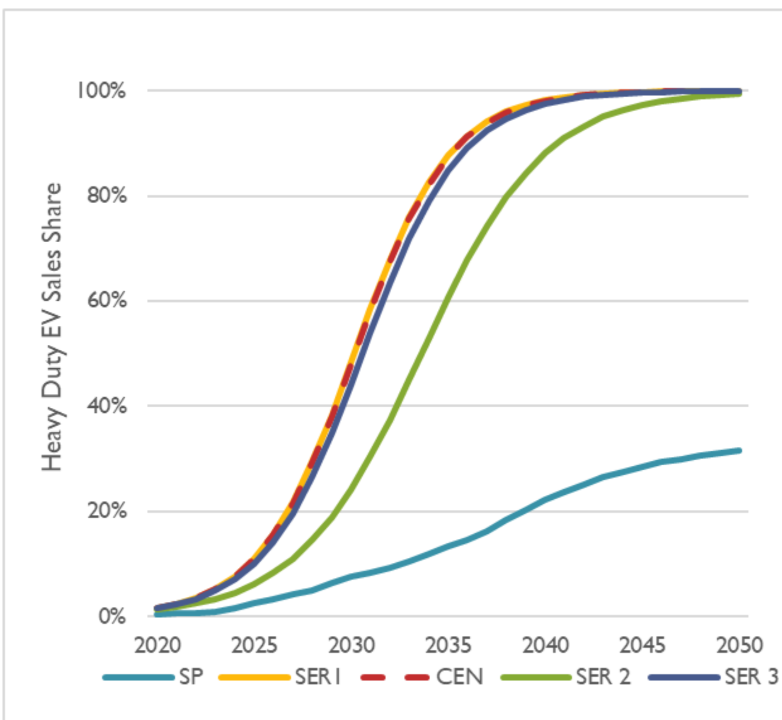


Figure 14. Percent of new heavy-duty vehicle sales that are EVs.

MODELING ASSUMPTIONS FOR BUILDING SECTOR

Table 31 lists the assumptions for the building sector modeling for the sustained policy baseline and the four decarbonization scenarios. We provide more detailed metrics for each scenario in Appendix C of this report.

Table 31. Modeling assumptions for building sector.

Scenario	Description
Sustained Policy (SP): Continue with electrification and efficiency measures in place	• 19% cumulative residential space heat energy reduction by 2050 through weatherization and new construction. • 18,000 residential heat pumps installed between 2021 and 2030. • Commercial heat pump market share reaches 29% among systems replacing oil boilers and 4% of systems replacing natural gas boilers.
SER1: Aggressive electrification	• 19% cumulative reduction in residential space heating energy consumption by 2050 through weatherization and new construction (8% by 2030). • Aggressive residential electrification (18,568 year-round homes with heat pump retrofits by 2030 and 45,295 by 2050; 15,100 year-round homes with whole-home heat pumps by 2030 and 46,223 by 2050). • Aggressive commercial electrification (2.8 million square feet of commercial space served by heat pumps in 2030 and 29.4 million square feet by 2050).
CEN: Aggressive electrification	• 19% cumulative reduction in residential space heating energy consumption by 2050 through weatherization and new construction (8% by 2030). • Aggressive residential electrification (18,568 year-round homes with heat pump retrofits by 2030 and 45,295 by 2050; 15,100 year-round homes with whole-home heat pumps by 2030 and 46,223 by 2050). • Aggressive commercial electrification (3.4 million square feet of commercial space served by heat pumps in 2030 and 30.3 million square feet by 2050).
SER2: Aggressive efficiency with electrification	• 25% cumulative reduction in residential space heating energy consumption by 2050 through weatherization and new construction. • Slightly less aggressive residential electrification (18,568 year-round homes with heat pump retrofits by 2030 and 48,944 by 2050; 8,501 year-round homes with whole-home heat pumps by 2030 and 40,052 by 2050).
SER3: Increased year-round population	• 19% cumulative reduction in residential space heating energy consumption per home by 2050 through weatherization and new construction (8% by 2030). • Aggressive residential electrification (18,568 year-round homes with heat pump retrofits by 2030 and 48,944 by 2050; 18,506 year-round homes with whole-home heat pumps by 2030 and 73,824 by 2050). • Aggressive commercial electrification (2.8 million square feet of commercial space served by heat pumps in 2030 and 29.4 million square feet by 2050). • 50% of currently seasonal housing units are assumed to become occupied year-round due to an increase in year-round residents.

Figure 15 through Figure 19 graphically depict the number of residential households in Barnstable County that use each type of fuel to heat their home. For all of these figures, "heat pump/fuel oil" and "heat pump/natural gas" refer to households with both energy sources to heat their home.[25] Note that while we did include seasonal homes in our analysis using the Commission's calculated energy use in seasonal homes relative to year-round homes, we decided not to show the seasonal homes in the stock charts (Figure 15 through Figure 19) because they use less energy than year-round homes and therefore did not seem to be equivalent.

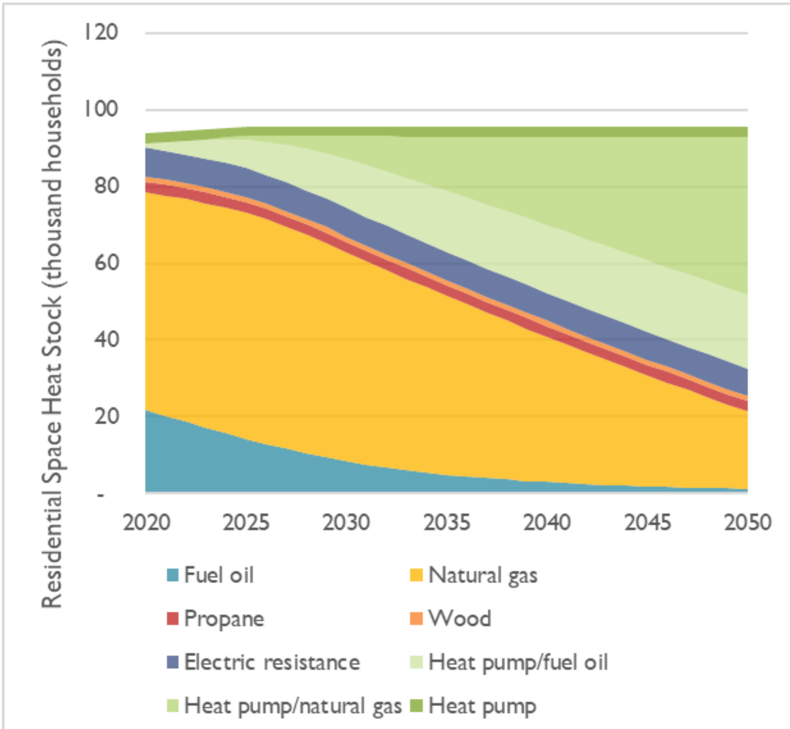


Figure 15. Sustained policy residential space heating stock (year-round households).

[25] The dual fuel households install ductless mini split heat pumps to displace oil or gas consumption but use the legacy oil or gas system for supplemental heating on cold winter days. Customers sometimes choose these installations to save money by displacing most consumption of heating fuels while spending less on the heat pump installation.

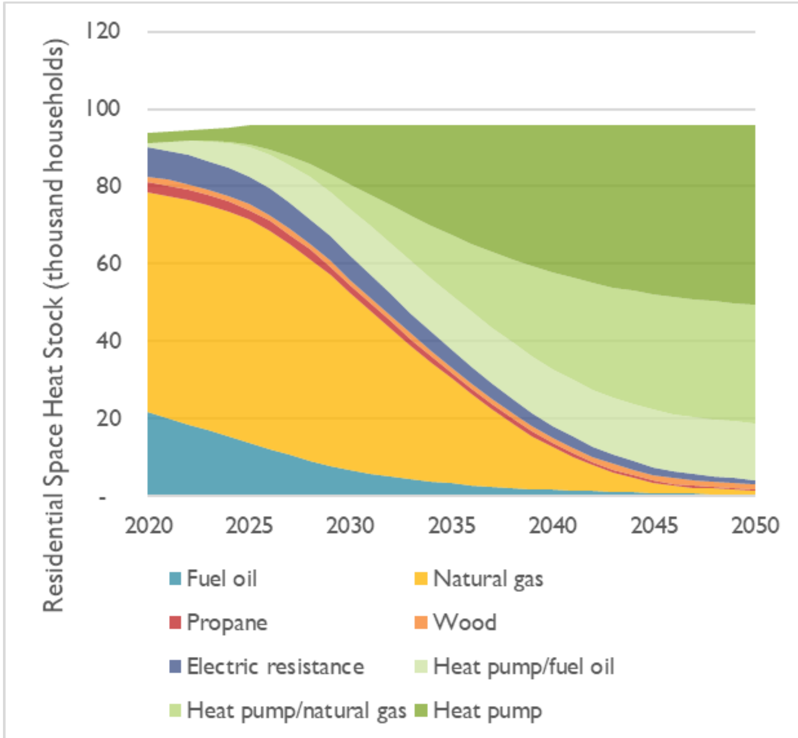


Figure 16. SER1 residential space heating stock (year-round households).

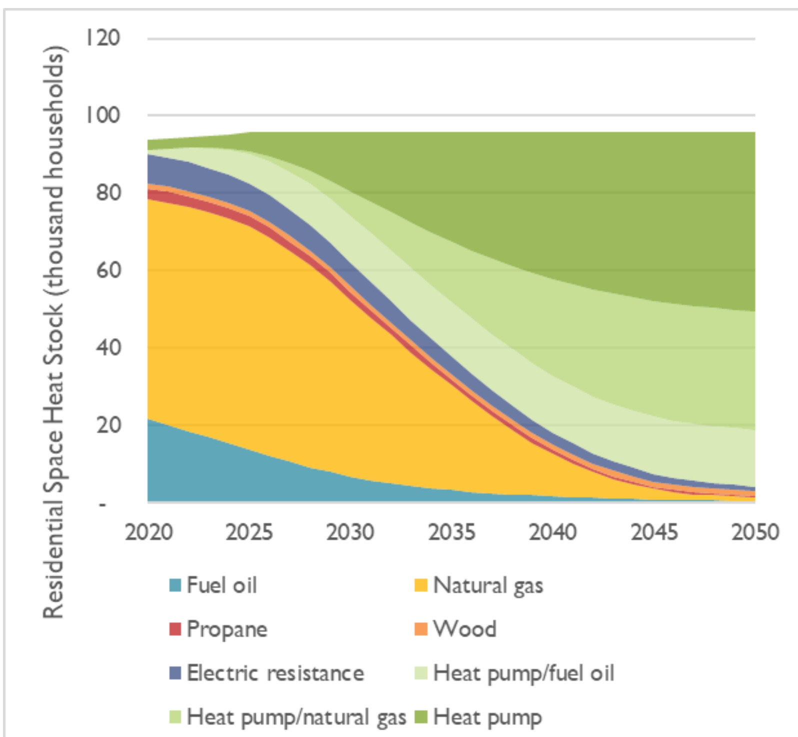


Figure 17. CEN residential space heating stock (year-round households).

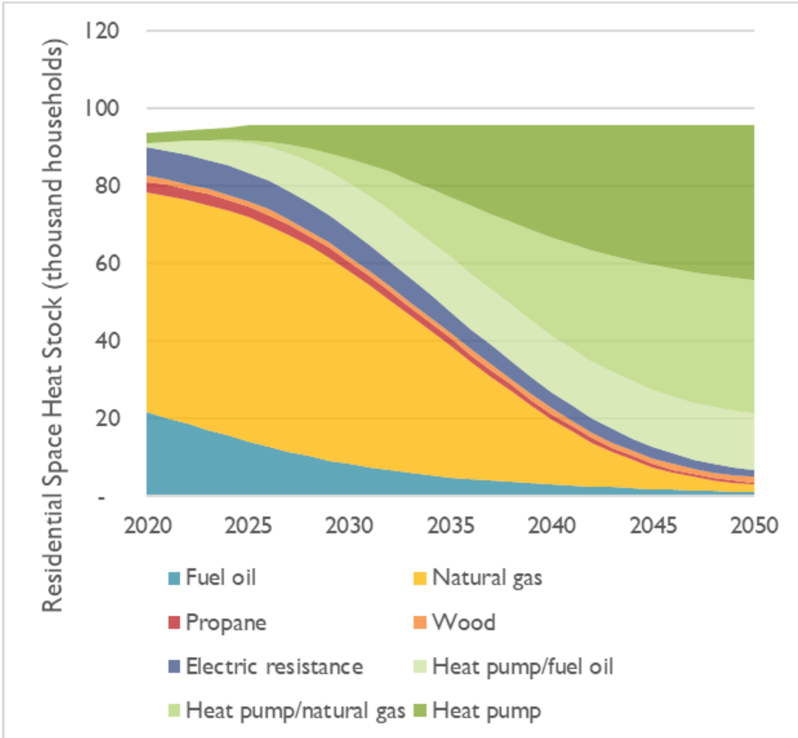


Figure 18. SER2 residential space heating stock (year-round households).

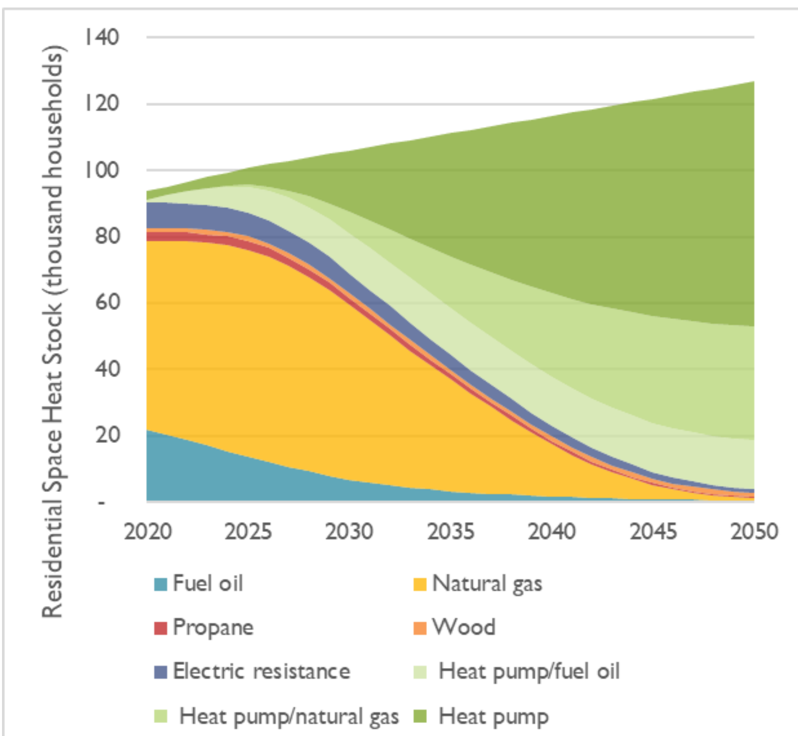


Figure 19. SER3 residential space heating stock (year-round households).

MODELING ASSUMPTIONS FOR THE ELECTRICITY SECTOR

Table 32 presents our assumptions for the percent of energy that will come from non-emitting sources in 2030 and 2050 for all decarbonization scenarios, as well as the sustained policy scenario.

Table 32. Electricity sector clean energy levels (non-emitting sources).

Scenario	2030	2050
SP	47%	80%
SER 1	75%	89%
CEN	75%	98%
SER 2	75%	91%
SER 3	87%	94%

Results

In this section, we first present results for the transportation, building sector, and electric sector modeling. We then present the overall emissions, which incorporate results from these three sectors, as well as all other sectors that generate emissions.

TRANSPORTATION SECTOR RESULTS

Figure 20 presents the total electricity load needed with EV charging over time for all transportation decarbonization scenarios and the sustained policy case.

Figure 21 presents the total emissions from the vehicle fleet over time for all transportation decarbonization scenarios and the sustained policy case. While Appendix C presents more detailed metrics associated with each scenario, key takeaways from the transportation modeling include:

- All decarbonization scenarios require significant growth in the share of new vehicle sales that are light-duty EVs. Even the SER2 case, with reduced VMT relative to the other decarbonization cases, requires 63 percent of new vehicle sales to be EVs by 2030. The SER3 scenario requires 85 percent by 2030. SER1 and CEN each require 93 percent of new sales to be EVs by 2030. By 2050, all decarbonization scenarios require 100 percent of new vehicle sales to be EVs.
- By 2050, SER1, CEN, and SER2 result in approximately 210,000 light-duty EVs on the road in Barnstable County. The SER3 sees an additional 73,000 light-duty EVs resulting from an increase in year-round residents by 2050.
- Electrification of transportation significantly increases Cape Cod's electricity consumption. On the low end, electricity consumption for EV charging in 2050 equals 0.8 TWh in the SER2 scenario. On the high end, the SER3 scenario sees electricity for EV charging equal to 1.2 TWh in 2050. The SER3 scenario has more year-round residents and thus more EVs charging from the grid.

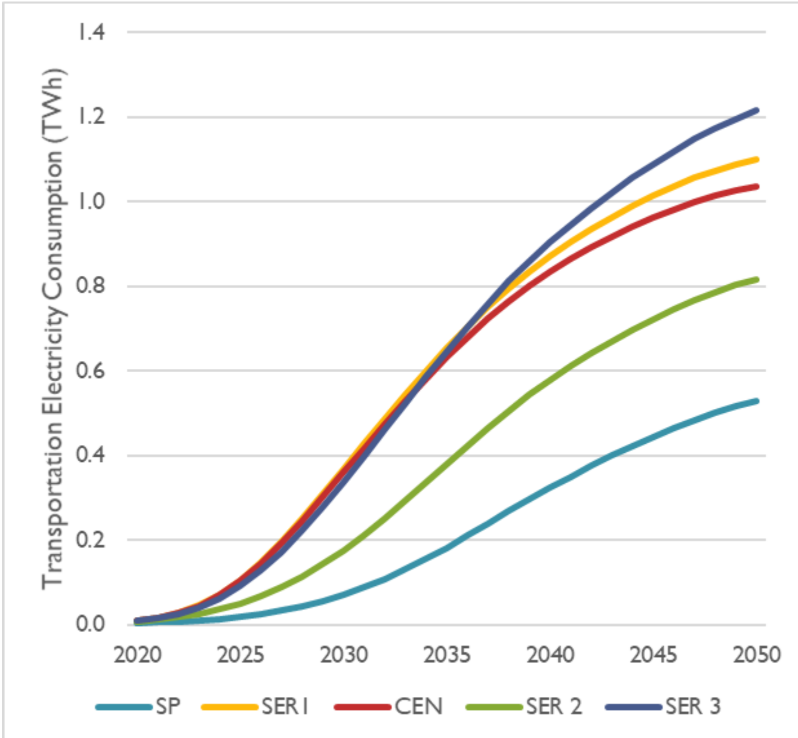


Figure 20. Total load associated with EV charging over time by decarbonization scenario.

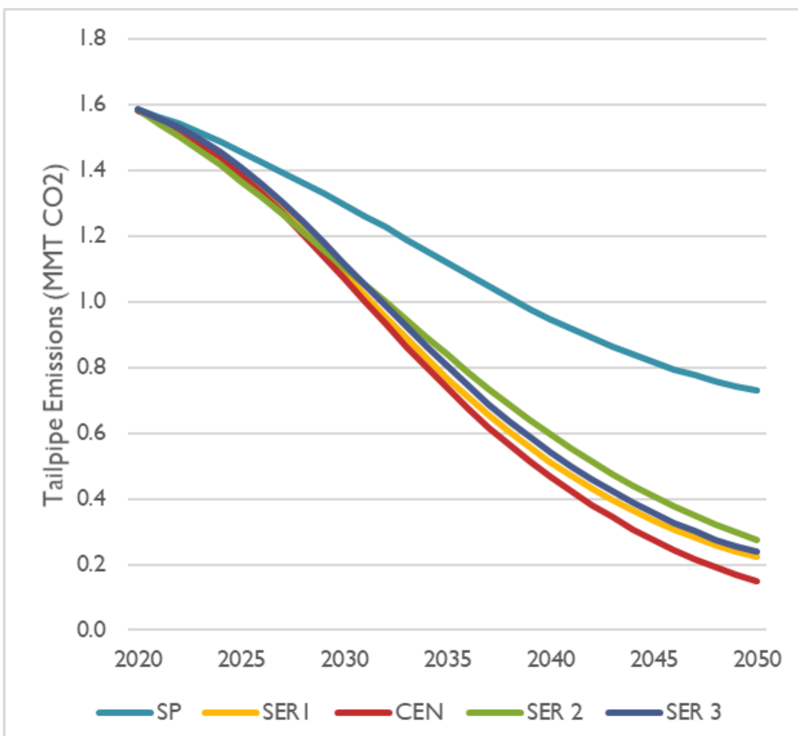


Figure 21. Total GHG emissions from vehicle fleet overtime by decarbonization scenario.

BUILDING SECTOR RESULTS

Figure 22 presents the total electricity consumption in Barnstable County for space and water heating over time by decarbonization scenarios, including the sustained policy case.

Figure 23 presents the total onsite GHG emissions in Barnstable County associated with buildings over time for all decarbonization scenarios including the sustained policy case.

One key takeaway is all decarbonization scenarios require significant growth in the use of heat pump systems, for both retrofits and whole home systems. SER1, CEN, and SER2 all result in similar electricity use for space heating, with around 0.7 to 0.8 TWh in 2030 and approximately 1.5 to 1.7 TWh in 2050. The SER3 scenario sees electricity use for space heating reach about 0.9 TWh in 2030 and 2.2 TWh in 2050.

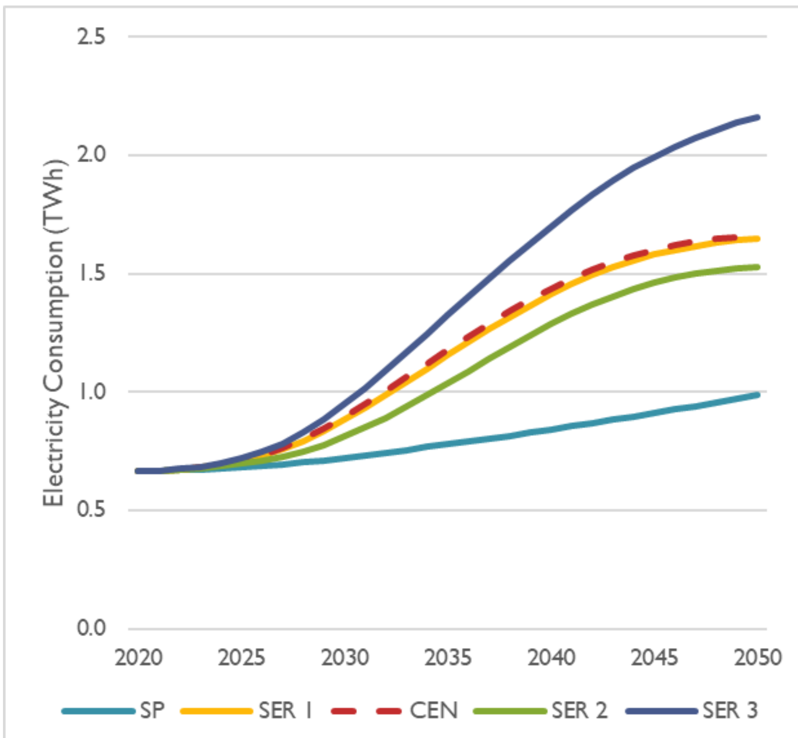


Figure 22. Total load associated with electric heating over time by decarbonization scenario.

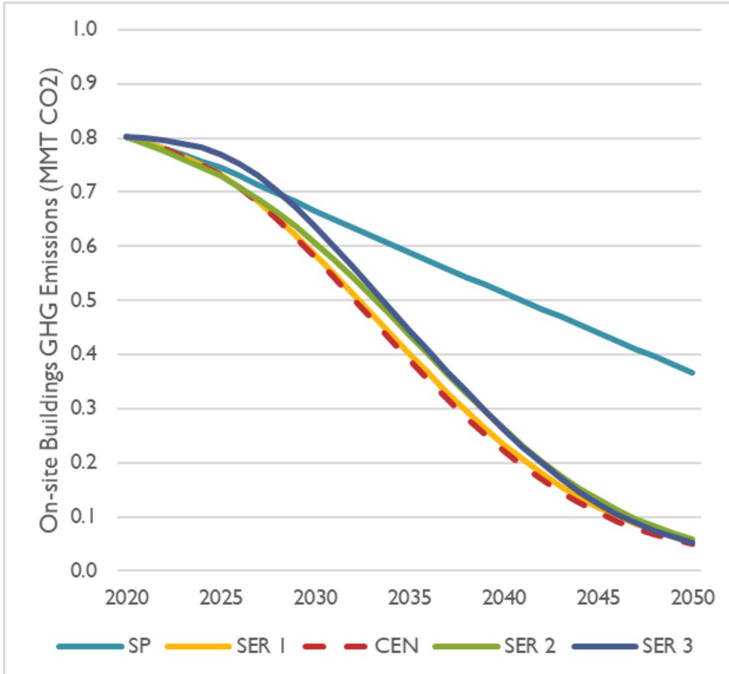


Figure 23. Total GHG emissions from buildings over time by decarbonization scenario.

ELECTRICITY SECTOR RESULTS

Figure 24 presents the electricity needs over time for each decarbonization scenario. This figure incorporates the electricity needs from the corresponding scenarios from the transportation and building sector analyses above, as well as other electricity needs.

Figure 25 presents total emissions from electricity over time from all decarbonization scenarios, as well as the sustained policy scenario.

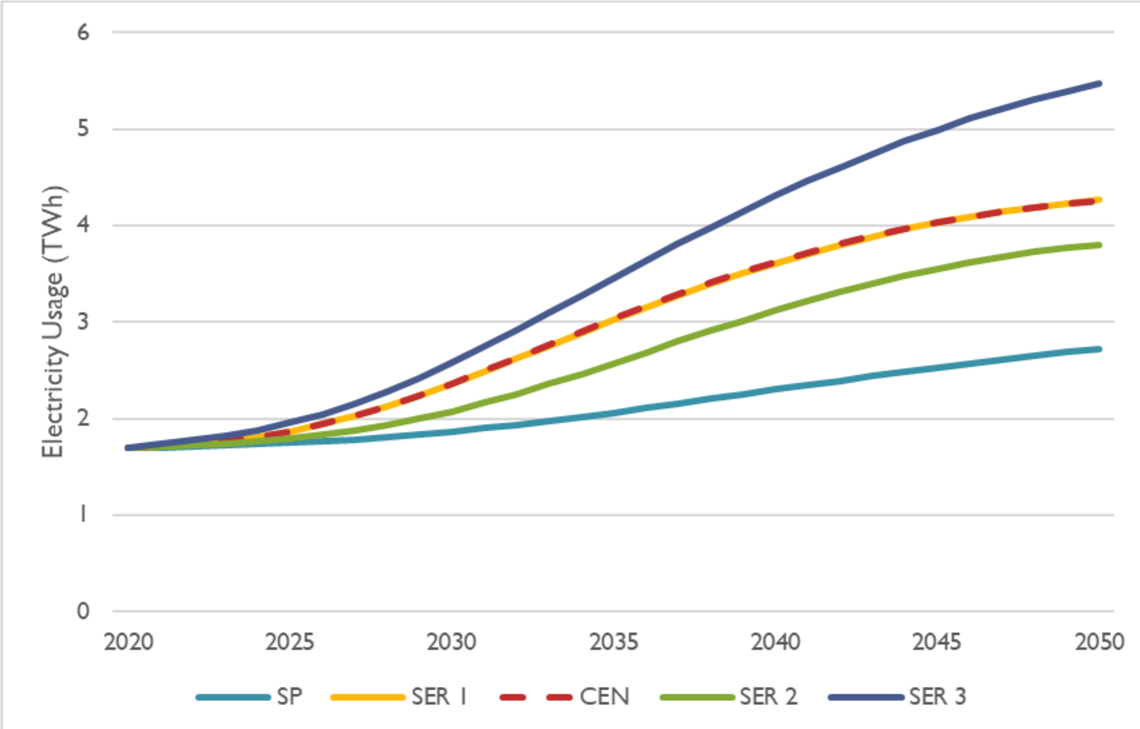


Figure 24. Total Barnstable County electric load over time by decarbonization scenario.

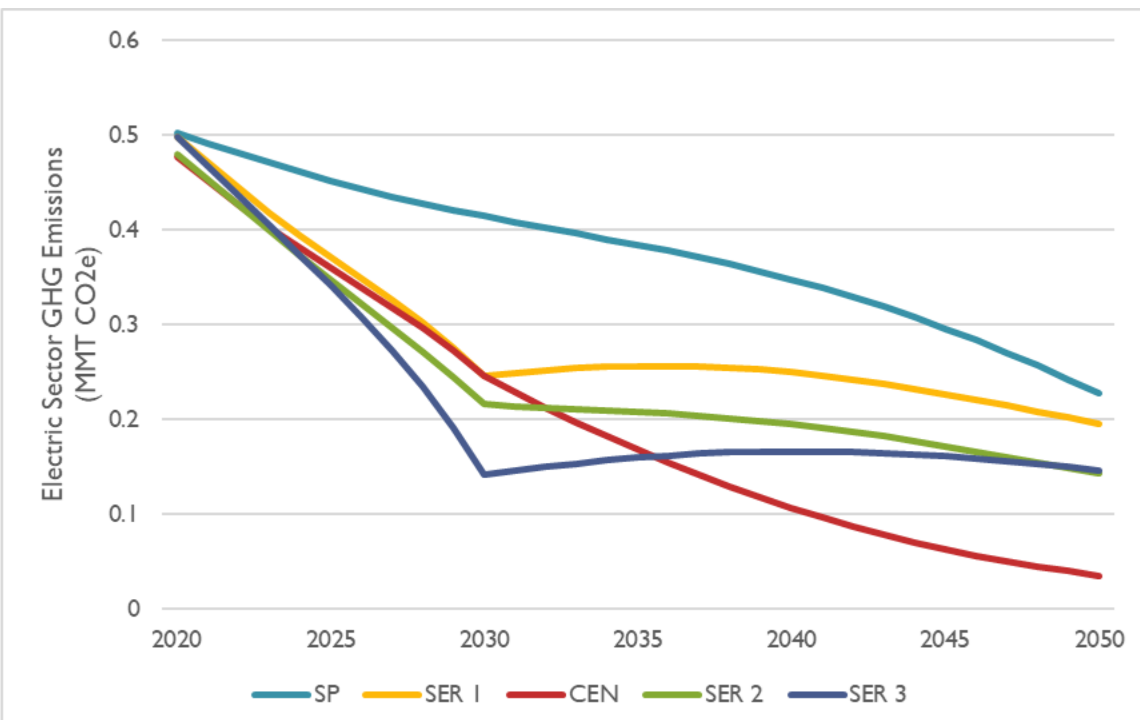


Figure 25. Total electric sector GHG emissions over time by decarbonization scenario.

SUSTAINED POLICY (BASELINE) EMISSIONS RESULTS

Figure 26 presents the economy-wide emissions associated with the sustained policy or baseline scenario in Barnstable County. The figure demonstrates that Barnstable County is unlikely to meet the state's GHG emissions reductions targets given current policies and trends.

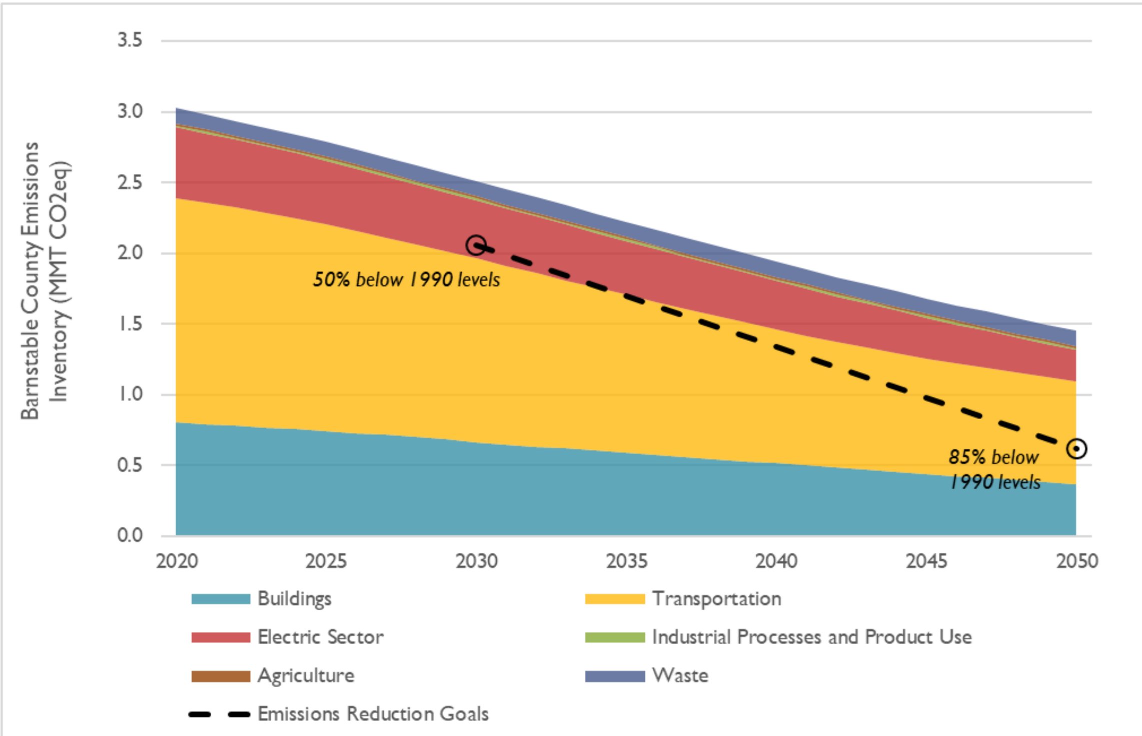


Figure 26. Economy-wide GHG emissions for sustained policy scenario in Barnstable County.

The sustained policy scenario fails to achieve GHG reduction in Barnstable County consistent with the overall goals in Massachusetts. Emissions are projected to decline through the study period. However, total emissions in 2050 are projected to be 1.5 million metric tons, which is a little less than 1 million metric tons above the 2050 target. The transportation sector continues to be the largest source of emissions through 2050, representing 48 percent of economy-wide GHG emissions.

ECONOMY-WIDE EMISSIONS RESULTS (ALL SECTORS)

Figure 27 through Figure 30 present total emissions in Barnstable County over time for each of the decarbonization scenarios. All of the "SER" scenarios meet the 2030 and 2050 emissions reduction goals. The CEN scenario exceeds the goal of 85 percent reduction by 2050, as we developed it to meet net neutrality by 2050.

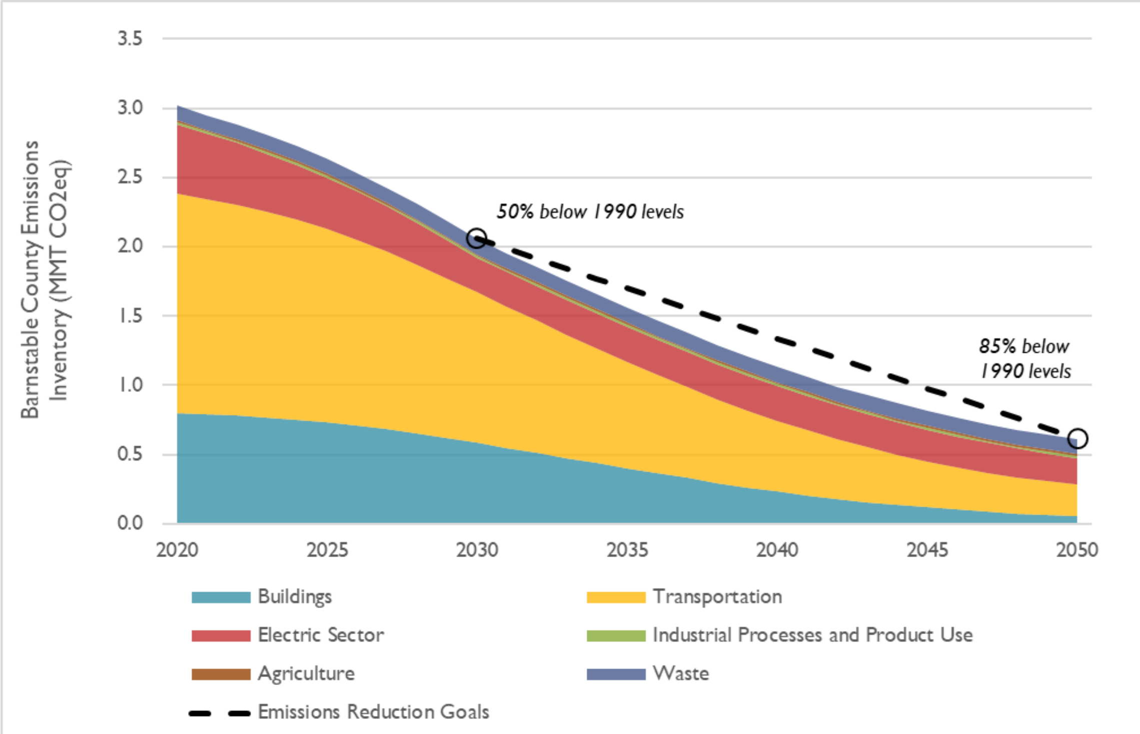


Figure 27. Economy-wide GHG emissions for SER1 scenario.

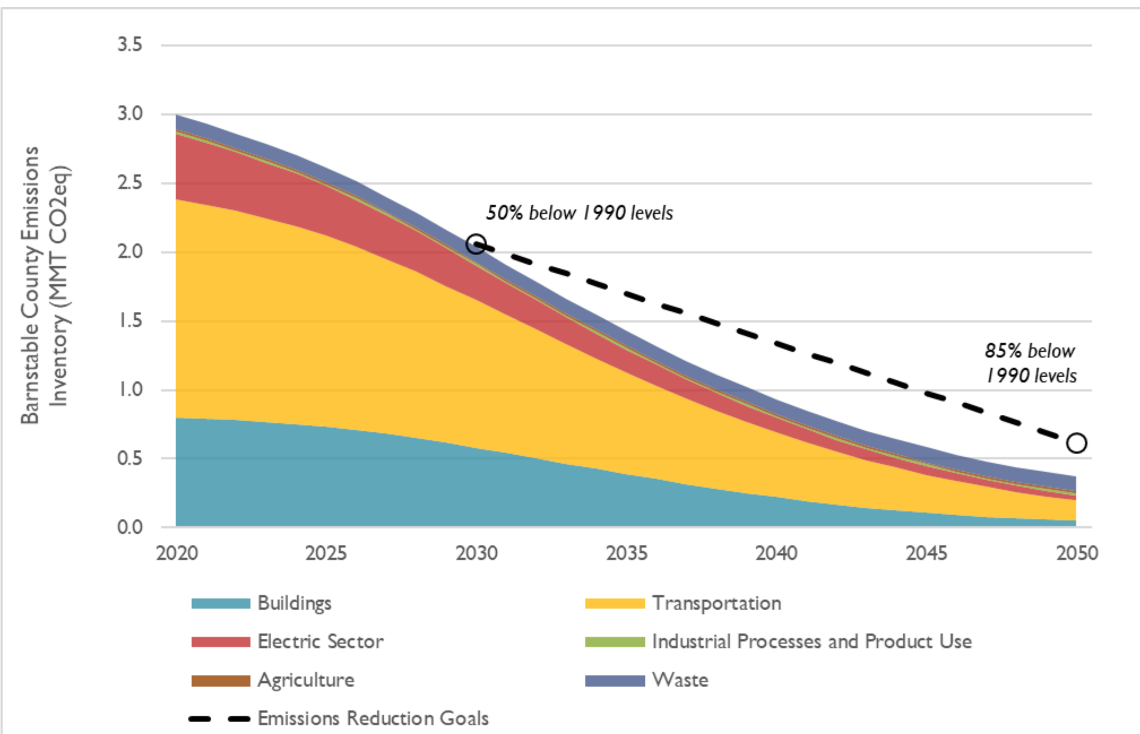


Figure 28. Economy-wide GHG emissions for CEN scenario.

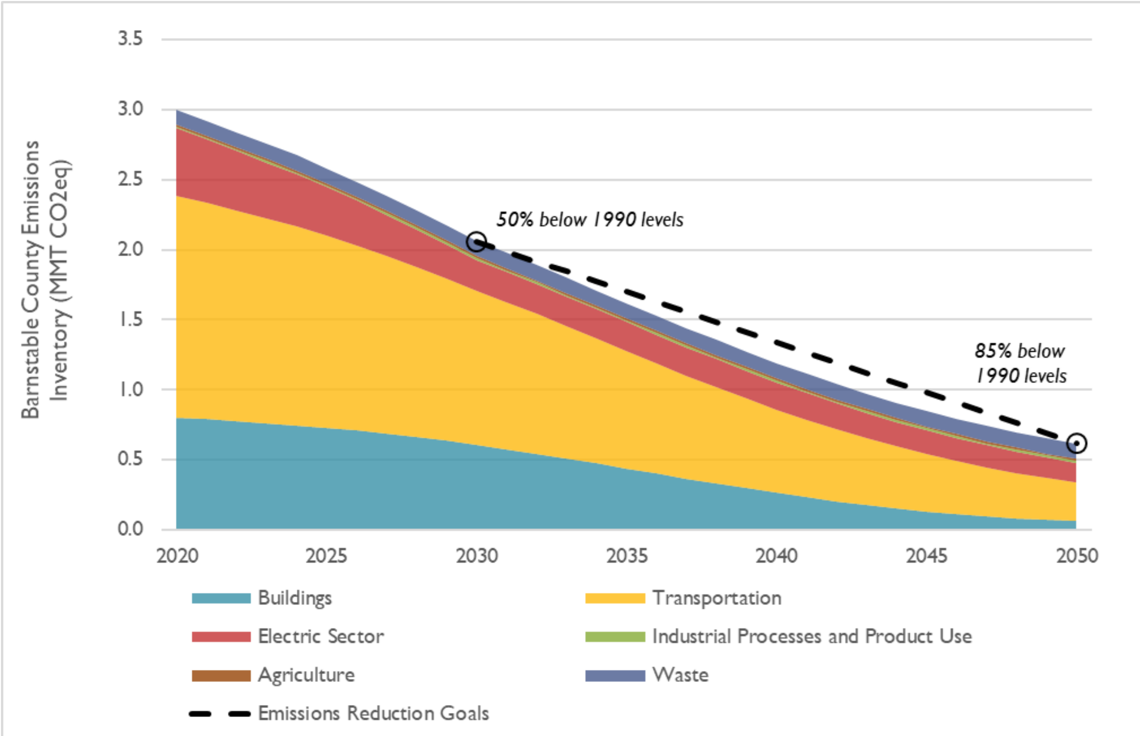


Figure 29. Economy-wide GHG emissions for SER2 scenario.

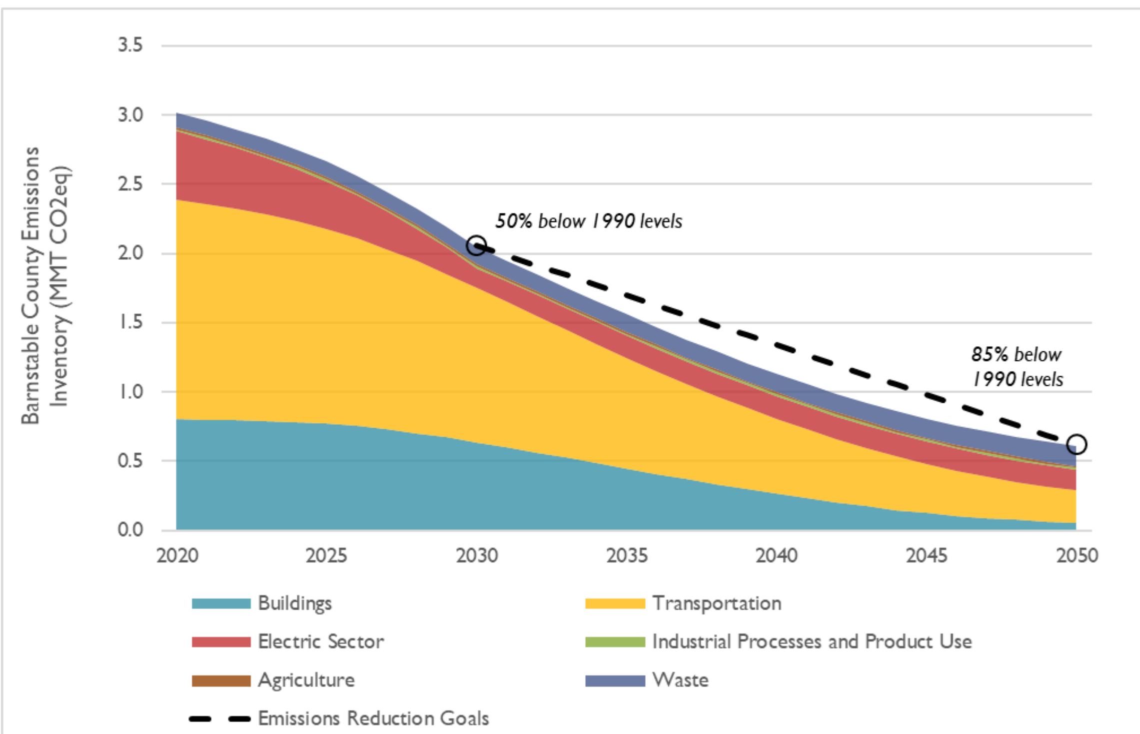


Figure 30. Economy-wide GHG emissions for SER3 scenario.

Table 33 presents the projected emissions by scenario and sector in 2030, 2040, and 2050.

Table 33. Projected emissions by scenario and year (MMT CO_2e).

Scenario	Sector	2030	2040	2050
SP	Residential Buildings	0.480	0.347	0.217
SP	Commercial Buildings	0.186	0.167	0.150
SP	Transportation	1.296	0.947	0.728
SP	Electric Power	0.414	0.348	0.228
SP	Industrial Processes	0.013	0.013	0.013
SP	Agriculture	0.015	0.015	0.015
SP	Waste	0.108	0.108	0.108
SP	Total	2.512	1.945	1.459
SER1	Residential Buildings	0.412	0.147	0.039
SER1	Commercial Buildings	0.173	0.087	0.018
SER1	Transportation	1.087	0.512	0.225
SER1	Electric Power	0.246	0.250	0.196
SER1	Industrial Processes	0.013	0.013	0.013
SER1	Agriculture	0.015	0.015	0.015
SER1	Waste	0.108	0.108	0.108
SER1	Total	2.054	1.132	0.613
CEN	Residential Buildings	0.410	0.144	0.037
CEN	Commercial Buildings	0.170	0.078	0.013
CEN	Transportation	1.073	0.467	0.150
CEN	Electric Power	0.247	0.107	0.036
CEN	Industrial Processes	0.013	0.013	0.013
CEN	Agriculture	0.015	0.015	0.015
CEN	Waste	0.108	0.108	0.108
CEN	Total	2.035	0.932	0.371
SER2	Residential Buildings	0.433	0.176	0.042
SER2	Commercial Buildings	0.173	0.087	0.018
SER2	Transportation	1.102	0.595	0.276
SER2	Electric Power	0.217	0.195	0.143
SER2	Industrial Processes	0.013	0.013	0.013
SER2	Agriculture	0.015	0.015	0.015
SER2	Waste	0.108	0.108	0.108
SER2	Total	2.061	1.189	0.615
SER3	Residential Buildings	0.444	0.164	0.037

Scenario	Sector	2030	2040	2050
SER3	Commercial Buildings	0.193	0.098	0.016
SER3	Transportation	1.116	0.542	0.238
SER3	Electric Power	0.142	0.167	0.146
SER3	Industrial Processes	0.013	0.013	0.013
SER3	Agriculture	0.015	0.015	0.015
SER3	Waste	0.120	0.131	0.143
SER3	Total	2.042	1.130	0.608

Table 34 presents the approximate emissions reductions compared to 1990 emissions levels. This assumes Barnstable County accounted for the same fraction of state emissions in 1990 as it did in 2017.

Table 34. Approximate emissions reductions from 1990 emissions levels.

Scenario	2030	2050
SP	39%	65%
SER 1	50%	85%
CEN	51%	91%
SER 2	50%	85%
SER 3	50%	85%

Key takeaways from the overall emissions analysis include:

- Emissions from the SER1, SER2, and SER3 scenarios all meet the emissions reduction goals of a 50 percent reduction from 1990 levels by 2030 and 85 percent reduction from 1990 levels by 2050.
- Emissions from the CEN scenario will meet the emissions reduction goals of a 50 percent reduction from 1990 levels by 2030 and the net neutrality goal by 2050.
- The differences between decarbonization scenarios are small when compared with the much larger difference between the decarbonization pathways and the sustained policies case. Rapid transformations are required across all sectors in order to be on pace to meet decarbonization targets. Even the sustained policies case would require significant action (e.g., many more EVs and heat pumps, and much more carbon-free electricity) and results in significant emissions changes relative to 2020, and the decarbonization cases require more action and show even more change in emissions.
- Transformations at this scale likely require substantial action and assistance from state and federal governments, but at the same time the homeowners, drivers, and business owners on the Cape are the fundamental actors who can decide to choose electric options for their next heating system or vehicle. Organizations such as the Cape Light Compact

can be a key enabler for electric sector decarbonization, as well as for engaging customers about their energy choices.

Part 3. Economic Analyses of Adaptation and Mitigation Strategies

Our economic analyses of adaptation and mitigation strategies to support the Cape Cod Climate Action Plan are designed to inform whether an economic case exists to implement the strategies. In some cases, economic analyses can be used to refine adaptation strategies to ensure an economic case for implementation (e.g., focus shoreline protection in denser areas). Given the diversity of strategies selected for economic analyses and the range of data available, the strategies are evaluated based on a variety of metrics as described in the section that follows.

Strategy prioritization in the Climate Action Plan should not be based on economics alone, especially as our team was only able to evaluate a subset of the strategies that emerged from the Cape Cod Climate Action Plan planning process. Other key factors to consider include political feasibility and equitable distribution of costs and benefits.

We performed several types of economic analyses in this part of the report that vary depending on the strategy:

- **Benefit-cost analysis:** This could include both market and non-market (e.g., the value of recreation even though it is free, and no money may change hands) benefits and costs. The output is often presented as a ratio of benefits to cost or a net benefit over some period of time.
- **Cost-effectiveness analysis:** Particularly for GHG reduction and sequestration strategies, we present the lifetime cost—which could be a cost increase or cost savings, as well as a negative cost-effectiveness value—per metric ton of CO_2 reduced.
- **Economic impact analysis:** This could refer to the change in wages, number of jobs, or revenue as a result of implementing a strategy.

The strategies for economic analysis are organized into two primary groups: 1) mitigation-focused strategies and 2) adaptation-focused strategies.

We have done our best to present findings at several geographic scales to be flexible to future regional and town needs.

GHG Mitigation-Focused Strategies

Reducing greenhouse gas emissions from buildings

The energy efficiency of buildings can be greatly increased by reducing the amount of energy needed for heating and cooling, known as "weatherization" (e.g., improved insulation, energy-efficient windows) and by replacing outdated and inefficient heating and cooling systems with heat pumps. At the consumer level, taking these actions can provide cost savings over many years. On a regional level, these actions can help reduce CO_2 emissions and lessen the impacts of climate change. These actions can also lead to a decrease in criteria pollutant emissions, including $PM_{2.5}$, NO_x, and SO_2, which impacts the health of those in the region.

METHODS

ERG conducted a literature review to understand the consumer benefits and costs associated with weatherization and heat pump installation.

Weatherizing a building incurs an upfront cost, but does not require any operational costs over time, and in fact reduces the cost of heating or cooling a building over time. Replacing inefficient heating and cooling systems with a heat pump requires both an upfront cost and an operational cost over time, but these operational costs are lower than older, more inefficient systems that most homes in Barnstable County currently rely on.

According to the U.S. Department of Energy (DOE), the average home weatherization cost is between $4,695 and $6,812 (DOE, 2015; DOE, 2018). This initial cost often consists of a combination of many different measures to decrease energy consumption and increase energy efficiency, including installing insulation where needed, performing air sealing, repairing minor roof and wall leaks, installing programmable thermostats, and insulating water heating pipes. Once a building has been weatherized, less energy is needed to heat and cool the building throughout the year. The DOE's Office of Energy Efficiency and Renewable Energy estimates that weatherization can provide an annual energy cost savings of $283 per home unit (DOE, 2018).

Heat pumps can decrease a homeowner's heating and cooling costs, while lowering their GHG impacts. There are three types of heat pumps—air-to-air, water source, and geothermal—that collect heat from either the air, water, or ground and redistribute it for use inside a home or building.

Air-source heat pumps (ASHPs) are the most common type of heat pump (Energy.gov, n.d.). The Massachusetts Clean Energy Center (MassCEC) publishes state and county level data for the cost of installing an ASHPs in homes. In 2019, there were 541 ASHPs installed in Barnstable County, with a median cost was $3,733 per heating ton.[26] A 2,100- to 2,700-square-foot home would require a 4.0-ton ASHP, resulting in a total capital cost of $14,900. This value is in line with MassCEC's estimate of $15,000-$20,000 for a whole-home replacement system (Massachusetts Clean Energy Center, 2020). Conventional fuel boilers have a lower capital cost, but much higher annual costs. The capital costs associated with conventional fuel boilers and ASHPs are provided in Table 35. The capital cost reported in Table 35 for the conventional fuel boilers is based on the national average cost reported by Fixr, a cost comparison website.[27]

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[26] Cost per ton is a standard way to compare the prices of heat pumps. One ton is equivalent to 12,000 BTU per hour.

[27] https://www.fixr.com/

Table 35. Capital cost of conventional fuel boilers and air-source heat pumps.

Heating Fuel	Capital Cost
Natural gas boiler	$8,150
Heating oil boiler	$6,500
Propane boiler	$7,500
ASHP	$15,000

The annual heating cost to a Massachusetts homeowner using conventional heating fuel can be pricy. According to the Massachusetts Home Heating Profile, the five-year annual average heating costs can range from $899 to $2,280 for conventional heating fuels like natural gas, propane, and heating oil (Mass.gov, 2020). The estimated heating cost for a Massachusetts resident with an ASHP is $269, much lower than the cost associated with conventional fuels, although it is important to note that this reflects only the heating costs and does not incorporate any additional electricity costs (Mass.gov, 2020).

We estimated the annual cost to heat the average house in New England based on four fuel sources: natural gas, heating oil, propane, and ASHPs. The average house in New England is assumed to be 2,186 square feet with a heated area of 1,861 square feet (Mass.gov, 2020). Massachusetts provides household heating consumption projections for different fuels and the associated approximate heated square footage per household (Mass.gov, 2020). We calculated the consumption per heated square foot based on these published values and used estimates of fuel costs from the U.S. Energy Information Administration to estimate the annual heating cost. Table 36 presents the annual cost associated with each heating fuel. By using an ASHP, the annual heating costs can be three to seven times cheaper as compared to traditional heating fuel sources.

Table 36. Fuel consumption per square foot for heating fuels (Source: Mass.gov, 2020).

Heating Fuel	Consumption per Heated Square Foot	Annual Residential Fuel Cost (2020$)	Annual Cost (2020$)
Natural gas	0.36 therms/heated sq ft	$14.86/1000 ft^3	$1,010
Heating oil	0.40 gallons/heated sq ft	$3.12/gallon	$2,320
Propane	0.39 gallons/heated sq ft	$2.98/gallon	$2,140
ASHP	0.91 kWh/heated sq ft	$0.19/kWh	$320

The total cost to the consumer must incorporate both the initial capital cost of installing a heating unit, as well as the annual cost over the expected lifespan of the unit. Energystar.gov recommends replacing natural gas, heating oil, and propane boilers after 15 years and replacing ASHPs after 10 years.

We also assessed the reduced CO_2 emissions and criteria pollutants that will result from increasing heat pump usage in the residential sector. Synapse modeled the CO_2 and criteria pollutants emissions associated with a sustained policy (SP) scenario and an aggressive electrification scenario (SER1). The SER1 scenario assumes the same amount of weatherization through 2050 as the sustained policy scenario, however the SER1 scenario assumes more residential and commercial use of heat pumps. By comparing the CO_2 and criteria pollutant emissions from the sustained policy scenario to the SER1 scenario, we were able to estimate the emission reductions associated with significant heat pump adoption in the residential and commercial sectors. Table 37. Emissions reductions from the residential sector from switching to the aggressive electrification scenario (SER1) from the sustained policy scenario (SP) shows the reduced CO_2 and criteria pollutant emissions from switching to the SER1 scenario from the sustained policy scenario by decade.

Table 37. Emissions reductions from the residential sector from switching to the aggressive electrification scenario (SER1) from the sustained policy scenario (SP).

Years	Reduced CO_2 Emissions (MMT of CO_2)	Reduced $PM_{2.5}$ Emissions (Metric Tons)	Reduced SO_2 Emissions (Metric Tons)	Reduced NO_x Emissions (Metric Tons)
2021–2030	0.2	14.2	111.3	150.1
2031–2040	1.5	91.3	393.9	1045.1
2041–2050	2.0	124.5	411.4	1463.0
Total	**3.7**	**229.9**	**916.6**	**2,658.2**

We then monetized the value of these reduced emissions, using both a market price and SCC to estimate the benefit of the CO_2 reduction. Massachusetts is part of the Regional Greenhouse Gas Initiative (RGGI), a cooperative effort among ten states in the Northeast to reduce GHG emissions from the electric power sector. RGGI is a cap-and-trade system where each state places a cap on CO_2 emitted from the electric power sector and CO_2 allowances are issued and can be traded to maintain compliance with the emission caps. RGGI holds quarterly auctions where these allowances can be bought and sold, and they publish the clearing price per short ton of CO_2 based on these transactions.[28] Although the price per short ton of CO_2 has ranged from about $2 to $7.50 since the RGGI program started in 2008. Since December 2018, the price has been above $5 per short ton of CO_2 (Figure 31). The future price of CO_2 based on the RGGI program is difficult to predict because periodic program reviews of the region's emissions can lead to adjustments in the CO_2 cap, ultimately influencing the market price (RGGI, 2017). We calculate the benefit of reducing CO_2 emissions based on a high ($7.50 per short ton) and low ($5.00 per short ton) estimate of the market price of CO_2.[29] For each high and low estimate, we assume the price is constant from 2020 to 2050.

[28] Clearing prices for quarterly RGGI auctions are available at https://www.rggi.org/Auctions/Auction-Results/Prices-Volumes.

[29] Synapse modeled CO_2 emissions in metric tons. One metric ton is equivalent to 1.10231 short tons. Therefore, we converted the high and low market price of carbon to a per metric ton basis for our calculations ($5.51 and $8.27 per metric ton, respectively).

Figure 31. Historical market price of CO_2 based on RGGI auction price data.

In Part 1 of this report, we used the SCC to estimate the impact to salt marshes and eelgrass ecosystem services. Similar to our high and low estimates of the market price of carbon, we use high and low estimates of the SCC to provide an understanding of the monetized benefit for different climate scenarios. We use extrapolated values of the SCC from 2020 to 2050 at a 3 percent discount rate as our low estimate of the SCC, and the 95th percentile outcome of a 3 percent discount as our high estimate (to account for high-risk climate scenarios).[30] Figure 32 shows the high and low estimates of the SCC from 2020 to 2050.

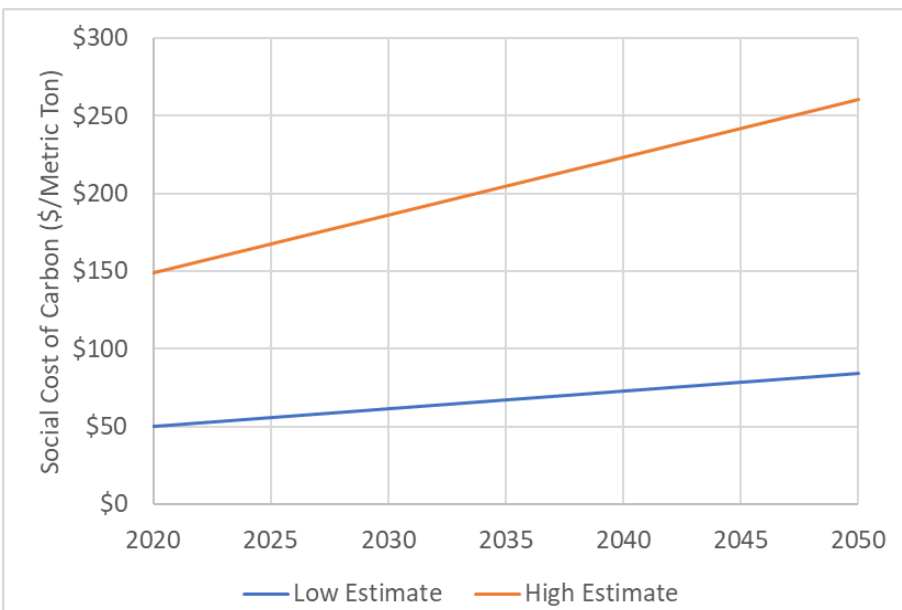

Figure 32. High and low SCC projections from 2020 to 2050 (2020$ per metric ton).

[30] See the Part 1: Impact to Salt Marshes and Eelgrass Ecosystem Services section beginning on page 28 for more information on how the SCC was estimated.

We used an EPA study to estimate the benefit of the CO_2 reduction by converting the criteria pollutant reductions into a dollar value based on the anticipated health impacts (i.e., average estimated reduction in mortality and morbidity) (US EPA, 2013). Table 38 shows the values in 2020 and 2030 for a one-ton reduction of $PM_{2.5}$, SO_2, and NO_x. We assumed the value in 2040 is the same as the value in 2030.

Table 38. Value of each ton of pollutant reduced for electricity generating units (2020$).

Category	Value of 1 Ton Reduction of $PM_{2.5}$	Value of 1 Ton Reduction of SO_2	Value of 1 Ton Reduction of NO_x
2020 value per ton reduced for electricity generating units	$365,900	$97,950	$14,150
2030 value per ton reduced for electricity generating units	$424,900	$114,500	$16,550

RESULTS

The lifetime cost to the consumer for ASHPs can be $5,000 to $23,000 cheaper than traditional heating units. Table 39 presents the lifetime cost and annual cost of ownership for three traditional heating units (natural gas boiler, heating oil boiler, and propane boiler) as well as for ASHPs. The annual cost of ownership for an ASHP is $1,820, which is less than both the annual heating oil and propane fuel costs ($2,320 and $2,140, respectively). Therefore, it is cost-effective to switch from a heating oil boiler or a propane boiler to an ASHP at any point in time, including before the boiler reaches the end of its lifespan. In contrast, the annual natural gas fuel cost ($1,010) is less than the annual cost of ownership for an ASHP. This means that it is more cost-effective for homeowners who use natural gas to wait until their heating unit reaches the end of its lifespan before switching to an ASHP.

Although the annual cost of ownership is lowest for ASHPs, the capital cost to install them can be twice that of conventional heating units (Table 39). This high initial cost can make ASHPs inaccessible for some homeowners. Smaller, less expensive ASHP units can be installed, but these may not be able to heat an entire home depending on the size of the home.

Table 39. Lifetime cost and annual cost of ownership to the consumer for different heating units.

Heating Unit	Capital Cost (2020$)	Annual Fuel Cost (2020$/year)	Expected Lifespan	Total Lifetime Cost	Annual Cost of Ownership
Natural gas boiler	$8,150	$1,010	15 years	$23,250	$1,550
Heating oil boiler	$6,500	$2,320	15 years	$41,250	$2,750
Propane boiler	$7,500	$2,140	15 years	$39,600	$2,640
ASHP	$15,000	$320	10 years	$18,200	$1,820

Heat pumps emit less CO_2 and criteria pollutants than conventional heating systems. When implemented on a regional scale, the aggregate emissions reduced can help to lessen the impacts of climate change and can reduce health impacts. We assessed these benefits by monetizing the emissions reduced from switching to the aggressive electrification scenario (SER1) from the sustained policy (SP) scenario.

The monetized benefit of the reduction in CO_2 emissions is provided in Table 40. Monetized benefit of reduced CO_2 emissions from residential sector (millions of 2020$) using both high and low estimates of the market and SCC (discussed in the methods section above). The monetized benefit of the reduction in criteria pollutants is provided in Table 41. By 2050, CO_2 emissions could be valued at over $20 million based on a conservative market price estimate, or as much as nearly $274 million using a conservative SCC estimate. The monetized benefit of reduced criteria pollutants is estimated to be around $244 million by 2050.

Table 40. Monetized benefit of reduced CO_2 emissions from residential sector (millions of 2020$).

Years	Market Value of Reduced CO_2 Emissions	Social Value of Reduced CO_2 Emissions
2021–2030	$1.3–$1.9	$13.8–$41.5
2031–2040	$8.1–$12.2	$101.4–$308.8
2041–2050	$11.1–$16.6	$158.9–$488.6
Total	**$20.5–$30.7**	**$274.0–$838.9**

Table 41. Monetized benefit of criteria pollutant reductions from residential sector (millions of 2020$).

Years	$PM_{2.5}$	SO_2	NO_x	Total
2021–2030	$5.5	$11.4	$2.2	$19.0
2031–2040	$38.8	$45.1	$17.3	$101.2
2041–2050	$52.9	$47.1	$24.2	$124.2
Total	**$97.1**	**$103.6**	**$43.7**	**$244.4**

LIMITATIONS AND FUTURE ANALYSIS

Although heat pumps provide an efficient and cost-effective way to heat and cool a home or building, they are less efficient in very cold weather. Fortunately, newer technology has made cold climate ASHPs practical in New England (EERE, 2017). Our analysis does not specifically focus on cold climate ASHPs. Future work should consider whether cold climate ASHPs will be necessary in the future as the climate warms and should look at the costs and benefits of installing cold climate ASHPs to understand at a more granular level the impact to Cape Cod consumers.

Reducing GHGs from Buildings: Key Takeaways

- It is cost-effective for consumers to switch from a heating oil boiler or a propane boiler to an ASHP at any point in time, including before the boiler reaches the end of its lifespan.
- From a cost perspective, consumers of natural gas should wait until their heating unit reaches the end of its lifespan before switching to an ASHP. To switch to an ASHP will be comparable (less than $100 per year difference).
- In addition to the financial benefits to consumers of switching to ASHPs to help reach 2050 emissions goals, the health benefit of reduced criteria pollutants will be about $244 million, and the market value of reduced carbon will be about $20 to $30 million from 2021 through 2050 (comparing SER1 scenario to sustained policy scenario).

Increase generation and use of clean energy

Using clean energy can provide a variety of benefits. Clean energy emits less CO_2 into the atmosphere, helping to lessen the contribution to climate change. Clean energy also emits less criteria pollutants such as $PM_{2.5}$, NO_x, and SO_2, which can help to improve the overall health of the region's population. Over the past few decades, the cost of clean energy has decreased dramatically. Today, clean energy is cost-competitive with fossil fuel energy sources.

METHODS

We conducted a literature review of the cost of renewable and nonrenewable energy sources. We focused on sources that provided the cost in terms of the levelized cost of energy (LCOE). The LCOE is commonly used to compare the costs of electricity generated from different sources because it estimates the cost per unit of electricity generated over the entire lifespan of the generating plant–including capital and operating costs. Therefore, the LCOE provides a consistent metric that can be used to compare the cost of energy generated from different sources.

Synapse modeled the CO_2, $PM_{2.5}$, NO_x, and SO_2 emissions from the electric power sector for the five scenarios they considered. We used the sustained policy scenario as our baseline and compared the emissions reductions that will occur if the SER1 scenario is followed. Table 42. Emissions reductions from switching to the aggressive electrification scenario (SER1) from the sustained policy scenario (SP) provides the reduced emissions by decade. By 2050, CO_2 emissions are projected to be reduced by nearly 3 million metric tons and criteria pollutants ($PM_{2.5}$, SO_2, and NO_x) are projected to be reduced by nearly 2,000 metric tons.

We monetized the reduced CO_2 emissions using high and low estimates of the market value and SCC. The reader is referred to the "Reducing greenhouse gas emissions from buildings" section of this report for a more detailed review of how these values were estimated. The high and low market price of carbon was assumed to be $5.51 per metric ton and $8.27 per metric ton, respectively. Our analysis assumes that these market prices are constant from 2020–2050 and uses annual estimates of the SCC from 2020–2050. The high SCC estimates range from about $150 per metric ton in 2020 to $260 per metric ton in 2050. The low SCC estimates range from about $50 per metric ton in 2020 to $84 per metric ton in 2050.

Table 42. Emissions reductions from switching to the aggressive electrification scenario (SER1) from the sustained policy scenario (SP).

Years	Reduced CO_2 Emissions (MMT of CO_2)	Reduced $PM_{2.5}$ Emissions (Metric Tons)	Reduced SO_2 Emissions (Metric Tons)	Reduced NO_x Emissions (Metric Tons)
2021–2030	0.90	62.7	136.7	410.1
2031–2040	1.26	88.0	191.7	575.2
2041–2050	0.64	44.9	97.8	293.3
Total	**2.8**	**195.6**	**426.2**	**1,278.6**

We used an EPA study (EPA, 2013) to convert the criteria pollutant reductions into a dollar value based on the anticipated health impacts (i.e., average estimated reduction in mortality and morbidity). As we did in the previous section, Table 38 (from the previous section) shows the values in 2020 and 2030 for a one-ton reduction of $PM_{2.5}$, SO_2 and NO_x. We assumed the value in 2040 is the same as the value in 2030.

RESULTS

The cost of renewable energy is increasingly becoming more cost-competitive with traditional nonrenewable energy sources such as natural gas and coal. For example, the cost for electricity from utility-scale solar photovoltaics (PVs) fell 82 percent globally between 2010 and 2019 (IRENA, 2020).

Table 43 and Table 44 provide the range of LCOE estimates for nonrenewable and renewable energy sources, respectively. We present the unsubsidized analysis findings from Lazard's 2020 Levelized Cost of Energy Analysis and provide additional estimates from the National Renewable Energy Laboratory's (NREL's) Open Energy Information Database and the EIA's 2020 Levelized Cost Analysis.

Table 43. Selected LCOE for Nonrenewable Energy Sources (2020$).

Nonrenewable Energy Source	Cost Range (US$/MWh)	Source
Natural gas	$32–$105	NREL, 2015
Coal	$65–$159	Lazard, 2020a

Table 44. Selected LCOE for Renewable Energy Sources (2020$).

Renewable Energy Source	Cost Range (US$/MWh)	Source
Solar—concentrated/utility-scale PV	$31–$42	Lazard, 2020a
Solar PV—rooftop residential	$150–$227	Lazard, 2020a
Wind—onshore	$9–$43	Lazard, 2020a
Wind—offshore	$26–$54	Lazard, 2020a
Biomass	$30–46	EIA, 2020

Renewable Energy Source	Cost Range (US$/MWh)	Source
Geothermal	$59–$101	Lazard, 2020a

As Cape Cod transitions to rely more on electrification, electric power use will increase. To deal with this likely increase in electricity use, Cape Cod should consider strategies that can help decrease the electricity demand on the grid at key times during the day.

Combined PV and energy storage projects are becoming increasingly price competitive and can provide additional electricity to the grid without the costly investments that may otherwise be needed to meet the projected increase in peak demand. Energy storage can help decrease the impact of higher electricity usage on the grid by storing energy during low-use times of the day and then providing electricity to the grid during high use times.

Energy storage systems are a popular "behind the meter" (BTM) strategy that can help electricity users lower their electricity costs. BTM strategies refer to anything that the user can do to lower their electricity costs. Until recently, the grid system relied on electricity generated at power plants and distributed to users. Therefore, the user's control over their electricity costs was limited to strategies such as turning off lights and equipment when not in use or using during off-peak times. With the increasing cost competitiveness of distributed renewable energy such as PV and decreasing costs of battery storage, the possibility for electricity users to lower their costs has grown. Residential, commercial, and industrial customers can install solar PV cells and energy storage to reduce their costs.

Power plants, large-scale distributed energy resources such as solar or wind, and the transmission and distribution lines that bring electricity to homes and businesses are all considered "in front of the meter" (IFTM)—that is, they deal with bringing the electricity to the user. Similar to recent trends in BTM energy storage strategies, IFTM strategies are also becoming more cost competitive.

Table 45 provides the LCOE for BTM and IFTM energy storage strategies based on Lazard's Levelized Cost of Storage Analysis.

Table 45. Selected LCOE for energy storage strategies (2020$).

Energy Storage Strategy (BTM or IFTM)	Strategy Description and Key Improvements	Cost Range (US$/MWh)
Residential PV and storage (BTM)	Regulates the power supply.	$406–$506
Commercial and industrial PV and storage (BTM)	Energy storage system designed to lower peak usage and reduce demand charge; designed to maximize the value of solar PV system.	$247–$319
Standalone commercial and industrial storage (BTM)	Energy storage system designed to lower peak usage and reduce demand charge; can provide grid services to a utility or wholesale market.	$432–$590

Energy Storage Strategy (BTM or IFTM)	Strategy Description and Key Improvements	Cost Range (US$/MWh)
Wholesale PV and storage (IFTM)	Designed to be used with large solar PV facilities; can help align timing of PV generation with demand on the grid.	$81–$140
Wholesale (IFTM)	Large-scale energy storage system designed to meet varying system needs.	$132–$250

Source: (Source: Lazard, 2020b)

Demand management strategies are another way to help ease the burden on the grid during peak electricity usage times. These programs aim to lessen the peak demand for electricity throughout the day by altering when people use energy. The programs often involve public education, outreach, and incentives to encourage energy use at off-peak times. A recent study compared demand management program effectiveness and found that the cost to reduce a MWh of electricity usage ranges from about $0.00004/MWh to $0.00821/MWh (Pratt & Erickson, 2020).

Table 46 shows the monetized benefit of the reduction in CO_2 emissions from the electric sector using both high and low estimates of the market and social costs of carbon. Table 47 shows the monetized benefit of the reduction in criteria pollutants. By 2050, CO_2 emissions reductions could be valued at over $15 million based on a conservative market price estimate, or as much as $187 million using a conservative SCC estimate. The monetized benefit of reduced criteria pollutants is estimated to be about $147 million by 2050.

Table 46. Monetized benefit of reduced CO_2 emissions from the electric sector (millions of 2020$).

Years	Market Value of Reduced CO_2 Emissions	Social Value of Reduced CO_2 Emissions
2021–2030	$5.0–$7.44	$52.3–$157.2
2031–2040	$7.0–$10.4	$85.0–$258.5
2041–2050	$3.6–$5.3	$50.3–$154.6
Total	**$15.5–$23.2**	**$187.6–570.3**

Table 47. Monetized benefit of criteria pollutant reductions from the electric sector (millions of 2020$).

Years	$PM_{2.5}$	SO_2	NO_x	Total
2021–2030	$23.7	$13.8	$6.0	$43.5
2031–2040	$37.4	$22.0	$9.5	$68.9
2041–2050	$19.1	$11.2	$4.9	$35.1
Total	**$80.1**	**$47.0**	**$20.4**	**$147.4**

LIMITATIONS AND FUTURE ANALYSIS

The literature review provides a range of cost estimates associated with different energy sources and technologies. The performance of these technologies, however, can be highly dependent on the geographic location that they are implemented in and the specific conditions of the site.

Therefore, the specific costs associated with implementing these technologies on Cape Cod will depend on local factors such as weather, wind speed and consistency, available biomass, geothermal potential, and others. Future analyses should focus more on the LCOE for implementing these technologies in the Cape Cod region.

Generation and Use of Clean Energy: Key Takeaways

- The levelized cost of onshore wind (less than $43 per MWh), offshore wind (less than $54 per MWh), and utility scale photovoltaic (less than $42 per MWh) is becoming cost-competitive and often cheaper than the levelized cost of coal ($65 to $159 per MWh) or natural gas ($32 to $105 per MWh) while the cost of rooftop residential is still more expensive (over $150 per MWh). Moreover, the levelized cost of renewable energy has dropped over 80 percent globally from 2010 through 2019 so should continue to become more cost-effective in the future. (The levelized cost of energy includes the capital costs of installation and operating and maintenance costs over the life of a panel, turbine, or electricity-generating unit).
- Additionally, there are major co-benefits of renewable energy. Increased renewable energy to reach 2050 emissions goals will generate health benefits from reduced criteria pollutants of nearly $150 million, and the market value of reduced carbon will be about $15 to $23 million from 2021 through 2050 (comparing SER1 scenario to sustained policy scenario).

Electrification of the transportation system

This study focused on electrification of EVs with a focus on personal automobiles (light-duty vehicles) because of data availability, and they account for the largest portion of transportation emissions. There will be a need to transition the entire transportation system (e.g., personal automobiles, buses, rail, air, ferry); however, this is not within the scope of this analysis and is being investigated by others, including the state.

EVs are becoming more accessible to more consumers as their purchasing costs are decreasing. Purchasing an EV will provide cost benefits to the consumer over the lifetime of the vehicle and can provide significant health benefits to the region on an aggregate level. The number and location of charging stations will have an impact on whether consumers feel that they are able to charge their vehicle over long distances. This reduction in “range anxiety” may encourage consumers to purchase EVs.

METHODS

As the cost of EVs has decreased, consumers have been steadily purchasing EVs over conventional internal combustion engine vehicles (ICEVs). We performed a consumer-level analysis to assess the benefits and costs associated with owning a light-duty EV, as well as a regional-level analysis to determine the number of charging stations that the growing number of light-duty EVs would need on the road. We also estimated the cost per metric ton of CO_2 reduced from the growing number of light-duty EVs in the region. This analysis assumed that the baseline is the SP scenario, and the benefit comes from the increased electrification of the transportation system that occurs under the SER1 scenario.

CONSUMER-LEVEL ANALYSIS

We performed a comparison of the lifetime costs of owning a light-duty EV as compared to an ICEV by incorporating both the initial capital cost and recurring annual costs into the analysis. The capital cost[31] of a light-duty ICEV is projected to remain around $29,000 through 2050. In contrast, the capital cost of light-duty EVs has decreased dramatically and is projected to continue to decrease through 2050 to about $32,000 (Figure 33) (NREL et al., 2017). Although the capital cost of an EV is currently more expensive than an ICEV, there are many state and federal EV subsidy programs that help make EVs more cost competitive. For example, the Massachusetts EV rebate program, MOR-EV, offers a $2,500 rebate on qualifying EVs and the DOE provides a $7,500 federal tax credit incentive for buying an EV.[32] In the short term, these subsidies can help lower the capital needed to purchase an EV and incentivize consumers to purchase an EV over an ICEV. In the longer term, the cost of EVs without subsidies is expected to be comparable with ICEVs. Our analysis does not take subsidies into account.

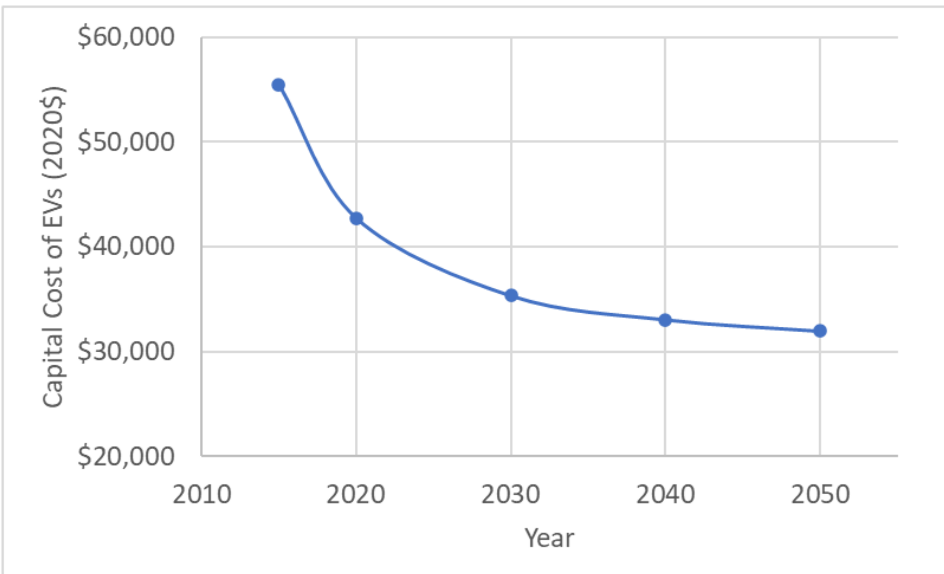

Figure 33. Capital cost of light-duty EVs (Source: NREL, 2017).

Consumers that own an EV must use either a public electric charging station to refuel, or they can install their own home charging unit. Barnstable County currently has 91 public Level 2 charging stations (DOE, n.d.). Although the number of public charging stations is likely going to increase as businesses invest in charging stations, we assume that consumers will purchase their own charging unit.

We also assume[33] that the electric vehicle supply equipment (EVSE) that consumers purchase to install in their homes will be Level 2 equipment. Level 2 EVSE charges faster than a Level 1

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[31] The capital cost of a light-duty EV is based on a vehicle with a 200-mile range and under a moderate technology advancement scenario. The capital cost of the light-duty ICEV is based on a similar mid-sized sedan.

[32] https://www.mass.gov/service-details/state-and-federal-electric-vehicle-funding-programs

[33] We do not have purchasing data to support this assumption, so if EV purchasers buy a Level 1 EVSE, this would make the purchase of an EV more advantageous. Our analysis includes a range of costs looking at no charger at all to the more expensive Level 2 EVSE. A Level 1 EVSE would fall somewhere in the middle.

EVSE and can be more convenient, but it is more expensive to install. According to the DOE's Office of Energy Efficiency and Renewable Energy, the cost of a Level 2 residential EVSE typically ranges from $500 to $2,000. We assume the cost of the Level 2 home charging unit is $1,250 in both 2030 and 2050.

Table 48 shows the capital costs associated with a light-duty EV and ICEV in 2030 and 2050. In 2030, light-duty EVs are $7,850 more expensive than ICEVs, but by 2050 they are projected to be only $4,340 more expensive than ICEVs.

Our estimated annual costs of owning an EV and an ICEV include both fuel and maintenance costs. A car travels about 11,500 vehicle miles per year (Federal Highway Administration, 2018). We used EIA's 2030 and 2050 projections of the cost of gas and electricity to estimate the annual fuel cost for a light-duty EV and ICEV. We assumed that the maintenance cost for a light-duty ICEV is $0.05 per mile driven (Prevedouros & Mitropoulos, 2016), and that the maintenance cost for an EV is 80% of the maintenance cost for an ICEV (NREL et al., 2017). Table 48 shows the annual costs for a light-duty EV and ICEV in 2030 and 2050.

Table 48. Capital and annual costs for a light-duty EV and ICEV in 2030 and 2050.

Cost (2020$)	2030 EV	2030 ICEV	2050 EV	2050 ICEV
Purchase Cost	$35,330	$28,730	$31,950	$28,860
Home Charging Unit Cost	$1,250	-	$1,250	-
Total Capital Cost	**$36,580**	**$28,730**	**$33,200**	**$28,860**
Annual Fuel Cost	$380	$910	$320	$940
Annual Maintenance Cost	$460	$570	$460	$570
Total Annual Cost	**$840**	**$1,480**	**$780**	**$1,510**

REGIONAL-LEVEL ANALYSIS

To assess the GHG emissions benefit associated with transitioning to EVs, we used Synapse-modeled emissions from the transportation sector for a sustained policy scenario (SP) and an aggressive electrification scenario (SER1). This comparison allows us to isolate the impact of EVs by keeping other transportation measures constant (like VMT reduction strategies).

Our modeling projected the number of light-duty EVs that will be on the road in each year from 2021–2050. We used EVI-Pro Lite to determine the number of charging stations needed to support the number of light-duty EVs projected to be on the road in 2030, 2040, and 2050 (California Energy Commission & National Renewable Energy Laboratory, n.d.).[34]

EVI-Pro estimates the number of workplace Level 2 charging plugs, public Level 2 charging plugs, and public direct current (DC) fast charging plugs needed to support the number of EVs

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34 EVI-Pro Lite is a tool developed by the National Renewable Energy Laboratory and the California Energy Commission and can be accessed here: https://afdc.energy.gov/evi-pro-lite

on the road and considers the percent of drivers with access to home charging units.[35] The EVI-Pro tool can only estimate the number of charging stations needed for up to 10 percent of the light-duty vehicles in the area. According to EVI-Pro, there were 329,500 light-duty vehicles in the Barnstable region in 2016.[36] Our EV projections exceeded this 10 percent threshold, so we used EVI-Pro to estimate the number of charging units needed by increments of 5,000 EVs up to the 10 percent threshold (30,000). We then extended these projections to estimate the number of workplace Level 2, public Level 2, and public DC charging plugs needed to support the number of EV vehicles in the projections. Figure 34 shows the EVI-Pro projections for charging plugs needed to support up to 30,000 EVs in Barnstable County.

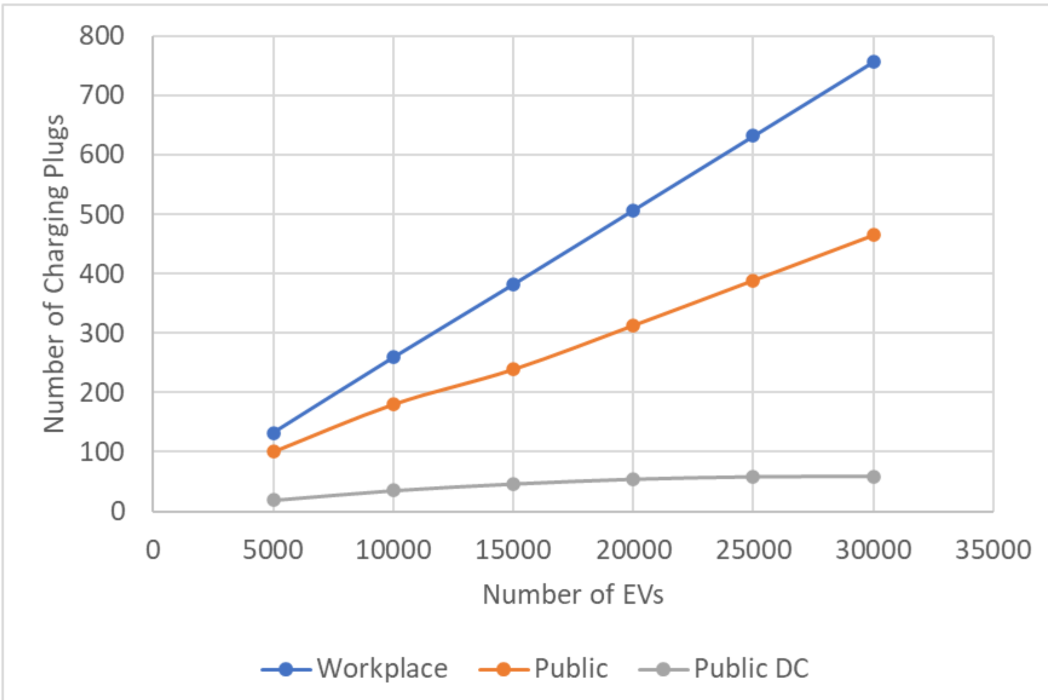

Figure 34. Number of charging units needed for up to 30,000 EVs in Barnstable County as estimated by EVI-Pro.

Table 49 provides the number of each type of charging station needed to support the number of light-duty EVs projected to be on the road under the sustained policy scenario (SP) and the SER1 scenario in 2030, 2040, and 2050, assuming that 100 percent of drivers have access to a home charging unit.[37]

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[35] DC is needed to charge car batteries. The Level 2 charging plugs provide alternating current (AC) to the vehicle, which is then converted to DC by the vehicle's onboard equipment. The DC charging plugs provide DC directly to the battery in the car. The car battery charges faster when DC is provided directly.

[36] The EVI-Pro tool does not delineate the Barnstable region exactly as Barnstable urbanized area defines it. RMV data reports that there are about 220,000 light duty vehicles on the road in Barnstable. Despite this discrepancy, our analysis is reasonable due to the large increase of vehicles that can be experienced because of the large visitor population in the region and demand for public charging from those visitors.

[37] EVI-Pro allows the user to identify the vehicle mix of the EV fleet. We used their default settings, which assumed that 15 percent of vehicles are plug-in hybrids with a 20-mile electric range, 35 percent are plug-in hybrids with 50-mile electric range, 15 percent are all-electric vehicles with 100-mile electric range, and 35 percent are all-electric vehicles with a 250-mile electric range.

Table 49. Charging stations needed to support light-duty EV projections under SP and SER1 scenarios.

Year (Scenario)	Number of Light-Duty EVs on the Road	Workplace Level 2 Charging Plugs Needed	Public Level 2 Charging Plugs	Public DC Fast Charging Plugs
2030 (SP)	13,998	358	230	40
2040 (SP)	67,596	1,698	1,002	126
2050 (SP)	117,766	2,953	1,725	206
2030 (SER1)	69,269	1,740	1,026	128
2040 (SER1)	167,507	4,196	2,441	286
2050 (SER1)	214,025	5,359	3,110	360

The cost to install a non-residential charging station is variable and depends significantly on site-specific factors. Table 50 provides cost ranges for workplace and public EVSE. In our analysis we assumed that the workplace Level 2 charging plugs cost $1,700, the public Level 2 charging plugs cost $4,500, and the DC fast charging plugs cost $25,000.

Table 51 presents the total cost of charging equipment needed for the SP and SER1 scenarios at the end of each decade.

Table 50. Cost of workplace and public EVSE (Source: EERE, 2015).

Type of EVSE	Cost Range	Appropriate Location
Level 2 basic pedestal	$1,200–$1,700	Workplace
Level 2 pedestal with low level data collection	$1,700–$2,700	Workplace or public
Level 2 pedestal with advanced features	$3,000–$6,000	Public
DC fast charging	$10,000–$40,000	Public

Table 51. Costs of EV charging equipment needed for the SP and SER1 scenarios.

Year (Scenario)	Number of Light-Duty EVs on the Road	Total Cost of Charging Equipment Needed
2030 (SP)	13,998	$2,640,000
2040 (SP)	67,596	$10,535,000
2050 (SP)	117,766	$17,925,000
2030 (SER1)	69,269	$10,781,000
2040 (SER1)	167,507	$25,252,000
2050 (SER1)	214,025	$32,104,000

Transitioning from ICEVs to EVs can help reduce GHG emissions and is an essential strategy because of the substantial emissions from vehicles to Barnstable County's emissions inventory. We estimated the reduced emissions from electrification of the transportation sector by comparing the light-duty vehicle emissions that we modeled for the sustained policy scenario and the SER1 scenario. The projected reduced transportation emissions are presented in Table 52. Using our emissions models, we estimated the cost per MMT of CO_2 reduced and the estimated difference in cost of installing the necessary EVSE.

Table 52. Cumulative reduced transportation CO_2 emissions by decade by transitioning from sustained policy scenario to SER1 scenario (only considering light-duty vehicle emissions).

Years	Reduced Transportation CO_2 Emissions (MMT of CO_2)
2021–2030	0.78
2031–2040	2.65
2041–2050	2.78
Total (2021–2050)	**6.21**

In addition to looking at the emission reductions specifically from light-duty EVs, we also monetized the benefits from overall emissions reductions in the transportation sector. This includes emission reductions from light, medium, and heavy-duty vehicles. Table 53 shows the reduced CO_2 and criteria pollutant emissions from 2020–2050. By 2050, around 9.2 million metric tons of CO_2 could be reduced through increased electrification of the transportation sector.

We monetized the reduced CO_2 emissions using high and low estimates of the market value and SCC. We monetized the benefit of reduced criteria pollutant emissions using values from a 2013 EPA report. The "Reducing greenhouse gas emissions from buildings" section of this report contains a more detailed review of how these values were estimated and used.

Table 53. Emissions reductions from the transportation sector from switching to the aggressive electrification scenario (SER1) from the sustained policy scenario (SP) (considering all vehicle emissions).

Years	Reduced CO_2 Emissions (MMT of CO_2)	Reduced $PM_{2.5}$ Emissions (Metric Tons)	Reduced SO_2 Emissions (Metric Tons)	Reduced NO_x Emissions (Metric Tons)
2021–2030	0.87	6.2	5.0	138.3
2031–2040	3.53	31.5	19.8	817.7
2041–2050	4.80	49.5	25.9	1,497.7
Total	**9.20**	**87.3**	**50.7**	**2,453.6**

RESULTS

CONSUMER-LEVEL ANALYSIS

The capital cost of EVs is currently higher than ICEVs; however, this cost is offset by the significantly lower annual costs associated with EVs. The lifetime cost of owning an EV as compared to an ICEV is cheaper for a consumer the longer they drive it. For example, if a consumer in 2030 chooses to purchase an EV and install a home charging unit, their lifetime costs will be less after 12 years of ownership than if they had chosen to buy an ICEV at that time. This breakeven point decreases from 12 to seven years for an EV purchased in 2050. If the consumer does not purchase a home charging unit, the breakeven point of owning an EV occurs in the tenth year of ownership if purchased in 2030 and in the fourth year of ownership if purchased in 2050. Figure 35 and Figure 36 show the cost of owning an EV and ICEV by the number of years the vehicle is owned based on 2030 and 2050 projections, respectively. The blue line represents the cost if the consumer purchases a home charging unit, and the grey line represents the cost without this purchase. The cost of purchasing an ICEV in 2030 and owning it for 10 years is $1,445 lower compared to purchasing an EV and a home charging unit (in the absence of an incentive). For vehicles purchased in 2050, it is projected to be more advantageous to purchase an EV, as 10 years of ownerships results in a $1,873 cost savings after purchasing an EV and a home charging unit, as compared to owning an ICEV for those 10 years.

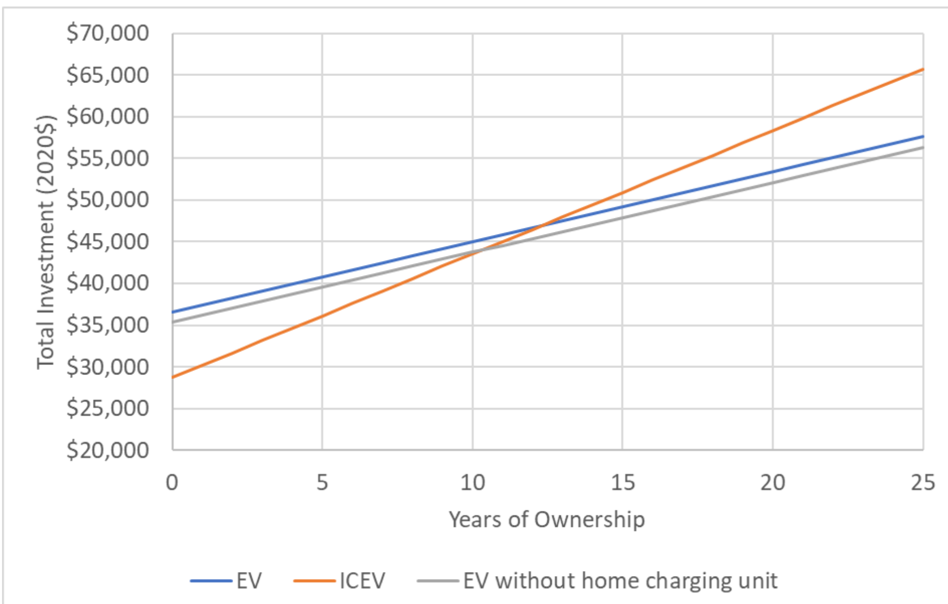

Figure 35. Cost of owning a light-duty EV and ICEV purchased in 2030 by the number of years the vehicle is owned.

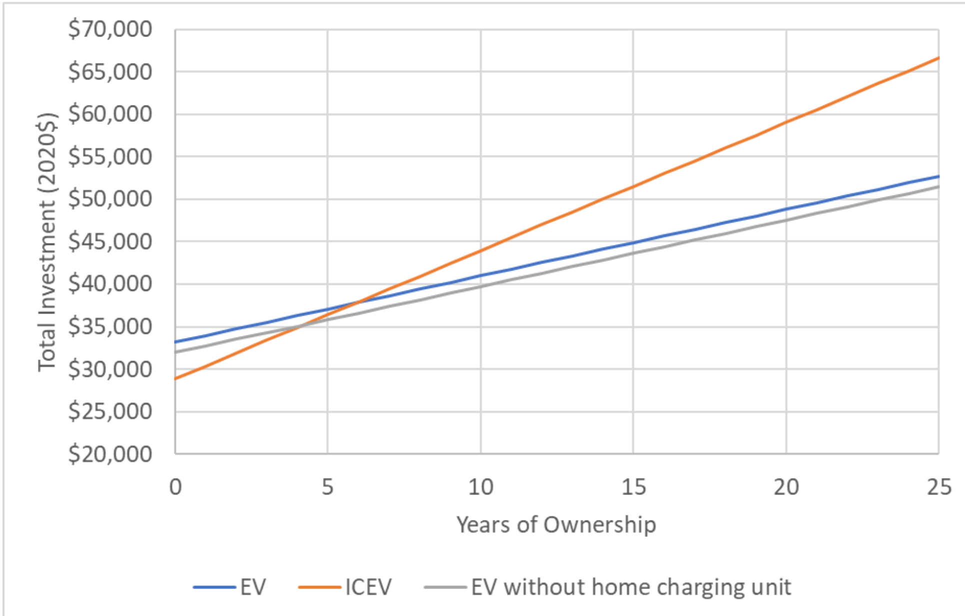

Figure 36. Cost of owning a light-duty EV and ICEV purchased in 2050 by the number of years the vehicle is owned.

REGIONAL-LEVEL ANALYSIS

Our regional-level analysis assumes that the sustained policy (SP) scenario is the baseline scenario from which we calculate the benefits of the aggressive electrification scenario (SER1). In other words, the SP scenario is the realistic projection of what will happen in the future based on current trends. The SER1 scenario is used to assess the benefits associated with increased electrification of the transportation sector.

The Cape Cod region is currently expected to have about 14,000 light-duty EVs on the road by 2030, increasing to nearly 118,000 by 2050. This increase in light-duty EVs is based on a sustained policy projection and does not consider any actions taken to reach the region's emission reduction goals.[38]

To support the projected growth in light-duty EVs under the sustained policy scenario, the region will need to install 4,883 charging stations by 2050 at an estimated cost of $17.9 million. This estimated cost assumes that 2,953 charging stations are workplace charging plugs, and therefore the cost would be paid by businesses and would not be paid by local government or state funds. The cost of public charging equipment needed to support the number of light-duty EVs on the road by 2050 is $12.9 million. Table 54 provides the total estimated cost of charging equipment needed for 2030, 2040, and 2050, as well as the cost of public charging equipment.

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[38] The sustained policy scenario assumed that EV market share will grow to 7 percent in 2025 and 24 percent in 2030. This projection is based on the Bloomberg New Energy Finance's projection of EV sales in the U.S.

We assume that government funding will cover the capital cost of the public charging equipment and the consumer is charged to use the equipment.[39] Therefore, we do not account for electricity costs associated with these charging units because they are passed onto the consumer. Our consumer-level analysis covers the cost to the consumer, including these electricity costs.

Table 54. Total cost and cost of public charging equipment needed to support light-duty EVs on the road by decade under the sustained policy scenario.

Year	Number of EVs on the Road	Number of Charging Stations Needed	Total Cost of Charging Equipment Needed	Cost of Public Charging Equipment Needed
2030	13,998	628	$2,640,000	$2,031,000
2040	67,596	2826	$10,535,000	$7,649,000
2050	117,766	4883	$17,925,000	$12,906,000

The SER1 scenario assumes that the emissions reductions from the transportation sector will come from high levels of EV adoption. Based on the SER1 scenario projections, the Cape Cod region is expected to have nearly 70,000 light-duty EVs on the road by 2030, increasing to over 200,000 by 2050. Table 55Table 55. Total cost and cost of public charging equipment needed to support light-duty EVs on the road by decade under the aggressive electrification (SER1) scenario provides the total estimated cost of charging equipment needed for 2030, 2040, and 2050, as well as the cost of public charging equipment needed to support the projected light-duty EV growth for the SER1 scenario. These costs are not incremental; rather, they present the total spending needed by that year.

Table 55. Total cost and cost of public charging equipment needed to support light-duty EVs on the road by decade under the aggressive electrification (SER1) scenario.

Year	Number of EVs on the Road	Number of Charging Stations Needed	Total Cost of Charging Equipment Needed	Cost of Public Charging Equipment Needed
2030	69,269	2,894	$10,781,000	$7,824,000
2040	167,507	6,922	$25,251,000	$18,119,000
2050	214,025	8,829	$32,104,000	$22,994,000

If Cape Cod follows the aggressive electrification scenario (SER1), it can reduce CO_2 emissions by over 6.2 MMT in 2050 for a cost of approximately $10 million. This is roughly $1.6 million per MMT of CO_2 reduced. Table 56 shows the cost to achieve these reduced CO_2 emissions for each decade through 2050. The reduction in emissions was calculated as the cumulative emissions reduced during the specified time period. The cost to achieve the reductions from 2021 to 2030 was calculated as the difference in cost from the public charging equipment needed to support the number of light-duty EVs on the road for SER1 ($7.8 million from the

[39] It is also possible private industry will cover the capital cost of infrastructure initially and this cost will be passed on to the consumer. Regardless of who pays, there will be a cost incurred for installing the charging infrastructure, which we include in the analysis below.

right column of Table 55) and SP ($2.0 million from the right column of Table 54). The cost to achieve the reductions from 2031 to 2040 and 2041 to 2050 were calculated as the incremental cost needed to support the additional EVs projected to be on the road during that time period. Between 2031 and 2040, the SP scenario projects an additional 53,598 EVs (Table 54) and the SER1 scenario projects an additional 98,238 (Table 55). The difference in the cost of the public charging units needed to support these projected increases in EVs is $4.67 million. We performed a similar calculation for 2041–2050 projections. Between 2041 and 2050, the SP scenario projects an additional 50,170 EVs and the SER1 scenario projects an additional 46,518 EVs. The year-to-year (incremental) difference in cost between the SP and SER1 scenarios becomes negative in year 2044 because SP projects a higher rate of increase of EVs on the road beginning in 2044 as compared to SER1 (although the total number of EVs on the road remains much greater for the SER1 scenario than the SP scenario). Therefore, the cost to achieve the emissions reductions from 2041–2050 is less for the SER1 scenario than the SP scenario. The total cost to achieve the 6.2 MMT of CO_2 reductions in 2050 was calculated as the difference between the estimated cost of public charging equipment needed in 2050 for the SER1 scenario ($23 million) and the SP scenario ($12.9 million). Switching to the SER1 scenario from the SP scenario results in a savings of over $137,000 per MMT of CO_2 reduced by 2050.

Table 56. Cost associated with reduced transportation emissions from switching to SER1 scenario from the sustained policy scenario (only considering light-duty vehicle emissions).

Years	Reduced Transportation CO_2 Emissions (MMT of CO_2)	Cost to Achieve Emissions Reductions	$/MMT CO_2 reduced
2021–2030	0.78	$5,792,000	$7,441,000
2031–2040	2.65	$4,678,000	$1,763,000
2041–2050	2.78	-$383,000	-$137,562
Total (2021–2050)	**6.21**	**$10,088,000**	**$1,624,000**

We estimated the overall benefits from electrification of the transportation sector by monetizing the reduced CO_2 and criteria pollutant emissions. The reduced emissions consider all types of vehicles and transportation, not just LDVs. Table 57 shows the monetized benefit of reducing CO_2 emissions from the transportation sector using both high and low estimates of the market and social costs of carbon. The monetized benefit of the reduction in criteria pollutants is provided in Table 58. By 2050, CO_2 emissions could be valued at over $50 million based on a conservative market price estimate, or as much as $673 million using a conservative SCC estimate. The monetized benefit of reduced criteria pollutants is estimated to be nearly $83 million by 2050.

Table 57. Monetized benefit of reduced CO_2 emissions from the transportation sector (millions of 2020$).

Years	Market Value of Reduced CO_2 Emissions	Social Value of Reduced CO_2 Emissions
2021–2030	$4.80–$7.20	$51.33–$154.4
2031–2040	$19.4–$29.2	$241.3–$734.8

Years	Market Value of Reduced CO_2 Emissions	Social Value of Reduced CO_2 Emissions
2041–2050	$26.5–$39.7	$380.9–$1,171.7
Total	**$50.7–$76.1**	**$673.5–$2,060.9**

Table 58. Monetized benefit of criteria pollutant reductions from the transportation sector (millions of 2020$).

Years	$PM_{2.5}$	SO_2	NO_x	Total
2021–2030	$2.4	$0.5	$2.0	$4.9
2031–2040	$13.4	$2.3	$13.5	$29.2
2041–2050	$21.0	$3.0	$24.8	$48.8
Total	**$36.8**	**$5.8**	**$40.4**	**$82.9**

LIMITATIONS AND FUTURE ANALYSIS

We used the EVI-Pro tool to determine the number of charging stations needed to support the projected growth in EVs. This tool focuses on traditional trip patterns, and therefore it does not necessarily capture the needs for a region with many tourists whose trip patterns may differ from traditional trip patterns.

The EVI-Pro accounts for the percent of drivers with access to home charging units. We assumed that 100 percent of the drivers had access to home charging units. If a lower percent of drivers has access to home charging units, the number of charging stations needed would increase. Future analyses should look at how the number of charging stations needed changes based on the assumption of the percent of drivers with a home charging unit.

Electrification of the Transportation System: Key Takeaways

- In 2050, a consumer will save nearly $2,000 on an EV compared to an ICEV after 10 years of ownership.
- In 2030, a consumer will pay less than $1,500 more for an EV and home charging unit (with no subsidies) compared to an ICEV after 10 years of ownership.
- The cost-effectiveness of implementing enough public charging infrastructure to support aggressive vehicle electrification and meet 2050 emissions goals compared to the cost of implementing enough charging infrastructure in the sustained policy scenario is less than $2 per $MTCO_2e$ reduced (over the period of 2021 through 2050).
- The health benefits associated with aggressive electrification (SER1) compared to sustained policy are over $80 million and the market value of reduced CO_2 is approximately $50 to $76 million. This benefit far exceeds the incremental cost of implementing additional charging infrastructure (approximately $10 million incremental cost from SER1 compared to sustained policy scenario).

Opportunities for green economy jobs

Implementation of many of the adaptation and mitigation actions identified in the Cape Cod Climate Action Plan planning process will necessitate job creation, with many jobs requiring skilled labor. Jobs are needed to support wetlands restoration, housing retrofits, and expanded production of renewable energy, among many other needs. In this section, we will quantify projected job creation associated with expanded use of renewable energy on Cape Cod.

METHODS

This section focuses on quantifying the benefits (number of jobs created) from renewable energy and residential electrification. Our team conducted a literature review of jobs created per megawatt of solar and hours of labor required to install a heat pump, and then scaled jobs and labor hours for future heat pump adoption and solar development under GHG emissions scenarios developed in Part 2. Costs related to job creation in these areas were not evaluated as they may include training programs and/or business loans and will need to be fully evaluated in the future when necessary to foster these businesses and jobs locally.

Heat pumps: A UCLA Luskin Center for Innovation report looking at workforce needs for decarbonizing California suggests using residential repair cost estimators (like Homewyse.com) to estimate labor hours involved in installing several types of residential heat pumps (UCLA Luskin Center for Innovation, 2019). The latest estimates from Homewyse, which draws on national labor hour estimates and local rates, found that several types of residential heat pumps require 14.3 to 14.8 hours of licensed contractor labor (*Homewyse Calculator*, n.d.). We multiplied an average value of 14.6 hours to install each heat pump by target heat pump units under the future GHG emissions scenarios to identify future labor hour needs. Labor hours are converted into an estimated number of job-years[40] by dividing by 2,080 hours in a work year.

Solar: The Solar Foundation reports that the solar industry requires about 15.5 job-years per installed megawatt. These jobs include installation, manufacturing, sales and distribution, and project development, among other roles in the solar development and maintenance process (The Solar Foundation, 2015). We drew on solar targets within the "Massachusetts 2050 Decarbonization Roadmap" to estimate future solar capacity on Cape Cod. The Roadmap projects that in 2050, 32 percent of non-emitting generation will be solar (Massachusetts Executive Office of Energy and Environmental Affairs & The Cadmus Group, 2020). Applying this percentage to our forecasted clean energy generation needs under SER 1, we calculated 1,196 GWh of solar generation for the Cape in 2050. By applying capacity factors from the National Renewable Energy Lab's Annual Technology Baseline (19 percent for fixed solar), we see that the county would need approximately 0.6 GW alternating current (AC) of solar,[41] including both rooftop and utility scale. We then multiply by 15.5 job-years to estimate future solar jobs created.

Offshore wind: The "Massachusetts 2050 Decarbonization Roadmap" calls for 15–20 GW of installed offshore wind capacity by 2050. Specifically, it calls for 65 percent of non-emitting

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[40] Job-years refers to the years of full-time equivalent employment (assuming 2,080 hours of work per year).

[41] Solar panels tend to be rated in terms of the direct current (DC) power they can produce, but this power is converted to AC by an inverter before it is sent out to the grid.

generation to be offshore wind by 2050. We have drawn on analyses of labor needs to construct and operate wind projects in Massachusetts and applied those findings to estimates of the Cape's future offshore wind capacity. This provides estimates of labor needs to meet that capacity.

RESULTS

Heat pumps and solar: We expect the need for contractors who install heat pumps to grow from 25 contractor job-years today to between 443 and 862 contractor job-years in 2050, as presented in Table 59.

Table 59. Labor hours and jobs to expand residential heat pumps.

Scenario	Heat Pump Units: 2020	Labor Hours, Job-Years (2020)*	Heat Pump Units: 2030	Labor Hours, Job-Years (2030)	Heat Pump Units: 2050	Labor Hours, Job-Years (2050)
Sustained Policy	3,543	51,732 hrs, 25 job-years	21,319	311,255 hrs, 150 job-years	63,147	921,944 hrs, 443 job-years
SER 1	3,543	51,732 hrs, 25 job-years	33,669	491,563 hrs, 236 job-years	91,519	1,336,172 hrs, 642 job-years
CEN	3,543	51,732 hrs, 25 job-years	33,669	491,563hrs, 236 job-years	91,519	1,336,172hrs, 642 job-years
SER 2	3,543	51,732 hrs, 25 job-years	27,069	395,211 hrs, 190 job-years	88,996	1,299,340 hrs, 625 job-years
SER 3	3,543	51,732 hrs, 25 job-years	37,074	541,282 hrs, 260 job-years	122,768	1,792,413 hrs, 862 job-years

*Job-years refers to the years of full-time equivalent employment (assuming 2,080 hours of work per year).

Under each greenhouse reduction scenario, there is also an expansion of heat pumps to serve additional square footage of commercial properties. We expect additional jobs to be created to meet this need; however, they are not analyzed here.

At about 15.5 job-years per installed megawatt and 0.6 GW of solar capacity in Barnstable County in 2050, we can expect approximately 9,300 job-years in order for the county's solar development to mirror the target 2050 solar capacity.

Offshore wind: Given the "Massachusetts 2050 Decarbonization Roadmap" calls for 65 percent of non-emitting generation to be offshore wind by 2050, we applied this percentage to our forecasted clean energy generation need under SER 1 and calculated 2,409 GWh of offshore wind generation in 2050. By applying capacity factors from National Renewable Energy Lab's Annual Technology Baseline (44 percent for offshore wind), we see that the county would need approximately 0.6 GW AC of offshore wind.

A 2018 study by the MassCEC evaluated how many jobs and what kind of training would be required to construct 1,600 MW of offshore wind. The study found that between 2,279 and 3,171 direct job-years is needed to construct 1,600 MW, assuming four 400-MW farms. This includes direct, indirect (supply chain), and induced impacts. Once the projects are producing power, a total of 140 to 256 direct jobs will be generated and sustained annually over the life of the wind farms. Including direct, indirect, and induced impacts, operations and maintenance are estimated to annually support between 964 to 1,748 job-years (2018 Massachusetts Offshore Wind Workforce Assessment, 2018). Focusing simply on direct jobs sustained annually over the life of the farms and based on the proportion of jobs created from the 1,600 MW mentioned above, we estimate that 0.6 GW of offshore wind capacity requires approximately 75 jobs to serve the Cape's consumption of offshore wind, in addition to indirect jobs).

The MassCEC assessment determines that Massachusetts can support labor needs in many categories, but for operations and maintenance technicians and water transportation workers in particular, new talent needs to be trained or recruited (Massachusetts Clean Energy Center, 2018). Cape Cod's workforce can help fill this gap. The assessment identifies Cape Cod Community College as uniquely positioned to educate candidates coming into the industry, though the college still requires certification from one of the global credentialing organizations such Global Wind Organization (GWO) or BZEE (Bildungszentrum für Erneuerbare Energien).

Targeting training on Cape Cod is an important step toward integrating the Cape into the offshore wind industry. The Commonwealth, wind developers, and philanthropists have started administering grants to colleges and trade unions to fill these training gaps, including one to Cape Cod Community College (Vineyard Wind, 2019). As noted in Part 1 of this report, many blue economy businesses are expected to be impacted by SLR (see Table 12). As the region move towards its emissions reductions goals, there will be more opportunity for training and employment in offshore wind and other renewable energy industries."

LIMITATIONS AND FUTURE ANALYSIS

This analysis does not assess the extent to which existing businesses doing heat pump and solar installation near, but outside of Barnstable County, are positioned to expand and meet growing demands on the Cape. This could be evaluated in future work. This analysis assumes that the County's local solar development will mirror the quantity of solar power it is targeted to receive through the grid under statewide decarbonization targets. Further analysis is needed in the future to determine to what extent the region will develop solar locally, or rely on other parts of the state to do so.

In considering opportunities in offshore wind for the Cape, more research is needed to understand opportunities to advocate for additional offshore wind hubs in the state. In addition to the Wind Technology Testing Center and the New Bedford Marine Commerce Terminal, Cape Cod could orient a harbor as a center of support for the industry and further expand job potential.

Opportunities for Green Economy Jobs: Key Takeaways

- Installing 60,000 to 120,000 heat pumps by 2050 will generate about 400 to 850 job-years over that period.
- Installing 0.6 GW of offshore wind capacity (as needed by the region to reach 2050 emissions goals) will generate approximately 75 jobs in construction and maintenance annually.
- Installing 0.6 GW of solar capacity (as needed by the region to reach 2050 emissions goals) will generate about 9,300 job-years.

Protection, Conservation, and Restoration of Natural Ecosystems

Protection, conservation, and restoration of natural ecosystems will help sequester carbon and can help the region reach net neutrality goals. These ecosystems can also provide many other valuable ecosystem services. For example, marshes can both sequester carbon (referred to as "blue carbon"), mitigate flood damage, and support fisheries, among many other benefits. Forests also sequester carbon and can provide valuable recreation opportunities.

We did not perform a quantitative analysis for this strategy. However, based on recent work for the state of Maine (Eastern Research Group, 2020), ERG estimated the return on investment for restoring marshes and conserving forests. For forests, ERG estimated a cost of about $4 to $19 per metric ton of CO_2 sequestered; however, this was based on being able to conserve land at about $115 per acre. This may be much less cost-effective in Barnstable County, where land costs are many times higher.[42] ERG also found that restoring marshes and eel grass cost well over $1,000 per metric ton of CO_2 sequestered, so was less cost-effective than other mitigation options. However, these options become much more cost-effective when they are sited to maximize their other ecosystem services, such as flood protection.

Adaptation Strategies

Solutions to coastal flooding and sea level generally fall into two categories: shoreline solutions and building-specific solutions. Shoreline solutions establishing a boundary along the shoreline, keeping out water to specific water level. Building-specific solutions adapt buildings to better handle storm tide flooding. We have explored these two categories of strategies below.

Support and promote protection, conservation, and restoration of natural ecosystems

Wetlands provide storm surge protection, improve water quality, store large amounts of carbon, and provide critical habitat for local fisheries. However, human development has degraded and destroyed 38 percent of Cape Cod's historic[43] salt marshes (Puy & Muramoto, 2015). As SLR threatens these ecosystems, restoring and conserving wetlands requires open space for marsh

[42] We did not have a comparable data source, but a search on Zillow suggests that land may exceed $100,000 per acre on the Cape; thus, purchasing land strictly for the purpose of sequestration may not be cost-effective.

[43] A specific time period was not reported by the authors.

migration. Protecting these wetlands will provide crucial storm surge protection, as well as a range of cultural, recreational, and environmental benefits to the surrounding communities on Cape Cod.

METHODS

Salt marsh restoration costs vary greatly due to marsh conditions. Restoration projects around the United States have cost $3,300 to $15,550 per acre of salt marsh to restore (Aerts et al., 2013; Grabowski et al., 2012). Wetland restoration costs in Massachusetts range widely depending on the complexity of the site. Some project costs, such as construction, materials, and design, are related to the size of the marsh. Other costs, such as bidding out, monitoring, and construction oversight, are more fixed. Restoration projects that require extensive excavation and/or revegetation can be more expensive, while projects that only need to restore natural hydrology tend to cost less. Some areas may need land to migrate to, while low-lying wetlands that are in danger of drowning and unable to migrate can be protected with relatively inexpensive earth-filled levees at $25.13 per foot each year (Aerts et al., 2013). Costs can also quickly increase if restoring tidal flow puts nearby infrastructure at risk of flooding.

Salt marsh restoration projects infuse money into the economy. For example, Samonte et al. (2017) found that each acre of restored salt marsh contributes $7,370 to the Massachusetts economy. Their study included labor-intensive restoration projects, such as building oyster reefs and removing invasive species.

To estimate the cost of protecting Barnstable County's nearly 14,000 acres of salt marsh would require assessing the current conditions and marsh migration potential of each wetland site. The Association to Preserve Cape Cod (APCC) created an inventory of salt marsh restoration areas, prioritized according to potential space for migration, number and type of barriers to restoration, and number of houses and culverts flooded with 2 feet of SLR (Puy & Muramoto, 2015). The APCC identified 16 sites (excluding Herring River Estuary) as priorities for restoration due to their marsh migration potential (Puy & Muramoto, 2015). We calculated the cost of restoring the marshes with the most migration potential by multiplying the number of sites identified by APCC by the average restoration cost per site. We focused on two of those sites to calculate the value of ecosystem services provided by each site using the methods applied in Part 1 of this report. We then performed a benefit-cost analysis for each site.

Georgeann Keer, an ecological restoration specialist at the Massachusetts Department of Environmental Protection, provided the restoration site costs (see Table 60). The upper and lower bound estimates are driven primarily by project complexity/presence of infrastructure (rather than acreage). The estimates for construction and materials are for a typical culvert restoration project. The lower bound estimate for construction and materials is based on projects on non-major roads. It should be noted that the Herring River Estuary is one of the sites that the APCC identified; however, due to its size and the complexity of restoration, its costs fall outside the typical range (G. Keer, personal communication, January 7, 2021).

Table 60. Breakdown of wetland restoration costs (in thousands of 2020$).

Project Stage	Low End	High End
Define project/project reconnaissance	$15	$50
Full feasibility/modeling	$25	$250
Concept designs	$20	$40
Design for permitting	$50	$250
Monitoring costs (pre-construction to post-construction)	$25	$50
Permitting process	$20	$80
Final designs	0	$50
Pre-construction costs	***$155***	***$770***
Bidding out	***$20***	***$40***
Construction oversight	$50	$100
Construction and materials	$250	$1,000
Contingency	10–20%	10–20%
Total	**$546**	**$2,197**

RESULTS

Cost of restoration: Typical wetland restoration costs range from around $546,000 to $2.2 million per project, averaging at $1.37 million per site (G. Keer, personal communication, January 7, 2021). It would cost around $20 million to restore all 16 sites (excluding Herring River Estuary) identified by the APCC as priorities for restoration, but each would provide numerous ecosystem services, including water quality improvements, biomass for commercial and recreational fisheries, and carbon sequestration. Some sites may also provide flood protection. Not all sites listed provided details on the area of restored or impacted marsh. The two sites for which we identified sufficient information to perform benefit-cost analyses are Parkers River and Pamet River.

The Parkers River Restoration Project was awarded to the Town of Yarmouth for $3.8 million to restore the natural hydrology of this 219-acre estuarine system, improving fish and shellfish habitat and restoring 60 acres in salt marsh, with an average cost of $17,450 per acre (U.S. Fish and Wildlife Service, 2018).

The Pamet River has 158 acres of open space available for marsh migration. Purchasing this land and placing it under a conservation easement could preserve the marsh by ensuring the open space is never developed. The average value of agricultural land in Massachusetts is around $11,400 per acre (Center for Agriculture, Food and the Environment, 2016), but the cost of land could be much higher as many lots in Zillow are currently $100,000 per acre or more in the region. Assuming this natural space is worth the same as agricultural land,[44] it would cost close to $1.8 million to purchase all 158 acres. Assuming the average cost of a restoration project is $1.25 million, the total cost of restoration is estimated at around $3 million. The Pamet River

[44] In the absence of an analysis for the open space, we have used an average value of agricultural land in Massachusetts as a proxy. This analysis can be updated to include actual purchase price of these acres.

restoration project could be complicated by low-lying properties in the area, which might require additional measures to protect them from flooding once hydrology is restored.

Table 61 summarizes the initial restoration cost compared to the projected annual ecosystem services and economic contributions of each restoration project. Only the Parkers River has an estimated economic output, as the restoration described for the Pamet River was less intensive and would likely require less labor expenditures. The SCC shown in Table 61 is valued for 2030, assuming these areas are restored in the next 10 years. The value of carbon sequestration will continue to increase each year.

The restoration of the Pamet and Parkers Rivers could almost recover the initial project cost in ecosystem services and contributions in under 10 years (see Table 62), assuming ecosystem services function at a similar level to marshes that have not recently undergone restoration. These estimates cover only some of the ecosystem services that wetlands provide.

Table 61. Costs and benefits of restoration projects (in thousands of 2020$).

Site	Acres	Restoration Cost	Nitrogen Removal	Carbon Sequestration (SCC at 2030)	Fisheries	Economic Output
Parkers	60	$10,500	$148–267/ year	$4.0–7.0/year	$14.2/year	$422
Pamet	158	$3,170	$390–705/ year	$10.7–18.4/ year	$37.4/year	-

Table 62. Benefit-cost ratio for case studies.

Site	Benefit-Cost Ratio 2021–2030	Benefit-Cost Ratio 2021-2050
Parkers	2.0–3.2	5.2–8.3
Pamet	1.4–2.4	4.2–7.2

Cranberry bog restoration: Wetlands in Barnstable County could be restored through cranberry bog restoration. As noted in Part 1, dozens of cranberry bogs are vulnerable to SLR. Many of these bogs were originally converted from wetlands. Restoring them back to wetlands will provide ecosystem services, including improved water quality and carbon sequestration. A recent project that restored 40 acres of bog back to wetlands in Plymouth, Massachusetts, cost around $2 million ($50,000 per acre) and required roadwork, dam removal, and the planting of more than 20,000 trees (Moran, 2019). The cost also included payments of $13,600 per acre to cranberry farmers (Moran, 2019). If the 410 acres of vulnerable cranberry bogs in Barnstable County are restored, assuming a cost similar to the Plymouth restoration project, the value in nitrogen removal alone would equal the cost of restoration in five to nine years, depending on the rate of removal (see Table 63). The value for carbon sequestration is calculated with the SCC at 2030. Every year, the value of carbon sequestered will increase.

Table 63. Annual benefits of restored cranberry bogs (in thousands of 2020$).

Acres of Bogs Impacted	Restoration Cost	Value of Nitrogen Removal	Value of Carbon Sequestration	Benefit-Cost Ratio 2021–2030
410.1	$20,505	$2,230–$4,036	$27.7–47.2	1.10–1.99

LIMITATIONS AND FUTURE ANALYSIS

This analysis presents a high-level overview of the costs and some of the benefits of preserving and restoring wetlands. It focuses on the initial costs of restoration, so the costs may be higher if including maintenance (where there was some limited information). Additionally, as climatic changes occur, the needs of the salt marsh may change, increasing maintenance costs over time. A detailed assessment of the marsh's hydrologic flow and migration potential is needed to better estimate restoration costs. Ecosystem service values are estimated using rates from existing marshes. It may take some time for restored marshes to provide services at the same rate. Wetlands can provide storm surge and flooding protection depending on the location and topography of the site. Future analysis could assess the potential of various sites to reduce wave attenuation and protect properties from flooding. Future analysis on willingness of homeowners, cranberry growers, and other landowners to restore land to marsh (through conservation easements, sales to conversation group or other means) will also be an important next step.

Support and Promote Protection, Conservation, and Restoration of Natural Ecosystems: Key Takeaways

- APCC has identified 16 wetlands sites as priorities for restoration. We can expect a large range in restoration costs per site. However, $1.37 million per site provides as average.
- The restoration of the Pamet and Parkers Rivers could almost recover the initial project cost in ecosystem services (nitrogen removal, carbon sequestration, and fisheries habitat) and economic contributions in under 10 years.
- Wave attenuation and flood protection provided by wetlands was not quantified and requires further study.
- If the 410 acres of vulnerable cranberry bogs in Barnstable County are restored, the value in nitrogen removal alone would equal the cost of restoration in five to nine years.

Adapting shorelines to Rising Seas

We assessed the benefits (avoided damages from SLR) and costs of raising buildings and protecting the shoreline to specified design standards. While the main goal of these solutions is to protect buildings and infrastructure from flood damage, we considered the additional benefits of avoided loss of wages, cranberry bog revenue, and tax revenue provided by shoreline solutions in our analysis. That said, this analysis does not comprehensively quantify all costs and benefits and tradeoffs for each shoreline solution. For example, living shorelines, constructed wetlands, and beach restoration projects provide additional public green space, erosion prevention, and water quality improvements—benefits that are not associated with sea walls.

Detailed analysis is needed in the future to study these tradeoffs for priority shoreline adaptation areas.

METHODS

We calculated the benefits and costs of shoreline to SLR and flooding for each town and for all of Barnstable County. Shoreline solutions provide additional benefits by preventing loss of land to SLR and protecting roads, businesses, and natural and working lands. This analysis focuses on shoreline adaptation strategies that would provide a protective barrier for up to 8 feet or 12 feet MHHW of SLR and/or storm surge. Following the state's SLR projections, 8 feet MHHW is approximately equivalent to sea level projected in the year 2100 plus a king tide event, while 12 feet MHHW is approximately equivalent to sea level projected in the year 2100 plus a 50-year storm surge.

Benefits: Constructing barriers on the shoreline around Barnstable County would prevent damage from SLR and, in some cases, storm surge. As such, we draw on the avoided damages (also known as benefits) for SLR flooding impacts on buildings, land (Table 7), job wages (Table 11), cranberry bog revenue (Table 29), and taxes (Table 9) that we calculated in the cost of doing nothing analysis. To consider shoreline adaptation benefits, we adjusted our cost of doing nothing analysis so that buildings that would have been flooded from SLR would no longer be abandoned and could therefore accrue more damages in the future if water levels surpass the barrier.

There are a range of cost-effective solutions to flooding and other coastal hazards, particularly in densely inhabited areas. Depending on the type of infrastructure used, these solutions can reduce erosion, increase natural habitat, and improve access to the coastline. Solutions are classified as nature-based (or green), gray, or integrated green-gray infrastructure. Nature-based solutions rely on natural habitats and materials for protection, such as restoring or building salt marsh, dunes, and berms. Gray infrastructure refers to man-made infrastructure such as seawalls, dams, and break walls. Integrated gray-green solutions combine standard infrastructure interventions such as seawalls with natural elements to enhance the marine or coastal environment. They can take many forms, such as building terraced wetlands, adding small structures on seawalls, creating tidepools, and terracing salt marsh along an estuary (Naylor et al., 2017).

Integrated solution costs vary depending on design complexity. Additions can add as little as $142 per linear foot to the cost of a traditional seawall ($4,620 per linear foot) to as much as $7,360 per linear foot to install terraced vegetation (Naylor et al., 2017; US Army Corps of Engineers, 2019). The level of protection and implementation location of each solution depend on the type of structure. Many green infrastructure solutions require a good amount of space to restore or build vegetation. Living shorelines typically cost around $1,500 per linear foot (US Army Corps of Engineers, 2015).[45] While this is less expensive than most gray solutions, such as seawalls, the level of protection that living shorelines provide and their suitability to conditions and needs differ. Living shorelines require more space and are not ideal for highly developed coastlines foot (US Army Corps of Engineers, 2015). Beach restoration can be another cost-

[45] Living shorelines can vary in design; the USACE (2015) example begins -2 feet below mean lower low water and a fill width of around 50 feet. It consists of a rock breakwater, sand fill behind the breakwater, and marsh grasses.

effective alternative, but they also require a larger amount of space and rates of erosion may increase the cost of maintaining beach and dune height. Because of these varying levels of protection and restrictions on where they can be built, we estimated the benefits and costs for solutions that had more flexibility in location and level of protection.

Table 64 summarizes the construction costs of three potential shoreline solutions for flood protection estimated by USACE and case studies from the University of Glasgow. For the USACE examples, each cost is calculated for a sample project in the North Atlantic; however, costs can vary depending on the methods used for installation and materials.

Table 64. Shoreline solutions in cost per linear foot (2020$).

Solution	Initial Cost (first vertical ft)	Cost per Additional vertical ft	Cost to Build 8 ft High	Cost to Build 12 ft High
Seawall	$1,325	$477	$4664	$6,572
Seawall with green infrastructure (artificial seashore habitats)	$1,467	$477	$5,164	$7,276
Berm[46]	$2,250	$810	$7,920	$11,160

Sources: (Heberger et al., 2009; Naylor et al., 2017; US Army Corps of Engineers, 2019)

For each town in Barnstable County as well as countywide, we estimated the construction costs for three shoreline barrier types: berms, seawalls, and seawalls combined with green infrastructure). We only included construction costs and did not include maintenance costs or co-benefits that exist for these barrier types. We calculated the amount of shoreline that would need a barrier by including mileage of shorelines under the proposed design standard of 8 and 12 feet MHHW (this calculation accounted for shoreline elevation). For example, we took the amount of shoreline in the town of Barnstable and calculated the proportion that would need to be raised to 8 feet MHHW to match our barrier built to MHHW. Then, we calculated the proportion that was already at 2 feet MHHW of elevation and would need to be raised 6 feet to match the height of our barrier. We used the Cape Cod Commission's digital elevation model to calculate shoreline elevation along the shoreline "vulnerability ribbon" applied in the Cape Cod Coastal Planner.

We used cost estimates for sample projects from USACE (2019), Naylor et al. (2017), and Heberger et al. (2007) that were each designed to a certain height. To determine the initial cost to build a linear foot and the cost for each additional foot of height, we used data from a Bourne Consulting Engineering (2013) study. Using cost data on seawalls of varying heights, we used a linear regression to calculate the base cost and multiplier for each additional foot. We then calculated the cost of the barriers based on the height and length of the barriers necessary for both individual towns and the entire county.

[46] U.S. Army Corps of Engineers defines a berm as an embankment constructed of compacted soil. It is wide at the base that tapers to toward the top, with grass or other non-woody vegetation planted to stabilize the structure (U.S. Army Corps of Engineers, 2019).

To calculate the benefit-cost ratio for the three shoreline solutions (berm, seawall, and seawall with green infrastructure) for each town, we used the following equation:

$$Benefit - Cost\ Ratio = \frac{Damages_{annual\ model} - Damages_{strategy}}{Cost_{strategy}}$$

$Damages_{annual\ model}$ are the damages accrued in the cost of doing nothing analysis. $Damages_{strategy}$ are the damages accrued after implementing the new strategy (i.e., the numerator represents the avoided loss or benefit). $Cost_{strategy}$ is the total cost of the strategy. We assessed the benefit-cost ratio at individual time periods beginning in 2021. For all analyses, we assumed the strategies were constructed in 2021 and were immediately viable.

RESULTS

Benefits: The benefit of a shoreline solution is the avoided damage over time from flooding. This analysis assumes we would protect each town to a design standard of 8 and 12 feet MHHW. Table 65 shows the countywide avoided damage (benefit) for each time period and barrier height and each of the benefit categories.

Table 65. Countywide benefits of shoreline solutions (in millions of 2020$).

Time Period and Barrier Height	Building Damage Avoided	Value of Land Loss Avoided	Lost Wages Avoided	Cranberry Damage Avoided	Tax Loss Avoided	Total Damage Avoided
2021–2030 avoided loss (protection to 8 ft MHHW)	$653.49	$5,019.50	$5.70	$1.69	$199.48	$5,879.85
2031–2050 avoided loss (protection to 8 ft MHHW	$1,635.94	$4,648.92	$28.07	$11.15	$1,136.03	$7,460.11
2051–2100 avoided loss (protection to 8 ft MHHW)	$2,300.79	$9,889.08	$535.77	$66.39	$7,255.48	$20,047.50
2021–2100 avoided loss (protection to 8 ft MHHW)	$4,590.22	$14,538.00	$569.53	$79.19	$8,590.99	$28,367.93
2021–2030 avoided loss (protection to 12 ft MHHW)	$685.96	$5,019.50	$5.70	$1.69	$199.48	$5,912.32
2031–2050 avoided loss (protection to 12 ft MHHW)	$1,775.70	$4,648.92	$28.07	$11.15	$1,136.03	$7,599.87
2051–2100 avoided loss (protection to 12 ft MHHW)	$11,816.61	$9,889.08	$535.77	$66.39	$7,255.48	$29,563.32

Time Period and Barrier Height	Building Damage Avoided	Value of Land Loss Avoided	Lost Wages Avoided	Cranberry Damage Avoided	Tax Loss Avoided	Total Damage Avoided
2021–2100 avoided loss (protection to 12 ft MHHW)	$14,278.27	$14,538.00	$569.53	$79.19	$8,590.99	$38,055.98

Additionally, we estimated building damages over time with no barrier, an 8-foot barrier, and a 12-foot barrier (as part of the cost of doing nothing analysis). Figure 37 shows cumulative damages over time for each strategy. All three strategies saw increasing damages year over year, but the strategies with barriers saw damages delayed. With a protective barrier to 8 feet MHHW, damages by 2060 are $330 million; a protective barrier to 12 feet MHHW accrued no damages by 2060. With no barrier, damages are over $3.7 billion by 2060. Between 2080 and 2100, damages under the scenario of a protective barrier to 8 feet MHHW grew significantly because damages to regular storm surge flooding accrue (even though the barrier provides SLR protection). These damage values, drawn from our cost of doing nothing analysis, are conservative, as our cost of doing nothing analysis focused on damages from 1 to 6 feet MHHW of SLR and storm surge. This shoreline adaptation analysis evaluates higher water levels, meaning that damages could be greater.

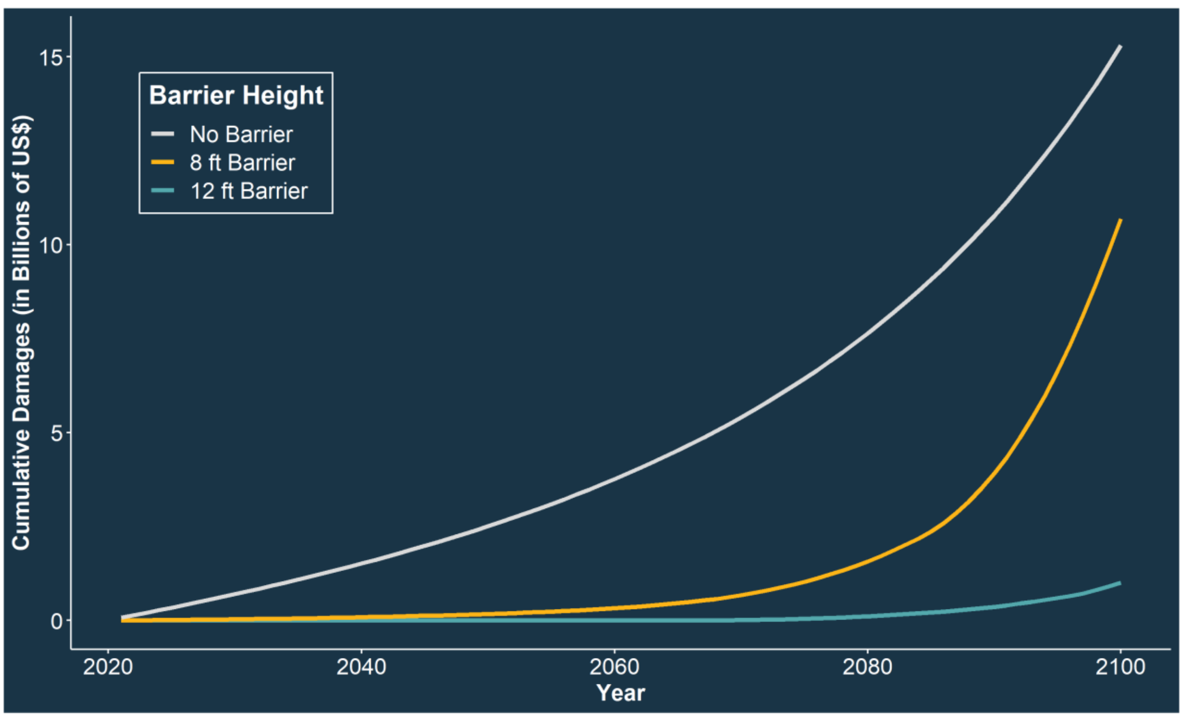

Figure 37. Median damages accrued from different barrier strategies over time.

Costs: Table 66 presents the costs of protecting the entire shoreline up to 8 feet and 12 feet MHHW for the seawall, seawall with green infrastructure, and the berm. Construction costs would be substantial for each solution, though berms are the most expensive at over $20 billion for an 8-foot barrier and over $32 billion for a 12-foot barrier, and this cost would likely need to be covered by a combination of local taxpayers and the federal government, depending on availability for federal funding resilience measures. The least expensive option is a seawall, which would cost over $12 billion for a barrier providing protection up to 8 feet MHHW and nearly $19 billion for a barrier providing protection up to 12 feet MHHW. As noted above, we did not include the maintenance costs over time or the co-benefits of these barrier types when calculating the costs.

Table 66. Construction costs of shoreline solutions (in millions of 2020$).

Town	Protection to 8 ft MHHW: Berm	Protection to 8 ft MHHW: Seawall	Protection to 8 ft MHHW: Seawall with GI	Protection to 12 ft MHHW: Berm	Protection to 12 ft MHHW: Seawall	Protection to 12 ft MHHW: Seawall with GI
Barnstable	$2,962.36	$1,744.50	$1,931.46	$4,533.92	$2,669.97	$2,956.11
Bourne	$1,809.10	$1,065.36	$1,179.54	$2,734.34	$1,610.22	$1,782.79
Brewster	$351.85	$207.20	$229.41	$571.06	$336.29	$372.33
Chatham	$2,473.90	$1,456.85	$1,612.98	$3,802.15	$2,239.04	$2,479.00
Dennis	$1,416.98	$834.45	$923.87	$2,163.00	$1,273.77	$1,410.27
Eastham	$721.40	$424.83	$470.35	$1,257.16	$740.33	$819.67
Falmouth	$3,242.47	$1,909.45	$2,114.09	$4,861.42	$2,862.83	$3,169.64
Harwich	$570.74	$336.10	$372.12	$865.87	$509.90	$564.55
Mashpee	$1,089.78	$641.76	$710.54	$1,641.39	$966.60	$1,070.18
Orleans	$1,302.77	$767.19	$849.41	$2,178.21	$1,282.72	$1,420.19
Provincetown	$538.60	$317.17	$351.16	$943.35	$555.53	$615.06
Sandwich	$885.35	$521.37	$577.25	$1,420.24	$836.36	$925.99
Truro	$629.00	$370.41	$410.11	$1,069.78	$629.98	$697.50
Wellfleet	$1,249.43	$735.77	$814.63	$2,130.81	$1,254.81	$1,389.29
Yarmouth	$1,319.47	$777.02	$860.30	$2,036.65	$1,199.36	$1,327.90
County-wide Total	$20,563.21	$12,109.45	$13,407.22	$32,209.34	$18,967.72	$21,000.49

GI = green infrastructure

Benefit-cost ratio: Table 67 shows the results from our shoreline strategies analysis. From 2021 to 2100, all three barrier types had a benefit-cost ratio greater than 1, meaning the benefits outweigh the costs. The berm, seawall, and seawall with green infrastructure had benefit-cost ratios of 1.2, 2, and 1.8 for protection to 12 feet MHHW, respectively. The ratios were slightly better for protection to 8 feet MHHW. Benefit-cost ratios were better over time as the barriers prevented damage, with the largest benefits occurring in the last time period from 2051 to 2100 as SLR compounded the damage from storms (e.g., a 100-year storm in 2100 floods to a higher water level than in 2030 because of SLR).

Table 67. Benefit-cost ratios for each barrier type across time periods.

Time Period	Berm Benefit-Cost Ratio	Seawall Benefit-Cost Ratio	Seawall with GI Benefit-Cost Ratio
2021–2030 avoided loss (protection to 8 feet MHHW)	0.286	0.486	0.439
2031–2050 avoided loss (protection to 8 feet MHHW)	0.363	0.616	0.556
2051–2100 avoided loss (protection to 8 feet MHHW)	0.731	1.241	1.121
2021–2100 avoided loss (protection to 8 feet MHHW)	1.380	2.343	2.116
2021–2030 avoided loss (protection to 12 feet MHHW)	0.184	0.312	0.282
2031–2050 avoided loss (protection to 12 feet MHHW)	0.236	0.401	0.362
2051–2100 avoided loss (protection to 12 feet MHHW)	0.762	1.294	1.169
2021–2100 avoided loss (protection to 12 feet MHHW)	1.182	2.006	1.812

Figure 38 shows the benefit-cost ratios for the three shoreline solution options by town. Overall, benefits are higher for the seawall and seawall with green infrastructure compared to the berm. The different color stacks represent different time periods. The gray bars represent the benefit-cost ratio achieved from 2021 to 2030, the teal bars represent the additional benefit-cost ratio from 2031 to 2050, and the yellow bars represent the benefit-cost ratio from 2051 to 2100. The combination of gray and teal bars represents the benefit-cost ratio from 2021 to 2050, while the entire stack represents the total benefit-cost ratio from 2021 to 2100 for each town. The red vertical line at a benefit-cost ratio of one shows the point at which the cost of the barrier equals the avoided damages.

For example, for an 8-foot-high seawall in Provincetown, the ratio between 2021 and 2030 was slightly less than 0.5, meaning that the avoided damages over that timeframe would be just under half the cost for the barrier. Between 2021 and 2050, the total ratio would be between 1 and 1.5, meaning that the damage that would have occurred in the absence of a barrier (avoided damages) would be greater than the costs of constructing of the barrier. By 2100, the barrier would help avoid damages totaling nearly four times the cost of constructing the barrier.

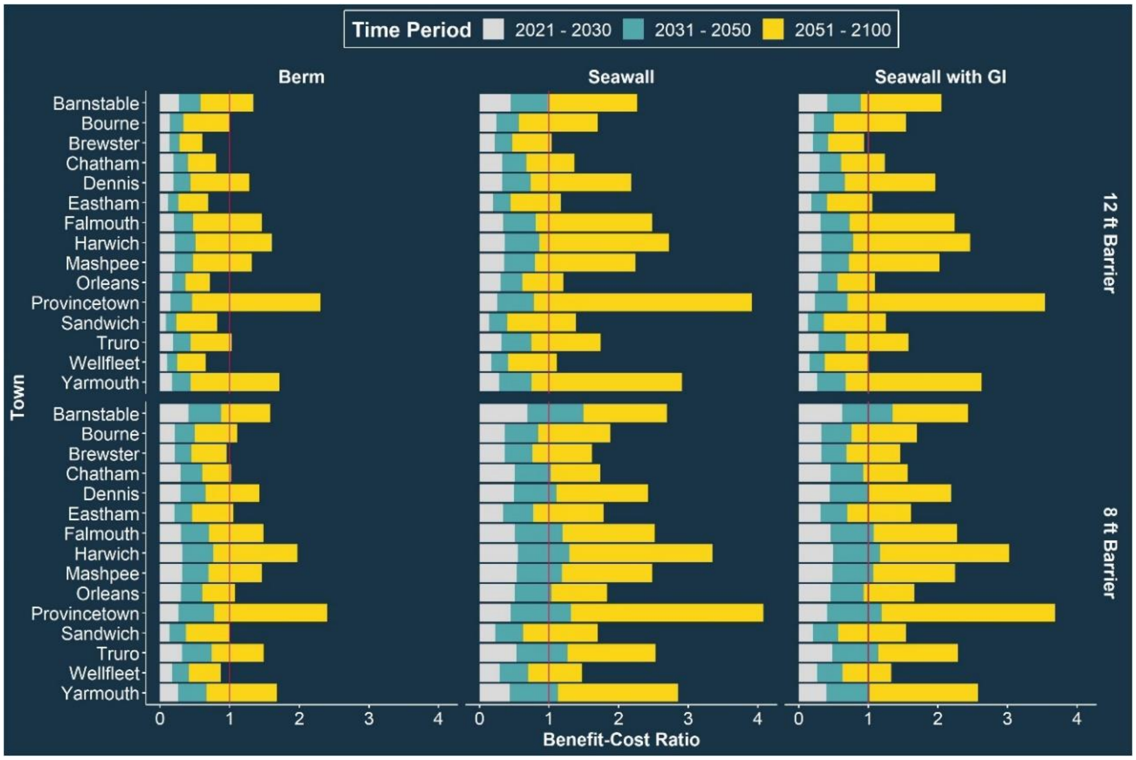

Figure 38. Benefit-cost ratios for shoreline solutions by town and barrier height.

LIMITATIONS AND FUTURE ANALYSIS

We considered initial building costs for each shoreline protection option, but operations and maintenance costs and co-benefits could alter the benefit-cost ratio. Co-benefits can offset the additional cost of green infrastructure. We assumed that any shoreline under a specific elevation would need protection, but it is likely that some areas with little to no infrastructure on the shoreline would not need this level of protection. In some cases, the entire shoreline may not need a barrier, depending on the topography and flood pathway. A flood pathway analysis of town shorelines is needed to determine the feasibility of and potential need for each type of barrier. Additionally, there could be regulatory challenges and limitations with implementing certain types of infrastructure such as seawalls. Future analyses could assess the costs and benefits of using alternative types of protection, green versus gray solutions (when all co-benefits are accounted for), multiple lines of defense in heavily developed areas, and adaptation over time (e.g., designing a seawall so additional height can be added in the future). Further analyses should also evaluate the costs or damages to ecosystems that could occur as a result of building hard infrastructure, like seawalls (e.g., loss of adjacent salt marsh, erosion of nearby beaches).

Adapting Shorelines to Rising Seas: Key Takeaways

- The approximate benefit-cost ratio for shoreline solutions evaluated here (sea wall, berm, and seawall with green infrastructure) around the entire Cape is about 2:1 for protecting against up to 12 feet of water level increase and about 2.2:1 for protecting against up to eight feet for 2021 to 2100.
- This analysis does not comprehensively quantify all costs and benefits and tradeoffs for each shoreline solution. For example, living shorelines can provide additional public green space and water quality improvements—benefits that are not associated with sea walls. Detailed analysis is needed in the future to study these tradeoffs for priority shoreline adaptation areas.

Retrofit buildings located within climate hazard areas

We analyzed several strategies to retrofit buildings to protect against storm surge and SLR. We compared the strategies against the cost of doing nothing to measure the economic benefit.

METHODS

We conducted a literature search for different methods of addressing potential damages from SLR and storm surge.

Building-specific solutions: Building-specific solutions include raising buildings above a floodplain and moving buildings out of a floodplain. Our literature review indicates that moving buildings out of a floodplain is not currently practical on a large scale and is often used for historical buildings where the historical benefit of preserving the structure outweighs the expense of relocating it (see "Relocate Vulnerable Buildings and Structures"). Moving residential structures would need to be cost-effective on a large scale in order to effectively protect enough residences, and not enough research exists to form an accurate cost model (Herrmann, 2017; Spidalieri et al., 2020). As such, we focused our assessment on the costs and benefits of raising buildings above the floodplain. This solution is effective at protecting buildings from storm tides, although it will not solve the issue of SLR vulnerability because it would isolate the building.

Table 68 shows the costs of raising a building (US Army Corps of Engineers, 2015). The costs when raising a house cover per-area and per-unit costs. For example, a 1,400-square-foot house would have an estimated elevation cost of $132,837 (1,400 square feet * $94.88/square foot), while a 2,000-square-foot house would have an elevation cost of $189,765. The temporary housing cost would be around $10,835 and does not depend on the size of the house (as the project length is often about two to four months). The contingency cost would typically be around 25 percent of the combined subtotal for temporary housing and elevation costs ($35,918 for the 1,400-square-foot house, $143,672 * 25 percent), while the construction and management costs would then be another 10 percent of the new subtotal. Finally, the engineering and design costs would be around $10,835 per house no matter the area. The right two columns in Table 68 show the subtotal and costs of each stage of raising a building to an 8-foot standard. We used our cost of doing nothing analysis to quantify the benefits (i.e., avoided damages) offered by protection up to 8 feet MHHW. First construction costs are equal to the total construction costs, not including any operations or maintenance and without interest or depreciation and would be $208,385 for a 1,400 square-foot house.

Table 68. Costs of raising a building 8 feet (in 2020 US$).

Category	Costs/ Percentage	Units	1,400 sq ft Building	Subtotals
Elevation	$94.88	Per square foot	$132,837	$132,837
Temporary housing	$10,835	Per unit	$10,835	$143,672
Contingency	25%	Per unit	$35,918	$179,590
Construction and management	10%	Per unit	$17,959	$197,550
Engineering and design	$10,835	Per unit	$10,835	$208,385
First construction cost			$208,385	

Source: (US Army Corps of Engineers, 2015)

RESULTS

Figure 39 shows the results from our building-specific analysis. Benefit-cost ratios above 1 are considered to be economically beneficial, while ratios less than 1 are not cost-effective (and another strategy like a buyout and retreat, which might cost approximately the value of the building, would be more cost-effective). Between 2021 and 2030, raising buildings is not an effective strategy, but it becomes more beneficial over time as the avoided damages increase. Ultimately, our analysis shows that all towns will benefit from raising buildings by 2100, though the strategy is particularly successful in Provincetown and Truro. These towns had a large amount of damage in our cost of doing nothing analysis (Table 6) that raising buildings can prevent.

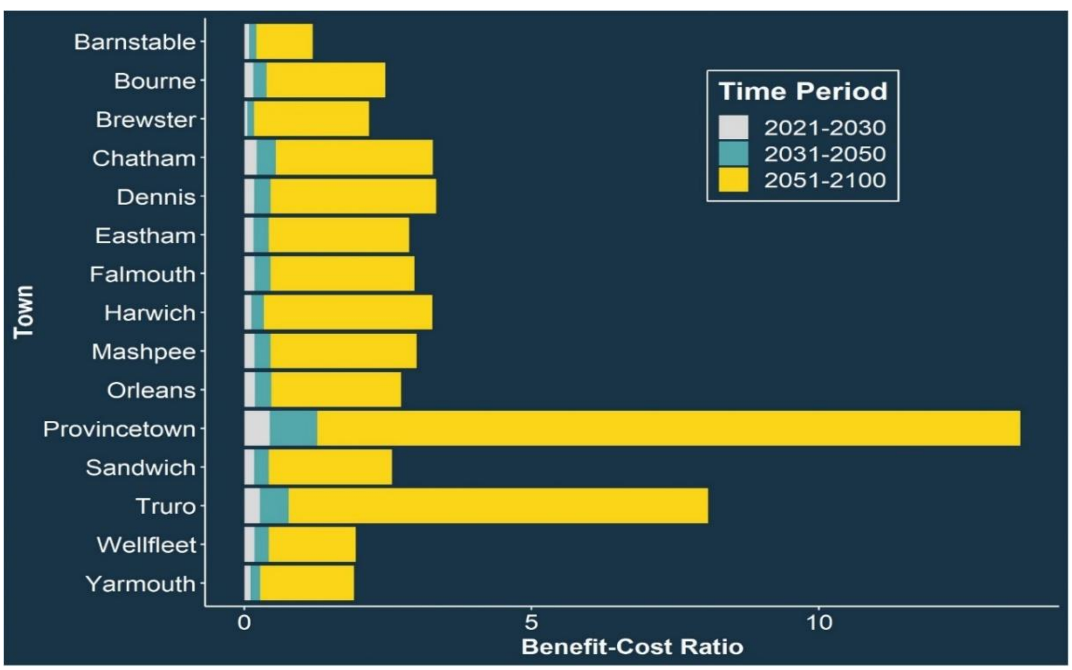

Figure 39. Benefit-cost ratios for raising buildings by town.

LIMITATIONS AND FUTURE ANALYSIS

We analyzed the cost of raising all buildings within Barnstable County to 8 feet MHHW. This is an appropriate strategy for houses but not for all buildings. Furthermore, some buildings, such as lighthouses and piers, are likely already protected against SLR, as discussed in the cost of doing nothing analysis. The COAST model does not account for water velocity, so storm tides could still cause damage even when buildings are raised.

Retrofit Buildings Located Within Climate Hazard Areas: Key Takeaways

- Raising buildings has a benefit of about $3 to $5 for every dollar spent.
- Building retrofits are particularly successful in Provincetown and Truro.
- Areas with less density per mile of shoreline may benefit from building-level strategies (e.g., flood-proofing and raising buildings) in the near term (to prevent damage from single events).

Relocate vulnerable buildings and structures

METHODS

Our literature review indicates that moving buildings out of a floodplain is not currently practical on a large scale, preventing us from assessing the costs and benefits of relocating buildings across the Cape Cod region. However, relocation may be a viable path forward for historic buildings or individual properties owners, specifically in situations where costs are not a major object or where costs may still be a major object for historic properties but are deemed worth it. Therefore, we have summarized cost findings and key considerations from case studies that may be useful as this issue is inevitably raised in planning discussions.

FINDINGS

Building relocation is a complex process with costs that can vary greatly depending on the structure size, shape, type, and distance to the new location. Estimates for labor range between 12 to 16 dollars per square foot, but that does not include many of the costs that can occur (Knorr, 2019). Railroads, underpasses and overpasses, utility wires, and even large trees can significantly increase the cost of moving a building.

Relocation also requires purchasing new land and building a new foundation, and it could possibly include renovations to bring the building up to code. In Detroit, Michigan, it costs $750,000 to move a 3,000-square-foot historic house around the block (Knorr, 2019). Building relocation requires significant planning and becomes more difficult and time-consuming in more densely developed areas.

The amount of effort and the large variance in cost is likely why most adaptation plans quickly rule out relocation as a communitywide strategy. It is much more common for state and local governments to use buyouts to move residents out of flood zones. These governments then use the land they acquire to improve community resilience. A project in Queens, New York, is piloting a land swap project where residents in a hazard mitigation zone can elect to receive a newly built, elevated home in a safer area or accept a buyout for their property from the city

(Spidalieri et al., 2020). In exchange, they transfer their title to the city, which demolishes the lots and uses them to build flood resilience. Many buyout programs also receive financial support from the state and federal government. Land acquisition as a form of adaptation requires support from all homeowners to be effective. Some communities may not find relocation to be an appealing option and may want to retrofit their houses and armor the shoreline instead.

Discussion of When to Implement Certain Types of Adaptation Strategies

This presents discussion of when to implement the adaptation strategies presented above. For more densely developed areas, it may be more economical for towns to invest in shoreline solutions rather than raising individual buildings. However, our analysis points to the need to consider the range of costs and benefits that each shoreline strategy provides, as avoided property damage and construction costs alone do not provide a complete picture. Living shorelines, constructed wetlands, and beach restoration projects provide multiple co-benefits, including additional public green space, erosion prevention, and water quality improvements. Berms require more space to build but can be integrated into trail systems to provide public access to recreation. Seawalls and levees have less adaptive capacity than green infrastructure, but floodwalls and levees may be better at reducing flooding given their height compared to wetlands and living shorelines. USACE recommends combining measures to improve redundancies and increase resilience.

Table 69. Benefits of shoreline strategies.

Solution	Co-Benefits	Flooding	Erosion	Wave Attenuation	Adaptive Capacity	Recommended Use
Raise properties	Low	High	Low	Low	Low	Less densely populated areas
Buyouts	High	High	High	High	High	In areas with severe and frequent flooding
Move structures	Low	High	Low	Low	Low	Preserving historical buildings
Seawall	Low	High	None	Low	Low	Areas with densely developed shoreline
Seawall with GI	Medium	High	None	Medium	Low	Areas with densely developed shoreline
Berm	Medium	High	Medium	Low	Medium	In densely developed areas with some space between the shoreline and development

Source: (US Army Corps of Engineers, 2015)

Shoreline solutions may only be cost-effective in densely populated areas and for high-value properties and assets. An analysis of topography and flood pathways is needed to effectively plan shoreline solutions. Analyzing the difference between densely and sparsely populated areas may change the outcomes of our benefit-cost analysis. Combining strategies could provide better flood protection in some areas while creating green space with segments of living shorelines in other areas; therefore, the benefits and costs of combined measures should be evaluated.

While we have focused on solutions that protect to a certain design standard (i.e., a certain level of flooding), wetland restoration and natural solutions—which do not always protect to a design standard—have been shown to have a strong return on investment. Most importantly, they come with strong co-benefits such as recreation, fisheries, and carbon sequestration that often make these the best solution. Moreover, engineered solutions like seawalls often have negative environmental impacts, which we did not account for in our study. There could be substantial regrets (both aesthetically and financially) to invest so heavily in gray infrastructure because of the uncertainty of SLR over the next 70 years.

Address vulnerabilities in the road network

Flooded roads may isolate properties from the road network and/or decrease the property value of nearby properties even if they are not explicitly flooded (see SLR impacts to tax revenue). Clearly, this creates major evacuation concerns. Land buyouts of properties that become isolated from the road network may be necessary. This analysis also supports adapting critical transportation infrastructure for climate change impacts.

METHODS

Building on our cost of doing nothing analysis, we calculated the potential loss in tax revenue from isolated homes and properties within ¼ mile of flooded roads from 1 to 6 feet MHHW of SLR using the Cape Cod Commission's data layers of roads exposed to SLR. We then interpolated and extrapolated this tax loss from 2021 to 2100. To determine the potential costs associated with land buyouts of isolated homes, we calculated the total land value of isolated homes for 1 to 6 feet MHHW of SLR. These values represent the benefit from fixing roads, allowing residents to remain in place rather than relocate through a buyout program. Homes were only counted as isolated if less than 50 percent of the property is expected to flood (if greater than 50 percent, the property is considered a loss). We already calculated the costs of adaptation from fixing roads in Table 23 of our cost of doing nothing analysis.

RESULTS

If no roads on Cape Cod that are projected to flood from SLR are fixed or raised, then the region could lose on average $0.36 and $0.51 million in tax revenue each year from isolated homes and properties located near flooded roads, respectively, until 2030 (see tables in Appendix B). This number could increase with a program that buys out properties that become isolated from flooding (Figure 40). Most of the expected tax revenue loss will be from devaluation of properties within ¼ mile of flooded roads (Figure 40).

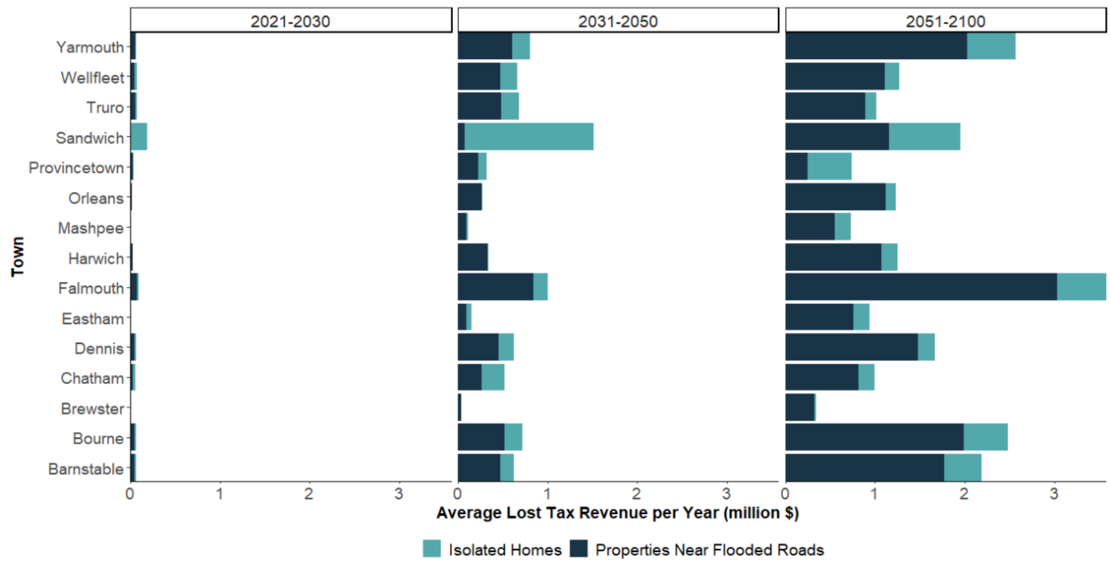

Figure 40. Average lost tax revenue per year from isolated homes and properties near flooded roads.

Table 70. Land values of homes isolated with each foot of SLR in millions of 2020$ (cumulative).

Town	1 ft MHHW (2040)	2 ft MHHW (2054)	3 ft MHHW (2066)	4ft MHHW (2076)	5ft MHHW (2085)	6ft MHHW (2093)
Barnstable	10.2	25.06	55.38	49.09	24.6	1.98
Bourne	11.54	30.38	60.88	40.1	26.14	0.53
Brewster	NA	0.64	0.97	1.61	1.28	NA
Chatham	42.93	33.98	37.01	36.58	14.22	2.38
Dennis	16.57	24.45	18.81	19.88	20.65	2.57
Eastham	0.48	18.45	16.84	16.77	10.72	0.32
Falmouth	12.93	23.88	74.75	52.56	41.16	2.72
Harwich	1.13	1.46	15.22	25.05	11.57	NA
Mashpee	NA	2.77	16.92	18.9	22.56	0.56
Orleans	NA	0.75	17.92	19.77	8.56	0.71
Provincetown	4.36	5.66	24.81	65.34	26.36	2.34
Sandwich	74.25	64.68	53.59	42.34	17.51	1.23
Truro	21.07	16.72	15.5	10.41	4.83	3.16
Wellfleet	15.23	13.56	14.69	12.81	8.88	5.54
Yarmouth	7.77	37.2	42.41	55	31.44	2.18
Total	**218.46**	**299.64**	**465.7**	**466.21**	**270.48**	**26.22**

To better understand the benefits and costs of fixing flooded roads, we outlined some hypothetical scenarios.

1 FOOT MHHW OF SLR IN 2040

With 1 foot MHHW of SLR projected in 204, 13.7 miles of road will flood on Cape Cod. This equates to $3.2 and $4.6 million of lost tax revenue from isolated homes and properties located near flooded roads, respectively. Buyout of land from isolated homes would equate to $218.5 million in total land value. So, the total cost of not fixing any of the flooded roads would be $226.3 million (in $2020).

The cost of rebuilding every mile of flooded road at $7 million per mile would be $95.9 million (see Table 23). However, the cost of fixing every mile of road would likely be much greater, as just rebuilding a flooded road may not be a permanent fix, and some roads may need to be elevated. Elevating roads can often cost many times more than a repair; for example, a recent project in Florida cost $60 million per elevated mile (Harris, n.d.). If we assume that all flooded roads in Barnstable County are elevated, this could amount to over $800 million. However, these costs may be overestimates, as there are likely optimum strategies that combine elevating, rebuilding, protecting, and abandoning flooded roads. The exact planning combination would require substantially more study.

LIMITATIONS AND FUTURE ANALYSIS

This analysis only considers hypothetical scenarios of the costs associated with fixing or elevating flooded roads. A more in-depth cost analysis should identify specific roads that lead to areas of importance for Barnstable County. Additionally, this analysis does not include costs associated with seawalls or other coastal protection measures that may preclude some roads from flooding.

Addressing Vulnerabilities in the Road Network: Key Takeaways

- Flooded roads will lead to the loss of approximately $290 million in tax revenue between 2021 and 2100 and will isolate just over $1 billion in property.
- To rebuild the 212 miles of roads expected to be flooded by 2100 would cost about $1.4 billion. Raising these roads might be eight to 10 times that.
- The cost of raising all roads will far exceed the benefit of the avoided financial losses. Raising roads will be most cost-effective for segments that serve highly traveled or critical routes.
- Shoreline solutions that can both protect buildings and keep roads dry will provide a dual benefit and make economic sense in denser areas.

Conclusion and Next Steps

This technical reported has presented results and findings that demonstrate the large and accelerating costs Barnstable County faces if it does not adapt to climate change. Additionally, there are paths to meet 2030 and 2050 emissions reductions goals that align with the goals for the Commonwealth of Massachusetts; however, achieving these goals will require aggressive electrification and renewable energy implementation. Finally, many strategies with strong returns on investment can help offset the impacts of climate change or mitigate emissions. The summary report provides a consolidated version of this report focused on key findings.

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Appendices

Appendix A. NAICS Codes in Blue Economy

Table A-1. NAICS codes used to determine blue economy businesses.

NAICS	NAICS Description	Blue Level
112511	Finfish Farming And Fish Hatcheries	3
112512	Shellfish Farming	3
112519	Other Aquaculture	3
114111	Finfish Fishing	3
114112	Shellfish Fishing	3
114119	Other Marine Fishing	3
211111	Crude Petroleum and Natural Gas Extraction	2
212321	Construction Sand and Gravel Mining	2
213111	Drilling Oil and Gas Wells	2
213112	Support Activities for Oil and Gas Operations	2
213113	Support Activities for Coal Mining	1
213114	Support Activities for Metal Mining	1
213115	Support Activities for Nonmetallic Minerals (except Fuels) Mining	1
221111	Hydroelectric Power Generation	3
221115	Wind Electric Power Generation	1
221118	Other Electric Power Generation	1
221122	Electric Power Distribution	1
236210	Industrial Building Construction	1
236220	Commercial and Institutional Building Construction	1
237110	Water And Sewer Line And Related Structures Construction	2
237120	Oil and Gas Pipeline and Related Structures Construction	2
237130	Power and Communication Line and Related Structures Construction	1
237990	Other Heavy and Civil Engineering Construction	2
238210	Electrical Contractors and Other Wiring Installation Contractors	1
238220	Plumbing, Heating, and Air-Conditioning Contractors	1
238320	Painting and Wall Covering Contractors	1
238350	Finish Carpentry Contractors	1
238990	All Other Specialty Trade Contractors	1
311712	Fresh and Frozen Seafood Processing	3
314910	Textile and Canvas	3
321114	Wood Preservation	1
324110	Petroleum Refineries	2

NAICS	NAICS Description	Blue Level
325510	Paint and Coating Manufacturing	1
331210	Iron and Steel Pipe and Tube Manufacturing from Purchased Steel	2
331221	Rolled Steel Shape Manufacturing	2
331314	Secondary Smelting and Alloying of Aluminum	2
331315	Aluminum Sheet, Plate, and Foil Manufacturing	2
331512	Steel Investment Foundries	2
332312	Fabricated Structural Metal Manufacturing	2
332313	Plate Work Manufacturing	2
332322	Sheet Metal Work Manufacturing	2
332410	Power Boiler and Heat Exchanger Manufacturing	2
332420	Metal Tank (Heavy Gauge) Manufacturing	2
332510	Hardware Manufacturing	2
332710	Machine Shops	2
332999	All Other Miscellaneous Fabricated Metal Product Manufacturing	2
333132	Oil and Gas Field Machinery and Equipment Manufacturing	2
333612	Speed Changer, Industrial High-Speed Drive, and Gear Manufacturing	2
333618	Other Engine Equipment Manufacturing	2
333923	Overhead Traveling Crane, Hoist, and Monorail System Manufacturing	2
333992	Welding and Soldering Equipment Manufacturing	2
334220	Radio and Television Broadcasting and Wireless Communications Equipment Manufacturing	2
334290	Other Communications Equipment Manufacturing	2
334511	Search, Detection, Navigation, Guidance, Aeronautical, and Nautical System and Instrument Manufacturing	3
334519	Other Measuring And Controlling Device Manufacturing	2
335314	Relay and Industrial Control Manufacturing	2
335911	Storage Battery Manufacturing	2
336214	Travel Trailer and Camper Manufacturing	1
336611	Ship Building and Repairing	3
336612	Boat Building	3
336999	All Other Transportation Equipment Manufacturing (ATVs, gocarts, golf carts, snowmobiles)	1
337127	Institutional Furniture Manufacturing	1
339920	Sporting and Athletic Goods Manufacturing	2
423510	Metal Service Centers and Other Metal Merchant Wholesalers	2
423610	Electrical Apparatus and Equipment, Wiring Supplies, and Related Equipment Merchant Wholesalers	2

NAICS	NAICS Description	Blue Level
423620	Household Appliances, Electric Housewares, and Consumer Electronics Merchant Wholesalers	1
423690	Other Electronic Parts and Equipment Merchant Wholesalers	2
423710	Hardware Merchant Wholesalers	2
423720	Plumbing and Heating Equipment and Supplies (Hydronics) Merchant Wholesalers	1
423740	Refrigeration Equipment and Supplies Merchant Wholesalers	1
423810	Construction and Mining (except Oil Well) Machinery and Equipment Merchant Wholesalers	2
423830	Industrial Machinery and Equipment Merchant Wholesalers	2
423840	Industrial Supplies Merchant Wholesalers	2
423860	Transportation Equipment and Supplies (except Motor Vehicle) Merchant Wholesalers	2
423910	Sporting and Recreational Goods and Supplies Merchant Wholesalers	2
423930	Recyclable Material Merchant Wholesalers	2
424460	Fish and Seafood Merchant Wholesalers	3
424710	Petroleum Bulk Stations and Terminals	2
424720	Petroleum and Petroleum Products Merchant Wholesalers (except Bulk Stations and Terminals)	2
424990	Other Miscellaneous Nondurable Goods Merchant Wholesalers	2
441210	Recreational Vehicle Dealers	1
441221	Motorcycle, ATV, and Personal Watercraft Dealers	3
441222	Boat Dealers	3
441228	Motorcycle, ATV, and All Other Motor Vehicle Dealers	1
444130	Hardware Stores	1
444190	Other Building Material Dealers	2
444210	Outdoor Power Equipment Stores	1
445220	Fish and Seafood Markets	3
447190	Other Gasoline Stations	1
451110	Sporting Goods Stores	2
481111	Scheduled Passenger Air Transportation	1
481211	Nonscheduled Chartered Passenger Air Transportation	1
483113	Coastal and Great Lakes Freight Transportation	3
483114	Coastal and Great Lakes Passenger Transportation	3
483211	Inland Water Freight Transportation	3
484220	Specialized Freight (except Used Goods) Trucking, Local	1
484230	Specialized Freight (except Used Goods) Trucking, Long-Distance	1
486110	Pipeline Transportation of Crude Oil	2

NAICS	NAICS Description	Blue Level
486210	Pipeline Transportation of Natural Gas	2
486910	Pipeline Transportation of Refined Petroleum Products	2
486990	All Other Pipeline Transportation	2
487210	Scenic and Sightseeing Transportation, Water	3
487990	Scenic and Sightseeing Transportation, Other	2
488119	Other Airport Operations	1
488190	Other Support Activities for Air Transportation	1
488310	Port and Harbor Operations	3
488320	Marine Cargo Handling	3
488330	Navigational Services to Shipping	3
488390	Other Support Activities for Water Transportation	3
488510	Freight Transportation Arrangement	1
488999	All Other Support Activities for Transportation	2
493110	General Warehousing and Storage	1
493120	Refrigerated Warehousing and Storage	1
493190	Other Warehousing and Storage	1
517210	Wireless Telecommunications Carriers (except Satellite)	1
522110	Commercial Banking	1
522120	Savings Institutions	1
522130	Credit Unions	1
522190	Other Depository Credit Intermediation	1
522220	Sales Financing	1
522291	Consumer Lending	1
523110	Investment Banking and Securities Dealing	1
524126	Direct Property and Casualty Insurance Carriers	1
524127	Direct Title Insurance Carriers	1
524130	Reinsurance Carriers	1
524210	Insurance Agencies and Brokerages	1
531120	Lessors of Nonresidential Buildings (except Miniwarehouses)	1
532120	Truck, Utility Trailer, and RV (Recreational Vehicle) Rental and Leasing	1
532292	Recreational Goods Rental	1
532411	Commercial Air, Rail, and Water Transportation Equipment Rental and Leasing	3
532412	Construction, Mining, and Forestry Machinery and Equipment Rental and Leasing	2
532490	Other Commercial and Industrial Machinery and Equipment Rental and Leasing	2
541110	Offices of Lawyers	1
541199	All Other Legal Services	1
541330	Engineering Services	2

NAICS	NAICS Description	Blue Level
541340	Drafting Services	1
541360	Geophysical Surveying and Mapping Services	3
541370	Surveying and Mapping (except Geophysical) Services	3
541420	Industrial Design Services	1
541614	Process, Physical Distribution, and Logistics Consulting Services	1
541620	Environmental Consulting Services	3
541711	Research and Development In Biotechnology	2
541712	Research and Development in the Physical, Engineering, and Life Sciences (except Biotechnology)	2
541990	All Other Professional, Scientific, and Technical Services	2
555555	Fish and Seafood Wholesaler	3
561311	Employment Placement Agencies	1
561599	All Other Travel Arrangement and Reservation Services	1
561990	All Other Support Services	1
562910	Remediation Services	1
611310	Colleges, Universities, and Professional Schools	1
611430	Professional and Management Development Training	2
611513	Apprenticeship Training	2
611519	Other Technical and Trade Schools	2
611620	Sports and Recreation Instruction	2
611699	All Other Miscellaneous Schools and Instruction	2
611710	Educational Support Services	1
711510	Independent Artists, Writers, and Performers	2
712110	Museums	2
712120	Historical Sites	2
712130	Zoos and Botanical Gardens	2
712190	Nature Parks and Other Similar Institutions	3
713930	Marinas	3
713990	All Other Amusement and Recreation Industries	2
721110	Hotels (except Casino Hotels) and Motels	2
721110	Hotels/Motels/BnBs	2
721110	Hotels/Motels/BnBs	2
721191	Bed-and-Breakfast Inns	2
721191	Hotels/Motels/BnBs	2
721191	Hotels/Motels/BnBs	2
721199	Hotels/Motels/BnBs	2
721199	Hotels/Motels/BnBs	2
721199	Hotels/Motels/BnBs	2
721199.1	Hotels/Motels/BnBs	2

NAICS	NAICS Description	Blue Level
721199.1	Hotels/Motels/BnBs	2
721211	RV (Recreational Vehicle) Parks and Campgrounds	1
722511	Full-Service Restaurants	2
722511.2	Full Service Rest	2
722513	Limited-Service Restaurants	1
722514	Cafeterias, Grill Buffets, and Buffets	1
722515	Snack and Nonalcoholic Beverage Bars	1
777777	Retail	3
811213	Communication Equipment Repair and Maintenance	2
811219	Other Electronic and Precision Equipment Repair and Maintenance	2
811490	Other Personal And Household Goods Repair And Maintenance	2
813312	Environment, Conservation And Wildlife Organizations	3
813910	Business Associations	1
924110	Administration of Air and Water Resource and Solid Waste Management Programs	3
924120	Administration Of Conservation Programs	3
926120	Regulation and Administration of Transportation Programs	1
928110	National Security (Navy, Coast Guard)	3

Appendix B. Potential Lost Tax Revenue by Town for Isolated Homes

Table B-1. Potential Lost Tax Revenue from isolated homes in each time period. Values shown in millions 2020 US$.

Town	2021 to 2030	2031 to 2050	2051 to 2100	Total
Barnstable	0.12	2.81	20.08	23.01
Bourne	0.16	3.84	23.98	27.98
Brewster	NA	NA	0.74	0.74
Chatham	0.3	4.84	8.73	13.87
Dennis	0.17	3.26	9.26	12.69
Eastham	0.01	1.11	8.63	9.75
Falmouth	0.15	3.1	26.79	30.04
Harwich	NA	0.2	8.82	9.02
Mashpee	0.02	0.44	8.57	9.03
Orleans	0.01	0.12	5.7	5.83
Provincetown	0.1	1.81	24	25.91
Sandwich	1.65	27.32	39.12	68.09
Truro	0.23	3.71	6.15	10.09
Wellfleet	0.21	3.5	8.18	11.89
Yarmouth	0.12	3.85	26.7	30.67
Totals	**3.25**	**59.91**	**225.45**	**288.61**
Av Each Year	**0.36**	**3.15**	**4.60**	**3.65**

Table B-2. Potential Lost Tax Revenue from properties within ¼ mile of flooded roads in each time period. Values shown in millions 2020 US$.

Town	2021 to 2030	2031 to 2050	2051 to 2100	Total
Barnstable	0.45	9.06	87.07	96.58
Bourne	0.45	9.87	97.5	107.82
Brewster	0.02	0.7	15.87	16.59
Chatham	0.24	5.13	40.23	45.6
Dennis	0.44	8.6	72.4	81.44
Eastham	0.06	1.75	37.43	39.24
Falmouth	0.67	15.96	148.74	165.37
Harwich	0.25	6.37	52.41	59.03
Mashpee	0.05	1.76	27.2	29.01
Orleans	0.2	5.14	54.88	60.22
Provincetown	0.25	4.41	12.38	17.04
Sandwich	0.08	1.52	56.52	58.12
Truro	0.48	9.17	43.69	53.34
Wellfleet	0.45	9.08	54.19	63.72
Yarmouth	0.49	11.45	99.19	111.13
Totals	**4.58**	**99.97**	**899.7**	**1,004.25**
Av Each Year	**0.51**	**5.26**	**18.36**	**12.71**

Appendix C. Metrics for GHG Mitigation Scenarios

Table C-1. Sustained Policy Scenario Metrics

Metric	2030	2050
Transportation: Number of light-duty EVs on the road	13,998	117,766
Transportation: EV share of light-duty vehicle sales	24%	64%
Transportation: Reduction in light-duty VMT per vehicle	0%	0%
Transportation: GHG emissions (MMT)	1.3	0.73
Buildings: Number of households with heat pump retrofits	18,688	60,341
Buildings: Number of households with whole-home heat pump systems	2,631	2,806
Buildings: Average Building Shell Improvement Relative to 2020	8%	19%
Buildings: GHG emissions (MMT)	0.67	0.37
Electric Power: GHG emissions (MMT)	0.41	0.22
All Sectors: GHG emissions (MMT)[47]	2.50	1.43
All Sectors: Emissions reductions from 2017	22%	55%
All Sectors: Emissions reductions from 1990	39%	65%

Table C-2. SER1 Scenario Metrics

Metric	2030	2050
Transportation: Number of light-duty EVs on the road	69,000	214,000
Transportation: EV share of light-duty vehicle sales	93%	100%
Transportation: Reduction in light-duty VMT per vehicle	0%	0%
Transportation: GHG emissions (MMT)	1.09	0.23
Buildings: Number of households with heat pump retrofits	18,568	45,295
Buildings: Number of households with whole-home heat pump systems	15,100	46,223
Buildings: Average building shell improvement relative to 2020	8%	19%
Buildings: GHG emissions (MMT)	0.58	0.06
Electric Power: GHG emissions (MMT)	0.25	0.20
All Sectors: GHG emissions (MMT)	2.05	0.61
All Sectors: Emissions reductions from 2017	36%	81%
All Sectors: Emissions reductions from 1990[48]	50%	85%

[47] This includes emissions from industrial, agricultural, and waste that are not shown in this table but make up the difference between the totaled and the amount in transportation, buildings (both commercial and residential), and the electric power sector.

[48] For all tables in this Appendix, this reduction from 1990 levels assumes Barnstable County accounted for the same fraction of state emissions in 1990 as it did in 2017.

Table C-3. CEN Scenario Metrics

Metric	2030	2050
Transportation: Number of light-duty EVs on the road	69,000	214,000
Transportation: EV share of light-duty vehicle sales	93%	100%
Transportation: Reduction in light-duty VMT per vehicle	2.5%	7.5%
Transportation: GHG emissions (MMT)	1.07	0.15
Buildings: Number of households with heat pump retrofits	18,568	45,295
Buildings: Number of households with whole-home heat pump systems	15,100	46,223
Buildings: Average building shell improvement relative to 2020	8%	19%
Buildings: GHG emissions (MMT)	0.58	0.05
Electric Power: GHG emissions (MMT)	0.25	0.04
All Sectors: GHG emissions (MMT)	2.04	0.37
All Sectors: Emissions reductions from 2017	36%	88%
All Sectors: Emissions reductions from 1990	51%	91%

Table C-4. SER2 Scenario Metrics

Metric	2030	2050
Transportation: Number of light-duty EVs on the road	39,000	200,000
Transportation: EV share of light-duty vehicle sales	63%	100%
Transportation: Reduction in light-duty VMT per vehicle	15%	25%
Transportation: GHG emissions (MMT)	1.1	0.28
Buildings: Number of households with heat pump retrofits	18,568	48,944
Buildings: Number of households with whole-home heat pump systems	8,501	40,052
Buildings: Average building shell improvement relative to 2020	12%	31%
Buildings: GHG emissions (MMT)	0.61	0.06
Electric Power: GHG emissions (MMT)	0.22	0.14
All Sectors: GHG emissions (MMT)	2.06	0.61
All Sectors: Emissions reductions from 2017	35%	81%
All Sectors: Emissions reductions from 1990	50%	85%

Table C-5. SER3 Scenario Metrics

Sector: Metric	2030	2050
Transportation: Number of light-duty EVs on the road	70,000	283,000
Transportation: EV share of light-duty vehicle sales	85%	100%
Transportation: Reduction in light-duty VMT per vehicle	9%	15%
Transportation: GHG emissions (MMT)	1.12	0.24
Buildings: Number of households with heat pump retrofits	18,568	48,944
Buildings: Number of households with whole-home heat pump systems	18,506	73,824
Buildings: Average building shell improvement relative to 2020	8%	19%
Buildings: GHG emissions (MMT)	0.64	0.06
Electric Power: GHG emissions (MMT)	0.14	0.15
All Sectors: GHG emissions (MMT)	2.04	0.61
All Sectors: Emissions reductions from 2017	36%	81%
All Sectors: Emissions reductions from 1990	50%	85%