MASSACHUSETTS 2050 DECARBONIZATION ROADMAP

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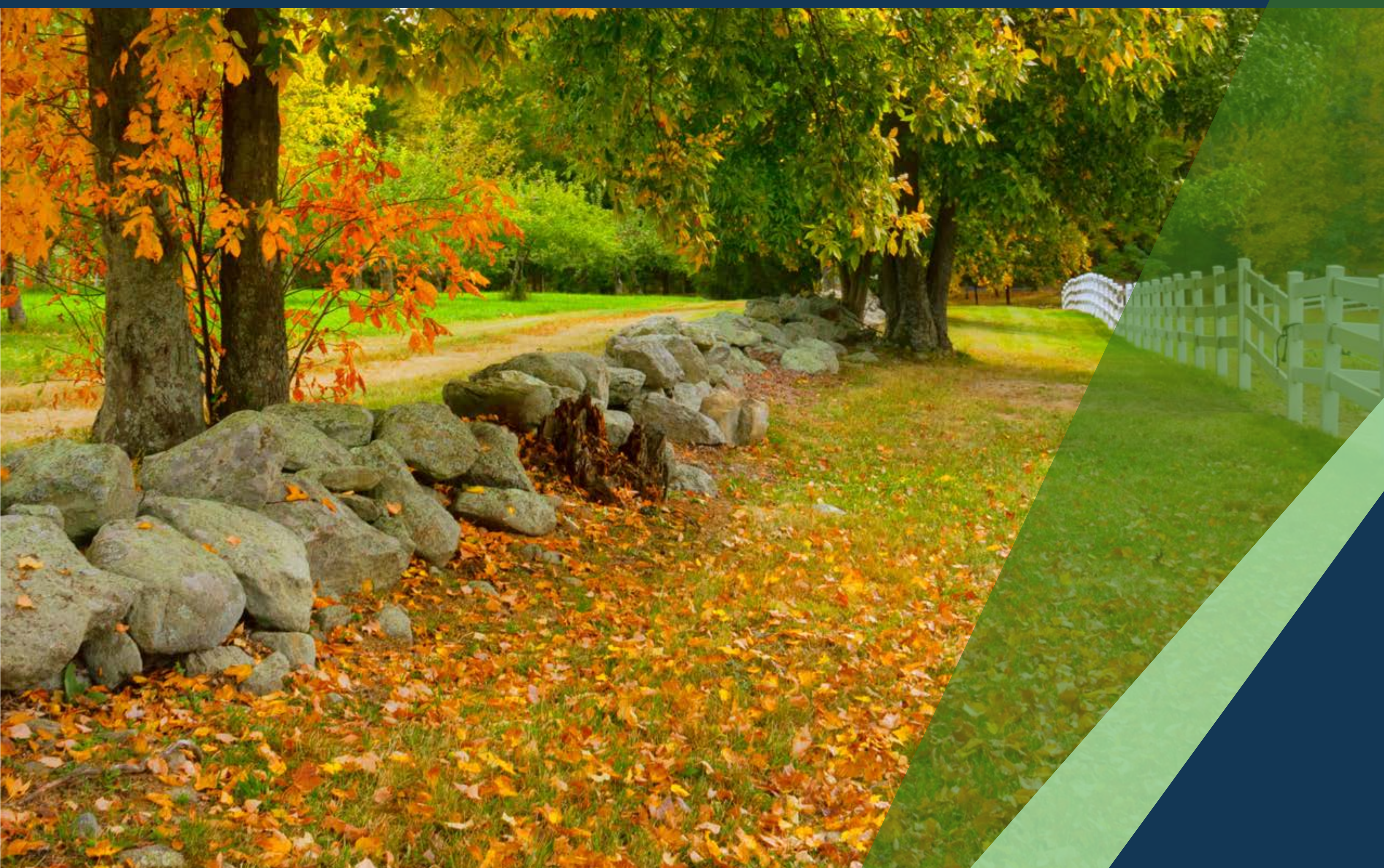

A report commissioned by the Massachusetts Executive Office of Energy and Environmental Affairs to identify cost-effective and equitable strategies to ensure Massachusetts achieves net-zero greenhouse gas emissions by 2050.

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Chapter 1

Project Overview and Mission

Under the Baker-Polito Administration, and within the framework of the Global Warming Solutions Act (GWSA), the Commonwealth of Massachusetts has committed to achieving Net Zero greenhouse gas (GHG) emissions by 2050.[1] Commissioned by the Executive Office of Energy and Environmental Affairs (EEA), the 2050 Decarbonization Roadmap Study (Roadmap Study) was designed to support the Commonwealth in this goal and culminates in this 2050 Decarbonization Roadmap Report (Roadmap Report). The goal of the Roadmap Study was to provide the Commonwealth with a comprehensive understanding of the necessary strategies and transitions in the near- and long-term to achieve Net Zero by 2050 using best-available science and research methodology. It also sought to understand the tradeoffs across different pathways to reach the levels of deep decarbonization required by that limit. The Roadmap Study will inform EEA's determination of the Commonwealth's interim 2030 emissions limit as well as the forthcoming Clean Energy and Climate Plan for 2030 (2030 CECP), the Commonwealth's policy action plan to equitably and cost-effectively achieve the 2030 limit while maximizing Massachusetts' ability to achieve Net Zero by 2050.

The Roadmap Study set out to address many complex issues related to statewide deep decarbonization, but maintained focus on one core question to guide analysis:

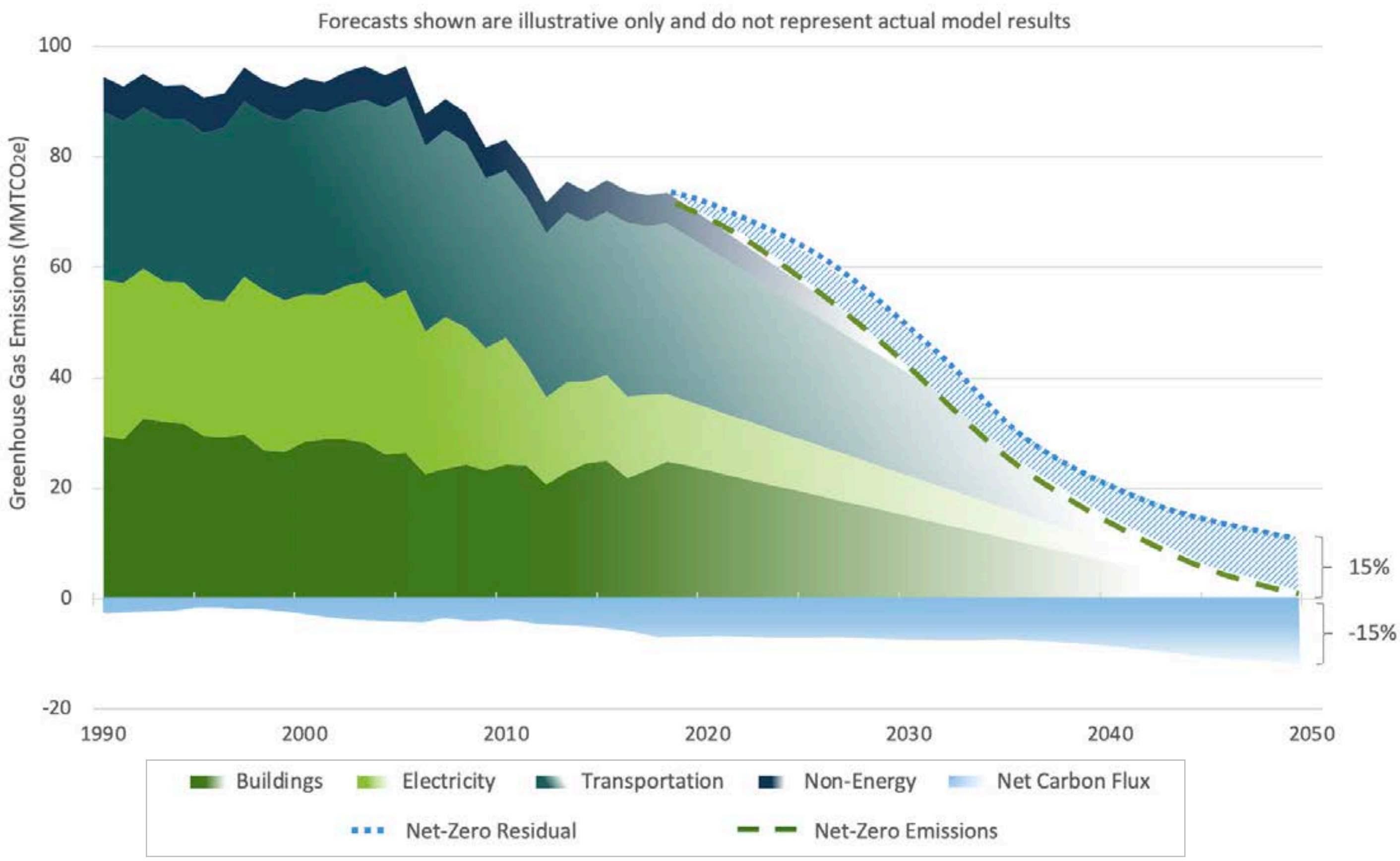
How can the Commonwealth achieve Net Zero while maintaining a healthy, equitable, and thriving economy?

In order to answer that question, this Roadmap Report synthesizes the Roadmap Study's expansive analytical effort. The full Roadmap Study included integrated, cross-sector energy system analysis (Figure 1) exploring eight distinct emissions reductions "pathways" to 2050, each capable of supporting the achievement of Net Zero emissions statewide in 2050.

[1] *Following the Governor's Net Zero declaration during his January 21, 2020 State of the Commonwealth address, and pursuant to authority granted by the GWSA, the Executive Office of Energy and Environmental Affairs set the Commonwealth's 2050 statewide emissions limit to require achievement of Net Zero emissions by 2050, defined as: "A level of statewide greenhouse gas emissions that is equal in quantity to the amount of carbon dioxide or its equivalent that is removed from the atmosphere and stored annually by, or attributable to, the Commonwealth; provided, however, that in no event shall the level of emissions be greater than a level that is 85 percent below the 1990 level." See Figure 1 for an illustration.*

It also comprised four sector-specific analyses focused on buildings, transportation, non-energy emissions, and the carbon sequestration potential of Massachusetts' natural and working lands, as well as a separate economic and health impact analysis. The companion technical reports and appendices for each of those elements of the Roadmap Study provide additional detail, context, and analysis that serve as the foundation for the information presented here.

Figure 1. Net Zero requires deeper emissions reductions than the Commonwealth's previous "80% by 2050" target, as well as a new requirement to balance any remaining emissions with the same amount of carbon removal from the atmosphere.



OVER A DECADE OF INTEGRATED CLIMATE ACTION

The Commonwealth has a history of taking dedicated action to address, adapt to, and mitigate climate change, including:

2008

The **Global Warming Solutions Act (GWSA)** and **Green Communities Act** signed into law. Massachusetts becomes one of the first states in the nation to formally commit to a regulatory program requiring greenhouse gas emissions reductions (at least 25% below 1990 levels in 2020, and at least 80% below 1990 levels in 2050) and to comprehensively reform its energy policy and procurement framework to align with that goal.

2010

Publication of the **Clean Energy and Climate Plan for 2020** (2020 CECP). The Commonwealth's first comprehensive climate action plan outlined an integrated portfolio of policies designed to ensure the achievement of the interim 2020 emissions limit.

2011

The **Climate Change Adaptation Report** is issued. The report was the Commonwealth's first comprehensive assessment of vulnerability and risk of climate change impacts across Massachusetts as well potential strategies to better prepare the Commonwealth for the changing climate.

2015

Publication of the **2020 CECP** Update, which provided updated policies and projections of emissions reductions and emissions reduction strategies to ensure achievement of the interim 2020 limit.

2016

Governor Baker signs **Executive Order 569** establishing an integrated climate strategy for the Commonwealth, and **An Act to Promote Energy Diversity** authorizing large procurements of offshore wind and hydroelectric resources.

2017

Baker-Polito Administration launches the first-in-the-nation **Municipal Vulnerability Preparedness Program**, providing support for cities and towns across the Commonwealth to identify climate change vulnerabilities, prioritize critical actions, and build community resiliency.

2018

Governor Baker signs into law **An Act to Advance Clean Energy**, setting new targets for offshore wind, solar, and storage technologies.

2018

The Commission on the Future of Transportation in the Commonwealth releases **Choices for Stewardship: Recommendations to Meet the Transportation Future**, and Massachusetts joins 9 other jurisdictions in the **Transportation and Climate Initiative** to develop a regional policy for low-carbon transportation.

2018

The **State Hazard Mitigation and Climate Adaptation Plan** is published. Massachusetts becomes the first state to fully integrate its state hazard mitigation and climate change adaptation planning framework to build long-term resilience and reduce risks associated with climate change.

2018

Publication of the **GWSA 10-Year Progress Report**. Demonstrates the Commonwealth is on-track to meet 2020 limits having successfully reduced its 2016 emissions to 21.4% below 1990 levels while growing its economy and supporting over 100,000 clean energy jobs in-state.

2020

Baker-Polito Administration establishes Net Zero as the Commonwealth's legal emissions limit for 2050.

2020

Massachusetts, Connecticut, Rhode Island, and the District of Columbia launch a regional cap-and-invest program, the Transportation and **Climate Initiative Program (TCI-P)**, designed to significantly reduce transportation emissions and generate $160 million per year in Massachusetts for transportation-related investments.

2020

Publication of the **Decarbonization Roadmap to 2050** and the **Clean Energy and Climate Plan for 2030**, outlining the long-term strategies and near-term actions for the Commonwealth to achieve net-zero emissions.

Chapter 2

Approach

Analytical Approach

The Roadmap Study was designed to provide the Commonwealth with a comprehensive understanding of the needs for the overall, long-range decarbonization transition; it will allow the Commonwealth to better understand the transition's implications and requirements, particularly in the near term. The analytical approach, consideration of equity, and stakeholder engagement activities for the Roadmap Study are discussed below.

The technical analysis conducted for the Roadmap Study was designed to achieve the following goals:

Start with the technical to enable policy and implementation – the analysis should seek to understand the fundamental physical requirements and technological options for achieving Net Zero. This is necessary to enable smart policy design to meet decarbonization goals while maintaining a healthy, equitable, and thriving economy.

Explore multiple pathways to Net Zero to support the development of robust and resilient decarbonization strategies – the analysis should test a range of technically and economically feasible pathways in order to gain insight into low-carbon system dynamics and cross-sector interdependencies. This approach will enable the Commonwealth to confidently make continual, meaningful progress toward Net Zero by focusing on "no-regrets" actions across 30 years of change and uncertainty.

Create optionality for the Commonwealth – the analysis should be designed to maintain as much flexibility and study as many decarbonization techniques as possible in order to develop a range of options for policymakers and stakeholders to assess and consider.

Use "back-cast" modeling to best understand the transformations needed to get to 2050 – the analysis should be rooted in the successful achievement of Net Zero in 2050 and analyze ways to get there. This approach has the added benefit of identifying potential "dead ends" that, while reducing emissions or cost in the near term, could either prevent the Commonwealth from achieving Net Zero or dramatically raise the future cost of doing so.

Produce granular data to unlock and enable policy implementation and market action – the analysis should result in data-based findings that can guide policy and program design by the Commonwealth, utilities, the business community, and the public in order to meet decarbonization goals.

With these goals in mind, two distinct modeling approaches contributed to the findings presented in this Roadmap Report, which are further detailed in the six companion technical reports. The approaches are summarized below and illustrated in Figure 2:

- An integrated, regional, cross-sector energy system pathways analysis consisting of results from eight differing high-level pathways (the *Energy Pathways Report)*;
- Massachusetts-specific analyses by sector for the buildings, transportation, non-energy, and land sectors (detailed further in the *Buildings Sector Technical Report*, the *Transportation Sector Technical Report*, the *Non-Energy Sector Technical Report*, and the *Land Sector Technical Report*, respectively) and an economic and health impacts analysis (detailed in the *Economic and Health Impacts Analysis Technical Report*).

While the 2050 Net Zero emissions limit specifies reduction of at least 85% of gross emissions, the Roadmap Study's quantitative analyses explored the costs, requirements, and system dynamics of achieving energy system emissions reductions comparable to a 90% below 1990 level by 2050 statewide. This was done to maximize the Commonwealth's options to 2050—balancing an optimal level of emissions reductions versus carbon capture, especially the marginal cost of each—that will together achieve Net Zero.

Equity Considerations for Deep Decarbonization

Achieving Net Zero in the next thirty years is an important element of the Commonwealth's ongoing, formal commitment to ensuring that all people in Massachusetts are protected from environmental pollution and are able to live in and enjoy a clean and healthy environment.[2] Indeed, for too long, too many people have disproportionately borne the environmental and health burdens associated with our current energy economy. This is particularly true for those living in Environmental Justice (EJ) communities, both rural and urban,[3] who experience higher than average rates of environmentally-related adverse health impacts due to their proximity to the localized cumulative impacts and long-term environmental degradation associated with, among other things, the combustion of fossil fuels. In addition to improving air quality across the entire Commonwealth, decarbonization promises to dramatically reduce many of those on-going, location-specific environmental burdens. It also will bring thirty years of sustained, new economic activity that has the potential to revitalize communities across Massachusetts which have been disadvantaged and at times devastated by historic shifts in the regional, national, and global economies.

Despite the far-reaching positive effects of decarbonization, the ability of Massachusetts residents to participate in this thirty-year transition will differ as a result of income level, race, ability to access and benefit from available resources, location in urban and rural settings, proficiency in English, and previous marginalization. That consideration is particularly important in planning short- and long-term strategies to achieve Net Zero, since the Roadmap Study analysis demonstrates that economy-wide decarbonization can succeed only when all of us–across the Commonwealth and in all our communities–are part of the solution. As a result, broad and sustained public engagement during policy and program development, particularly with EJ populations, communities of color, and low-income residents, will not only be necessary to avoid inequitable outcomes, it will be a key step in achieving a Net Zero future.

[2] *Protections as defined in Article 97, Constitution of the Commonwealth.*

[3] *As defined in EEA's 2017 EJ Policy, 33% of the residents of the Commonwealth living on 7% of the land resided in an EJ community. There are EJ communities in every county of the Commonwealth.*

Stakeholder Engagement

Internal and external stakeholder input was incorporated into the Roadmap Study throughout the study period and included updates and consultations with the GWSA Implementation Advisory Committee (IAC) and its Working Groups, a Technical Steering Committee (TSC), and staff representatives from state agencies and the Massachusetts Clean Energy Center (MassCEC). EEA also hosted a series of public meetings to gather feedback on some of the building blocks of the report, collected public comments through an online portal about the study, and held a dedicated public comment period around the setting of the 2050 Net Zero limit.

The IAC was originally established by the GWSA and meets regularly to discuss and provide advice to EEA on implementation of the law, particularly pertaining to strategies for achieving required emissions reductions. Members include representatives from many sectors including commercial, industrial, and manufacturing; transportation; low-income consumers and EJ communities; energy generation, distribution, and efficiency; environmental protection and conservation; and local government and academic institutions. The IAC also has several self-appointed Working Groups, including the Climate Justice Working Group which was newly formed in January of 2020 in order to directly advise on the design of policies that can benefit EJ populations and other historically marginalized communities. In addition to frequent public briefings with the IAC on the Roadmap Study development, the IAC Work Groups conferred with EEA and brought significant external expertise to the Roadmap Study.

The TSC was created specifically for this Roadmap Study to help advise EEA and the project team on technical elements of the analysis, including assumptions, modeling tools, calibration, and sensitivities. The TSC was made up of academics from the Commonwealth with expertise in a range of topics, including economics, transportation, social equity, biology, buildings, public health, policy, and energy systems.

EEA also engaged a broader coalition of stakeholders at the outset of the Roadmap Study before COVID-related health and safety measures intervened. In November 2019, over 100 participants were brought together in a visioning exercise to understand factors that will likely influence the Commonwealth's efforts to achieve Net Zero. Key topics discussed during the exercise were used to inform the energy system modeling pathways and sensitivities, and to help determine the Roadmap Study's inputs and priorities.

[4] The agencies include EEA, Department of Energy Resources, Department of Transportation, Department of Environmental Protection, and Department of Public Utilities; MassCEC is a quasi-public, ratepayer-funded economic development agency with the mandate to promote clean energy innovation and the growth of the clean energy economy in the Commonwealth.

Chapter 3

Transitioning to Net Zero in 2050

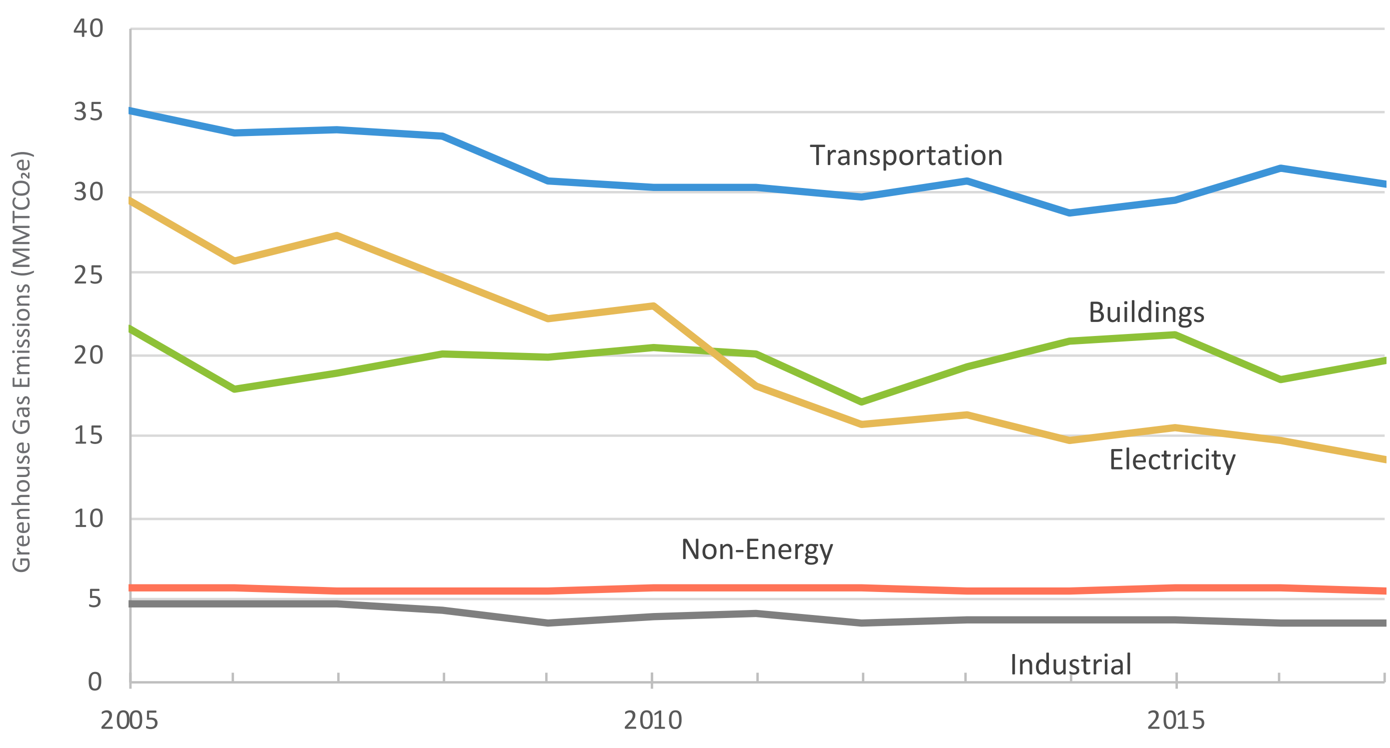
The Roadmap Study established that multiple viable pathways exist by which the Commonwealth can achieve Net Zero and that there are several robust decarbonization strategies that, together, will allow Massachusetts to achieve that goal affordably, and equitably, while continuing to grow and maintain a vibrant local and regional economy. But the analysis also indicated that the way in which Massachusetts and our neighbors pursue their climate goals – the choice between or among potential pathways – could dramatically impact the costs, risks, and broader environmental impacts associated with the deep decarbonization transformation. Regardless, in addition to achieving the Commonwealth's climate goals, all Net Zero scenarios will deliver significant economic and health benefits statewide.

While there is always a potential role for new and valuably disruptive technologies, the fundamental challenge in reaching Net Zero is not technical, but practical. The core technologies and techniques Massachusetts needs to achieve Net Zero are known and, for the most part, commercialized, although some significant barriers to deployment exist that must be actively managed and reduced. Achieving Net Zero will require Massachusetts and our neighbors to collaboratively implement a variety of strategies to transform how energy is produced and consumed, and how land resources are managed. A summary of these key transformations and a brief discussion of some of their key implications follows.

The Commonwealth's Emissions Outlook

The majority of the Commonwealth's GHG emissions come from the combustion of fossil fuels that provide the source energy for a variety of end uses – moving our vehicles; heating and cooling our homes and businesses; and powering our lights, computers, and industrial machinery.

Figure 3. Annual greenhouse gas emissions in Massachusetts.[5]



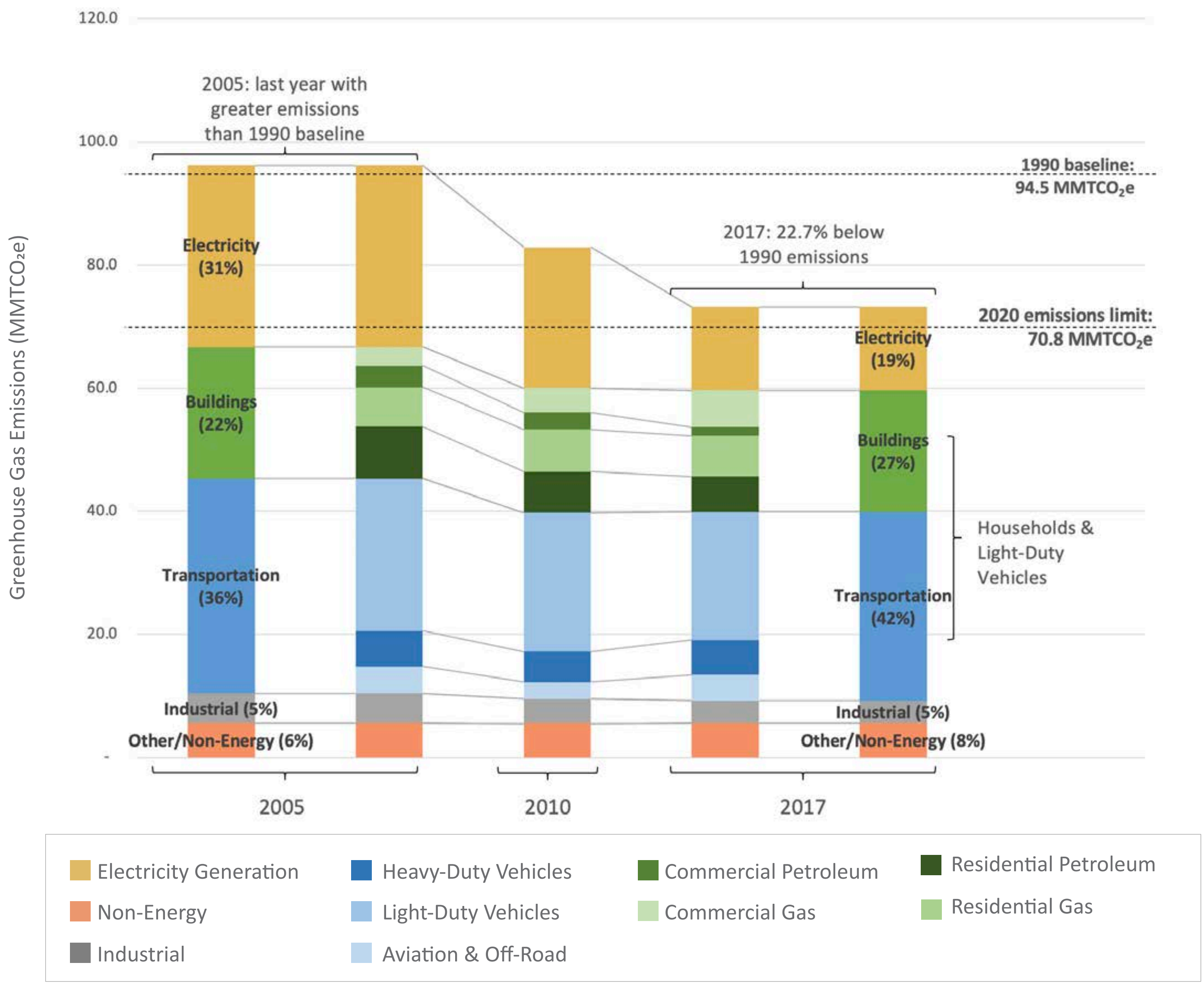
[5] MassDEP. "Massachusetts Annual Greenhouse Gas Inventory: 1990-2017." Available at https://www.mass.gov/lists/massdep-emissions-inventories

Over the last decade and a half, Massachusetts' decarbonization efforts have focused on reducing emissions associated with the supply of electricity, and to great effect: since 2005, the Commonwealth's electricity-related emissions have reduced by about 50% (Figure 3).

Although the Commonwealth's electricity supply must continue to become cleaner every year to achieve Net Zero, today about half of the emissions that must be cut by 2050 come from households and small businesses: 60% of transportation sector emissions come from light-duty passenger cars, trucks and sport utility vehicles (SUVs) and 60% of building sector emissions come from furnaces, boilers, and water heaters in homes and offices (Figure 4).

The remainder of statewide emissions come from a combination of industry and the non-energy sector; these sectors have unique decarbonization challenges and limitations.

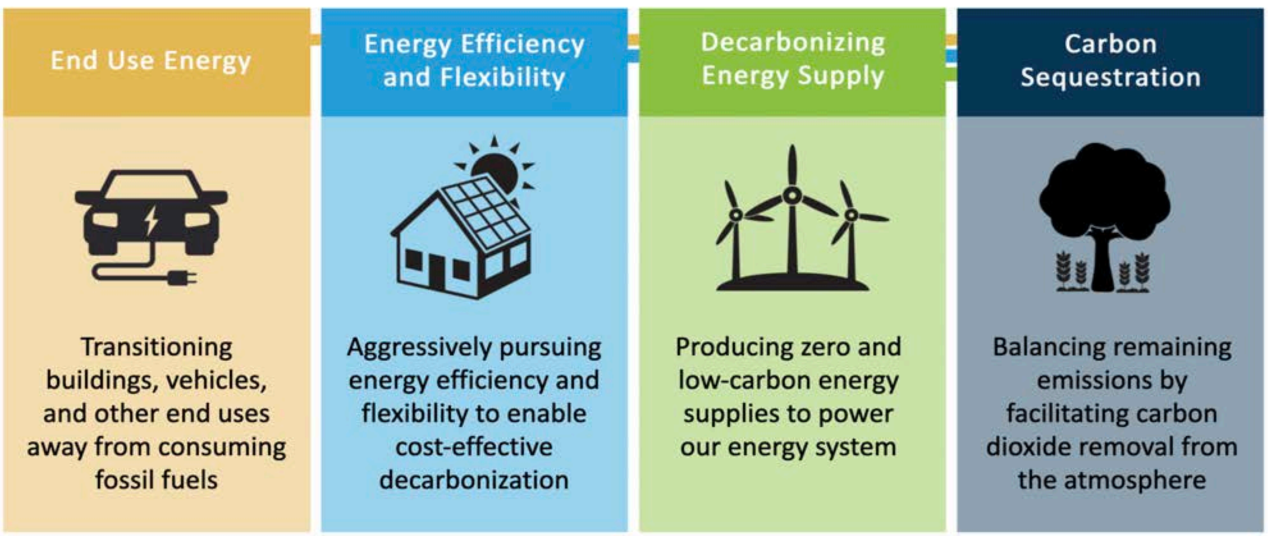
Figure 4.Distribution of current and historical GHG Emissions



Strategies for Reducing Emissions

Reducing emissions to align with Net Zero requires a holistic systems approach of complementary and integrative actions (Figure 5). To successfully decarbonize and do so affordably, the Commonwealth must: almost completely transition energy "end-uses" away from fossil fuels; deploy higher levels of energy efficiency and flexibility; rapidly decarbonize the energy supply to become predominantly reliant on renewable electricity generation; and remove carbon from the atmosphere by preserving and enhancing natural and other sequestration resources. These "pillars of decarbonization" have been identified in previous deep decarbonization studies[6] in the U.S. as well as internationally. These foundational elements also complement each other; each pillar addresses the limitations and maximizes the opportunities associated with the others to ensure that decarbonization is achieved cost-effectively and at low risk of failure across the economy.

Figure 5. Four key "pillars of decarbonization" for the Commonwealth



A Range of Solutions Led by Clean Electricity

With so many of the Commonwealth's remaining emissions coming from households and businesses –passenger vehicles and space heating/building services – deep decarbonization requires the deployment of affordable alternative technologies at scale. Reducing these "consumer level" sources of emissions to near-zero by 2050 is part of a robust and affordable economy-wide strategy, as it may not be feasible to decarbonize some end uses (commercial aircraft) or eliminate all non-fossil sources of GHGs (e.g., from wastewater treatment).

Although several clean options already exist for both light-duty transportation and for home and small business building services, across our in-depth analysis, electrification tends to be the most cost-effective – both individually and system-wide – and the easiest to deploy. Implementing electrification in this context implies the widespread deployment of EVs in place of gasoline and diesel engines and of heat pump-based electrified heating systems in place of gas and oil furnaces and boilers.

[6] *See, for example, the* **Deep Decarbonization Pathways Project**, *which has studied 16 countries since 2014 (including the U.S.):* https://www.iddri.org/en/project/deep-decarbonization-pathways-project; *United Nations Sustainable Development Solutions Network* **350 PPM Pathways for the United States** *(2019)* https://resources.unsdsn.org/350-ppm-pathways-for-the-united-states; **European Union Energy Roadmap to 2050** *(2011)* https://ec.europa.eu/energy/sites/ener/files/documents/2012_energy_roadmap_2050_en_0.pdf; *and* **Eurelectric Decarbonization Pathways** *(2018):* https://www.eurelectric.org/decarbonisation-pathways/.

Electrifying everything, however, is not necessary for achieving Net Zero. A variety of decarbonization strategies is preferable and a range of Net Zero-compliant fuels will play an important role in certain sectors and for certain end uses that have infrastructure, cost, and feasibility constraints. Under all scenarios examined, low-carbon fuels are likely to remain relatively scarce and costly even when scaled. As a result, low-carbon combustible fuels should be used strategically, reserved for those limited, non-consumer applications where they are most needed (or a technical necessity) to help the Commonwealth achieve Net Zero.

A Balanced Regional Electric Grid Dominated by Renewables

As electrification of buildings and vehicles dramatically increases, Massachusetts will need to significantly expand our clean electricity supply. Based on cost and availability, the vast majority of that new clean electricity will come from renewable generation, particularly the world-class offshore wind resource off the New England coast, which can provide "bulk" low-cost, carbon-free electricity in the majority of hours to the entire region and across the greater Northeast. However, even a massive buildout of offshore wind power will not provide enough carbon-free electricity generation to reach Net Zero. To affordably and reliably operate an electricity grid based on variable renewable generation, a balanced portfolio of clean generation technologies shared across a broad geographical region is needed. Together with offshore wind power, the Commonwealth needs a similarly large volume of solar generation deployed on rooftops and on land, additional energy storage, and several new high-voltage transmissions lines to Canada and New York that will allow sharing of low-cost clean energy, including hydropower, with the Commonwealth's neighbors in the Northeast.

Investments in energy efficiency and electric load flexibility are, and will remain, critical to reduce costs and improve system reliability, but do not fundamentally change the pathway forward. Indeed, due to the inherent efficiency of many electrification technologies, particularly EV drivetrains and heat pumps for heating and cooling, the electrification of end uses means that less energy can be used to provide the same service. However, because end-uses will shift from the fossil-based technologies that dominate today to electrified technologies, the demand for clean electricity is projected to nearly double by 2050.

The Energy System Transition to 2050

Meeting the Net Zero target will require a transformation of energy systems across the Commonwealth, with impacts to energy flows, demand and supply, and costs.

This two-page spread highlights the scale of change needed to get there, featuring two pathways from the *Energy Pathways Report*: a reference case to 2050 and the All Options pathway to 2050.

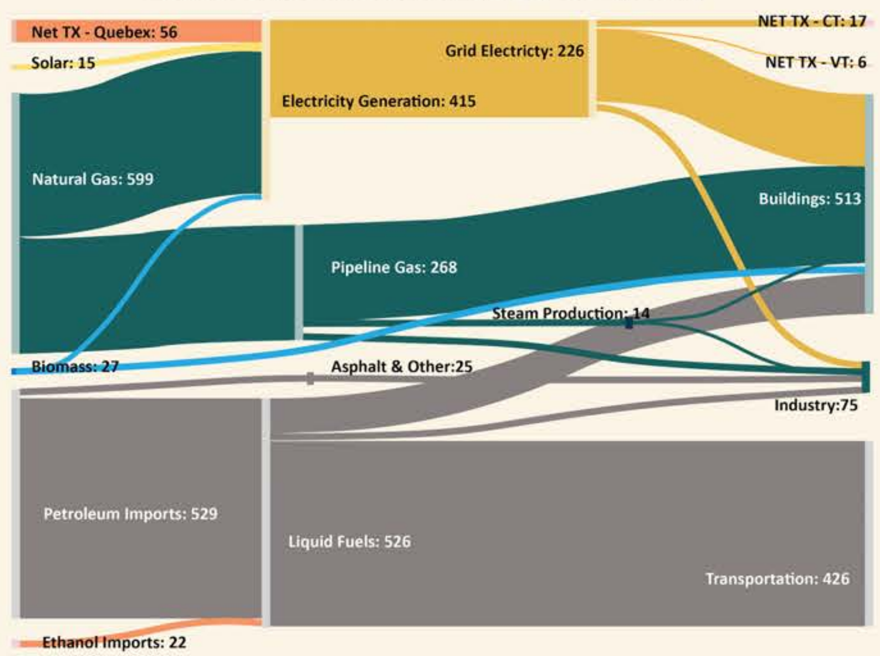
Energy Flows

The two figures below illustrate key changes in energy supply and end use from 2020 to 2050. On the left of each figure are energy sources. The height of a bar indicates the relative quantity of energy used. The right of each figure indicates the energy use sectors like transportation and buildings. The middle of each figure shows energy transformations.

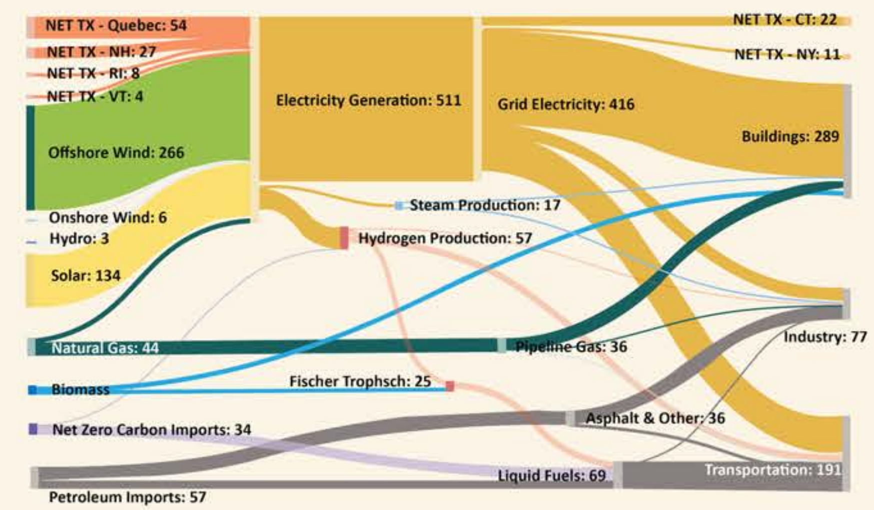
1. The Commonwealth shifts from being primarily powered by fossil fuels in 2020 to renewable resources in 2050. The main sources of energy in 2050 are offshore wind, solar, and electricity transmission imports.

2. The electrification of many end uses in the buildings and transportation sectors results in efficiency improvements and a reduction in overall energy demand. This is exhibited by the lower amount of primary energy sources in the figure with 2050 energy use.

2020 Commonwealth Energy Use (TBtu)



2050 Commonwealth Energy Use (TBtu)



3. Gas use declines significantly from 2020 to 2050 but is still used in 2050 for some electricity generation, building heating, and transportation uses.

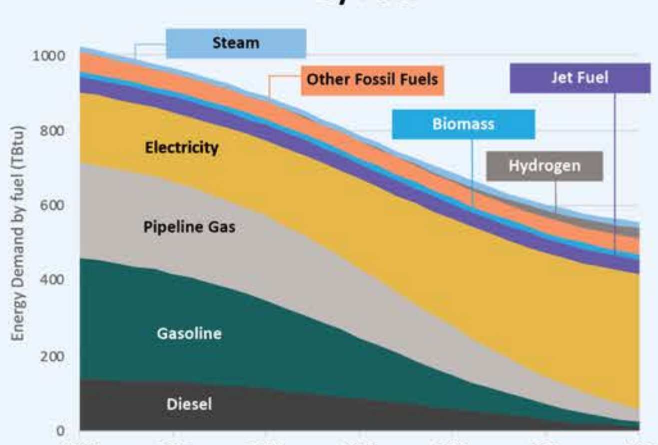
4. Sectoral coupling with flexible industrial loads (like steam and hydrogen production) help to balance the electricity generated by high levels of renewable energy.

Energy Demand and Supply

Rapid transformation of the energy system has impacts on energy services and supply.

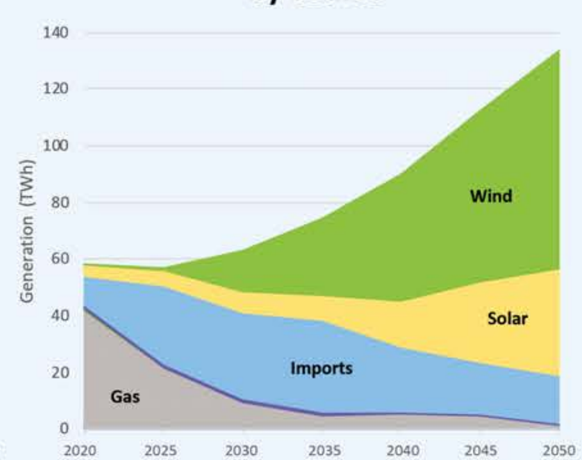
5. Over time, end uses in the buildings and transportation sectors are electrified resulting in efficiency savings and a reduction in overall energy demand.

Energy Demand by Fuel

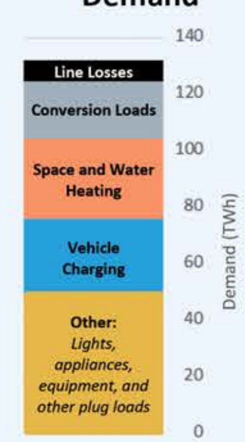


6. Electrification results in growing demand for electricity. Solar and wind generation increase dramatically from 2025 through 2050.

Electricity Generation by Source



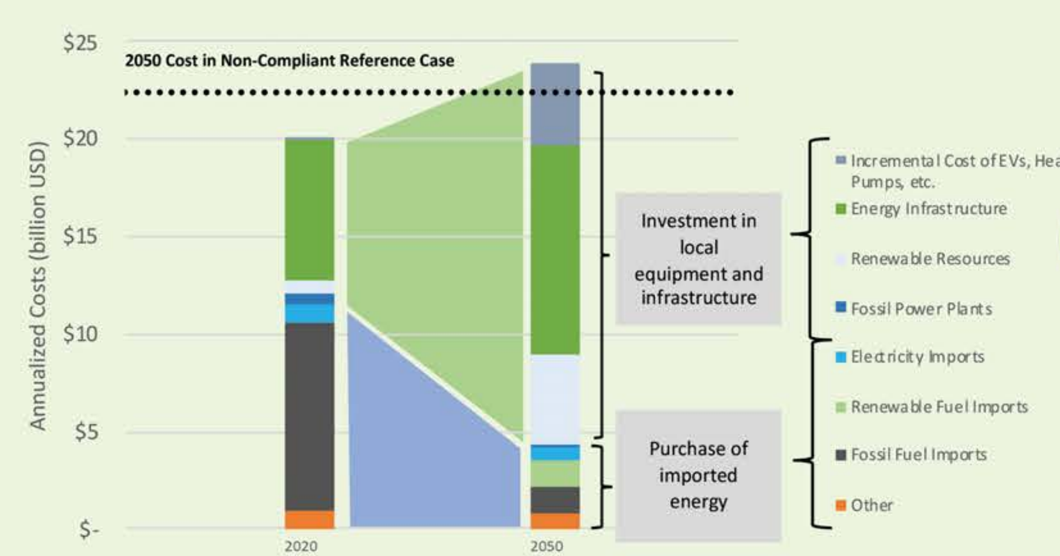
2050 Electricity Demand



Energy Costs

Decarbonized energy system costs are not significantly higher than the costs associated with a 2050 fossil-based system.

Annual Statewide Energy System Costs



7. Investment in local equipment and infrastructure increases from 2020 to 2050, allowing decreased operating costs.

8. The purchase of imported energy decreases from 2020 to 2050 due to the replacement of imported fossil fuels with a diverse, largely regional, energy mix.

Creating Negative Emissions Regionwide

To achieve Net Zero, the Commonwealth must also build and maintain the ability to remove carbon dioxide from the atmosphere and durably store or sequester it. Even after transforming and almost completely decarbonizing the energy system, residual emissions will remain in the Commonwealth's 2050 energy and non-energy sectors – from residual fossil fuel use, certain industrial processes, agriculture and forestry, solid waste disposal, and wastewater treatment. If properly managed and maintained, natural and working lands – primarily Massachusetts' 3.3 million acres of forested land – will play a critical role in absorbing and storing a large portion (about half) of those emissions. To achieve Net Zero by 2050, however, the Commonwealth will need to build and access a new market for carbon sequestration and other "negative emissions" that will help drive the development of mechanical direct air capture sources and will help support and grow the Commonwealth's natural resources while allowing the Commonwealth to support, grow, and access those of our neighbors across the Northeast.

Achieving Net Zero Affordably for All

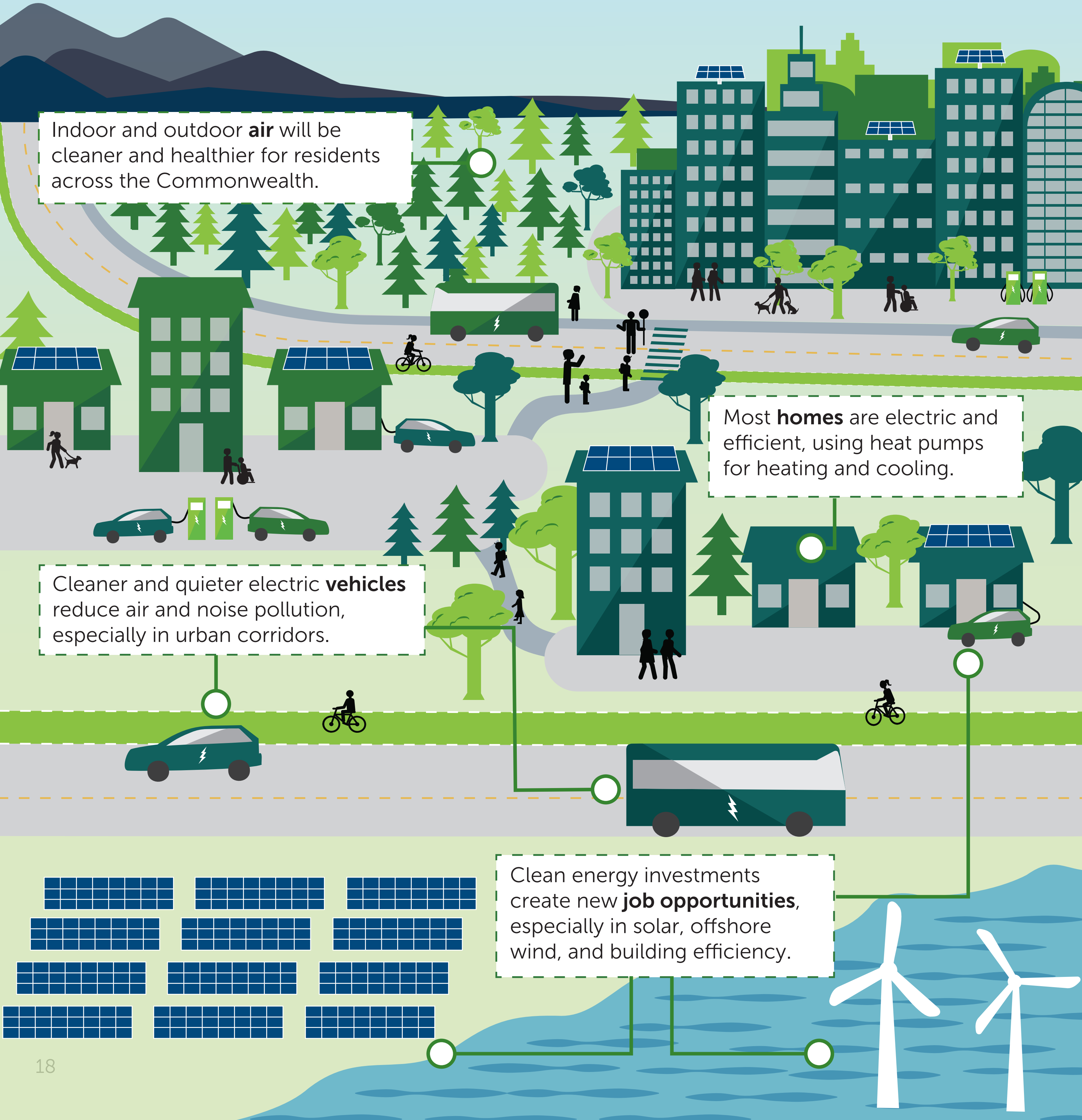
Decarbonizing the Commonwealth's energy systems will require substantial investments over the coming decades, but it is an investment that creates significant economic opportunity and that will pay dividends across the Commonwealth for generations to come. Each year, Massachusetts residents spend more than $15 billion on energy and energy-related equipment and infrastructure. Most of that money flows out of the region to states and countries that produce and refine fossil fuels. Investing a significant portion of that annual expense into clean technologies will reduce and stabilize overall energy demands and costs for businesses and families, providing economic benefits and job growth while improving air quality and resulting in lower healthcare costs. It is estimated that achieving Net Zero by 2050 would lead to a reduction in cardiac and respiratory illness that would result in the avoidance of 400 deaths and 25,000 days of missed work annually. These benefits are valued at $4.5 billion annually, exceeding pathway projected costs; approximately 98% of the benefit is attributable to a reduction in mortality.

In addition, investing in local energy production will recycle that "cost" as direct investment into the Commonwealth's local economy, creating growth in emerging clean energy industries and approximately 15,000 jobs annually across the next 30 years and making the Commonwealth and the Northeast region more self-reliant and resilient.

The total investment needed for full decarbonization – for individuals and for the Commonwealth as a whole – can be minimized by transitioning to clean technologies when old equipment reaches the end of its service life and must be replaced. This opportunity also represents a barrier, as such turnover points come infrequently: cars and trucks, for example, usually last for more than ten years, while furnaces and boilers may last for several decades. Achieving Net Zero in order to avoid the worst impacts of global warming thus requires a pace of transformation that will not be easy to achieve and sustain; in certain instances, this pace may feel uncomfortably fast. Massachusetts policy actions can and must help to ensure not only that this technological shift accelerates dramatically in the years to come, but also that it occurs with equitable access to the known benefits of decarbonization, while avoiding the potential inequitable distribution of costs.

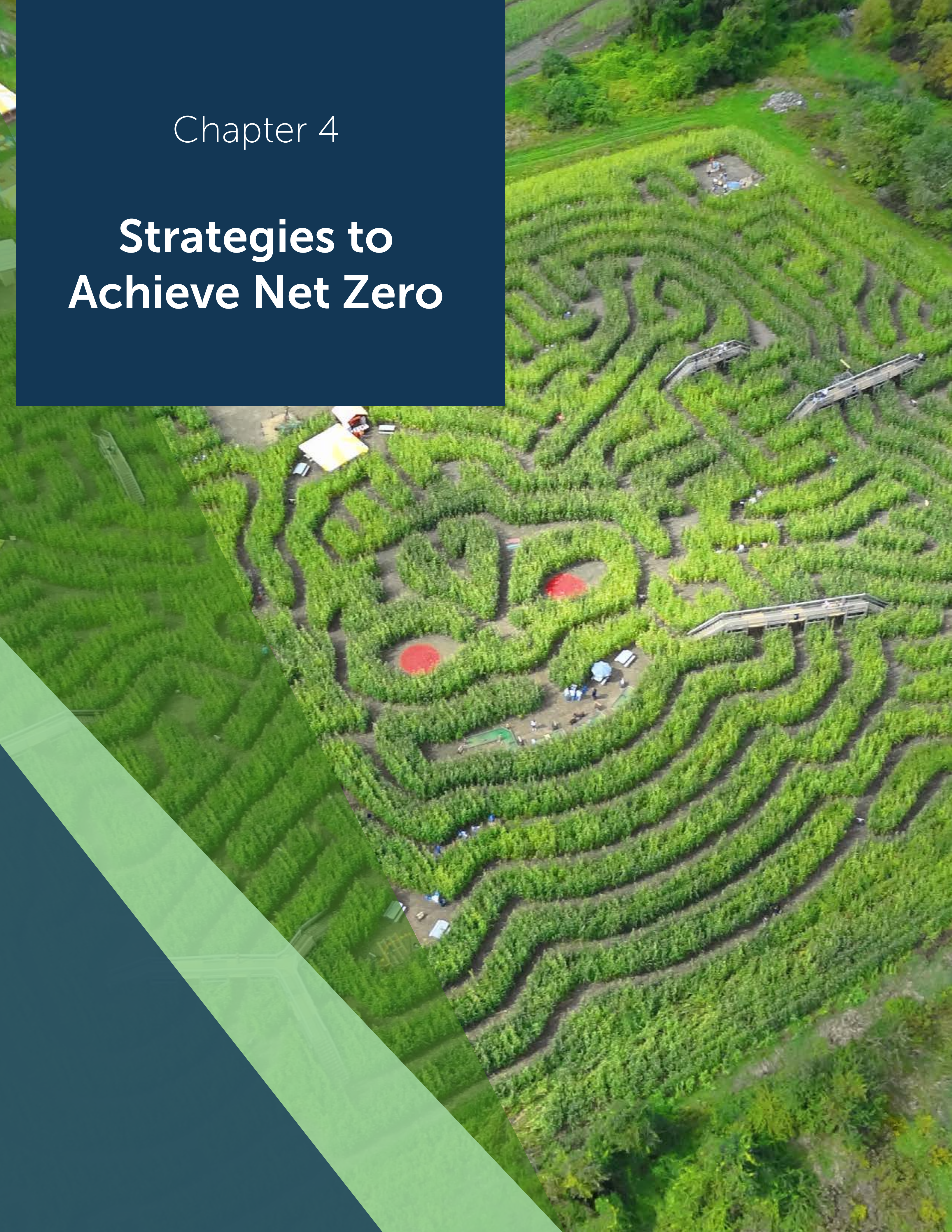
SEE YOURSELF IN 2050

The transition to Net Zero has benefits across all aspects of society. Massachusetts will become cleaner, healthier, and more resilient.



Chapter 4

Strategies to Achieve Net Zero

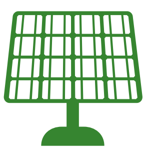


The Commonwealth's Net Zero limit mandates emissions reductions to a level that is at least 85% below the 1990 statewide level. While that limit allows for potentially deeper reductions, meeting the Net Zero limit will require that the Commonwealth emit no more than about 14.2 million metric tons of CO_2 equivalent ($MMTCO_2e$) of GHGs in 2050, while annually removing and storing an equivalent amount of carbon dioxide from the atmosphere.

A broad range of coordinated strategies must be simultaneously pursued over the next three decades in order to achieve that level: transitioning buildings, vehicles, and other end uses away from consuming fossil fuels; aggressively achieving energy efficiency and electric load flexibility to enable cost-effective decarbonization; producing zero and low-carbon energy supplies; and facilitating carbon dioxide removal. This chapter integrates these objectives into three overarching groups of strategies:

Strategies to reduce emissions from energy demand in end uses

through electrification, fuel switching, efficiency, and flexibility. Transforming the Commonwealth's energy end uses is fundamentally a problem of scale that will require replacing millions of pieces of equipment that are used daily by Massachusetts residents and businesses. The timing of these replacements, primarily in buildings and vehicles, is essential if costs and burdens are to be minimized and economic benefits maximized.



Strategies needed to reliably supply low-to-zero carbon energy

resources to Massachusetts residents. To support widespread electrification across the economy, large amounts of new, low-cost, zero-carbon–primarily renewable–electricity generation resources must be deployed, complemented by a range of new reliability resources. Barring major technological innovation, current physical constraints on their availability and production, as well as high cost, zero-carbon fuels use should be prioritized for particularly hard to decarbonize or difficult-to-electrify end uses. System planning is essential for ensuring that energy costs remain low for consumers.

Strategies that minimize residual emissions and maximize cost-effective carbon dioxide removal and storage.[7]

These strategies include addressing non-energy and industrial emissions that may be extremely costly or impossible to mitigate, as well as developing a robust framework for a range of "negative emissions" through carbon dioxide removal and storage methods. This Roadmap Study is the first comprehensive effort by the Commonwealth to understand how our natural and working lands–primarily our 3.3 million acres of forested land–can play an integral role in providing the negative emissions that Net Zero requires. Importantly, this analysis shows that even with the best land and timber management and conservation strategies, Massachusetts' natural resources alone are unlikely to be able to sequester the amount of carbon needed to achieve Net Zero. Other carbon dioxide removal methods including both direct air capture and the protection of natural resources in neighboring states will need to be pursued.

[7] Carbon dioxide removal (CDR), and carbon capture and storage or sequestration (CCS), are terms used to describe the removal of carbon dioxide from the atmosphere (biomass production, direct air capture) and the long-term storage of carbon in reservoirs (soil, forest, geologic formations, coastal wetlands). CDR generally refers to the process of removal, while storage or sequestration refers to the process of placing that carbon in a reservoir.

System Transformations to 2050

TRANSPORTATION

- Cars, trucks, and buses are emissions-free and mostly electric; zero-carbon fuels like hydrogen help power the rest of the transportation system.
- A healthy public transit system, bike lanes, sidewalks, and transit-oriented development complement vehicle electrification and help to reduce congestion.

BUILDINGS

- High-performance heat pumps provide clean, energy-saving heat and air conditioning for most homes.
- More energy efficient buildings and electric appliances help reduce monthly energy bills for most families and small businesses.

ENERGY SUPPLY

- Wind and solar power are widely deployed to decarbonize the grid and meet the growing demand for clean electricity.
- A diverse mix of energy resources ensures year-round reliability.
- Improved transmission and distribution systems increase access to a diverse set of low-cost resources and allow offshore wind to help power New England.

NON-ENERGY

- Organic wastes are composted at greater rates, single use plastics are reduced and recycled, and waste generation overall is minimized.
- Agriculture and industry are managed responsibly to reduce emissions.
- Potent industrial greenhouse gases are replaced by climate-friendly alternatives.

LAND USE

- Forests and other natural and working lands are managed strategically to enhance carbon sequestration while maintaining and building ecosystem health and resiliency.

Key Constraints

As Net Zero emissions reductions and sequestration strategies are evaluated and deployed, several system level dynamics and constraints become relevant and must be considered.

Land Use and Siting – Several decarbonization strategies require either using or conserving land, and thus have the potential to place various societal goals in conflict with each other. Siting energy projects has been a challenge in both rural and urban areas, and over the next 30 years will be a major priority given the importance of new infrastructure to decarbonization. Among natural systems, land has the potential to be one of the most impacted by human activity given its position at the nexus of food, water, housing, energy production, and other important human needs. That same dynamic is visible among decarbonization strategies and solutions, particularly when net-zero emissions is the goal. In addition to the other essential ecological, economic, and social services they provide, natural lands and ecosystems – particularly forests – serve as a stock of stored carbon and facilitate a flow of carbon from the atmosphere to further build up that stock. As a result, effective, data-driven siting and other land use strategies that balance land use priorities for conservation and sequestration with land use needs for new clean energy production and other human uses will be critically important going forward.

Bioenergy Availability and Impacts – Bioenergy production requires land, water, nutrients, and energy, often outside of a state's borders. Scaling the production of bioenergy resources in order to meet the fossil fuel replacement needs of whole sectors would put immense pressure on these resources, leading to indirect emissions and a range of socially unacceptable impacts.[8] Competition for other critically important uses of land functionally limit the ability to produce bioenergy locally, nationally,[9] or even globally. However, bioenergy should not be avoided entirely. Massachusetts currently generates zero-carbon energy from the conversion of organic waste to energy at several anaerobic digesters plants, most notably the resource recovery facility on Deer Island, and even a modest amount of dedicated bioenergy crops nationwide could be sustainably used to generate zero-carbon fuels for hard-to-electrify sectors such as aviation. Bioenergy is a valuable low- or zero-emissions fuel that is likely a necessary component of achieving Net Zero by 2050. However, it must be used strategically and with care to ensure that it avoids creating indirect emissions and stressing natural resources (See *Appendix: Modeling and Emissions Accounting of Biogenic Fuels*).

Low- and Zero-Carbon Combustible Fuels – Similar carbon tradeoffs, production constraints, and cost constraints also exist for other zero-carbon combustible fuels. First, there are competing needs for biomass or captured carbon, including as a feedstock for certain chemical processes (e.g. for production of plastics) that are anticipated to command a higher commercial value than as a combustion fuel. Second, once a low- or zero-carbon fuel is burned to power a useful energy end use, it releases the carbon back to the atmosphere, when instead the embodied carbon could have been sequestered and stored.

[8] *Intergovernmental Panel on Climate Change. Special Report on Global Warming of 1.5°C. https://www.ipcc.ch/sr15/ (2018).*

[9] *U.S. Department of Energy. 2016 Billion Ton Study Update. https://www.energy.gov/eere/bioenergy/2016-billion-ton-report (2016).*

These physical and economic constraints, as well as the related current and projected high costs of low- and zero-carbon fuels, are likely to limit their potential uses to certain high-value uses and sectors that are very difficult to electrify or otherwise decarbonize. The *Energy Pathways Report* demonstrates that net-zero fuels can be deployed more cost–effectively to displace the liquid fossil fuels used in heavy freight, aviation, and industrial processes, that require energy dense fuels. It is also worth noting that while the technologies to produce many zero-carbon fuels are relatively mature, few have yet been proven deployable at scale and at proven low cost. Strategies that rely on such fuels and, as a result, "lock in" combustion equipment for use through or beyond 2050 are at risk of these fuels failing to scale or remaining costly. Finally, dependence on out-of-state bioenergy resources would require spending outside of Massachusetts, lowering the levels of local spending, investment, and job creation that other lower cost and less risky decarbonization strategies promise.

[10] The same $30/MMBtu value was determined to be a reasonable estimate for renewable gas in 2050 based on a survey of recent studies including by the American Gas Foundation and based on consideration of the full range of potential feedstock as part of a recent study on building electrification prepared for the State of Rhode Island. Brattle Group (2020). Heating Sector Transformation in Rhode Island: Pathways to Decarbonization by 2050. http://www.energy.ri.gov/documents/HST/RI%20HST%20Final%20Pathways%20Report%204-22-20.pdf

Light-Duty Transportation

Contributions to Massachusetts Emissions

- Light-duty vehicles (LDVs) are currently responsible for about 27% of statewide emissions.

Transition Needed for Decarbonization

- By 2050, emissions from light-duty transportation will need to be reduced to nearly zero.
- The primary strategy to reduce light-duty transportation emissions is switching from fossil-fueled vehicles to zero emissions vehicles.
- This is supported by maintaining and supporting existing public transit systems, reducing single occupancy vehicle use where possible, making complementary land use decisions, and supporting active transportation infrastructure such as bike lanes and sidewalks.

Near Term Implications

- Given the expected pace of all new vehicle sales, the near term need to achieve significant emissions reductions, and the less-than-15 year average lifetime of most LDVs, it is critical that this transformation accelerate to scale as soon as possible.
- Deployment of EVs will require the development of dependable and accessible charging infrastructure throughout the Commonwealth and in residents' homes.

Continued Areas of Research and Further Investigation

- Development and deployment of policies and systems to enable and ensure managed charging, and
- Deployment of a statewide vehicle charging infrastructure strategy.

Complete adoption of zero emissions LDVs in 2050 would have public health benefits, including an estimated annual impact of:

27

avoided deaths from cardiovascular and respiratory illness.

1,700

days of work absences avoided.

$295 MILLION

in total health benefits.

NEARLY 4,000* JOBS

by 2050 will be created to support vehicle electrification and charging infrastructure.
*Deployed across the light, medium- and heavy-duty fleets.

Medium- and Heavy-Duty Transportation, Aviation, and Shipping

Contributions to Massachusetts Emissions

- Medium- and heavy-duty vehicles (MDHDVs), rail, and aviation are currently responsible for about 14% of statewide emissions.

Transition Needed for Decarbonization

- Battery-electric technology is emerging as a viable strategy for many MDHDVs classes. Given the diversity of duty-cycles and performance requirements, it is likely that an array of solutions, including hydrogen fuel cells and zero-carbon fuels, will complement electrification.
- Deployment of battery electric vehicles (BEVs) and hydrogen fuel cell electric vehicles (FCEVs) in the MDHDVs classes will require retrofits to depots and fueling stations to provide charging and/or hydrogen services.
- Given limited options for decarbonizing most commercial aviation, this sector will likely be a source of residual emissions in 2050, unless zero-carbon aviation fuels are rapidly scaled and become cost-effective.

Near Term Implications

- Decarbonizing this sector requires forward planning due to infrastructure needs and limited stock turnover points between now and 2050.
- Addressing issues including siting, permitting, interconnecting, rate design, and distribution system improvements are required to increase adoption.

Complete adoption of zero emissions medium- and heavy- duty vehicles in 2050 would have public health benefits, including an estimated annual impact of:

45

avoided deaths from cardiovascular and respiratory illness.

2,800

of work absences avoided.

$490 MILLION

in total health benefits.

NEARLY 4,000* JOBS

by 2050 will be created to support vehicle electrification and charging infrastructure. *Deployed across the light, medium- and heavy-duty fleets.

Residential and Commercial Buildings

Contributions to Massachusetts Emissions

- On-site combustion of fossil fuels in the residential and commercial buildings sectors – primarily for space and water heating – is currently responsible for about 27% of statewide GHG emissions.

Transition Needed for Decarbonization

- Electrification of space and water heating is a low-risk, cost-effective strategy for decarbonizing the majority of the Commonwealth's building stock.
- Investing in envelope efficiency drives down costs to consumers and the entire energy system.
- A limited amount of decarbonized fuels may be available and appropriate strategy for some buildings, but in order to achieve Net Zero, the use of gas for building heat must start to decline in the near term.

Near Term Implications

- Existing buildings: electrification and efficiency strategies rely on infrequent opportunities to change out heating, ventilation, and air conditioning (HVAC) equipment, such as equipment end-of-life or major renovation. Leveraging these opportunities early is essential for keeping costs low.
- New Construction: Buildings erected after 2025 less likely to be remodeled or have equipment reach end of life, which underscores the importance of enacting a high-performance code for new construction.
- Small residential buildings (<4 units) and single-family homes are relatively easy to modify and comprise over 60% of statewide building emissions. Residences built before 1950 have the most potential to lower occupant costs through energy efficiency upgrades.
- Larger, more complicated building typologies may necessitate more flexibility in both timing and technological solutions.

Complete electrification of heating in 2050 would have public health benefits including an estimated annual impact of:

200

avoided deaths from cardiovascular and respiratory illness.

12,400

days of work absences avoided.

$2.2 BILLION

in total health benefits.

OVER 5,400 JOBS

by 2050 will be created to support building electrification and efficiency.

Electricity and Energy

Contributions to Massachusetts Emissions

- The electricity system is currently responsible for about 19% of statewide emissions.

Transition Needed for Decarbonization

- As more end uses rely on the electricity system, the carbon intensity of emissions from the electricity system will need to approach zero at the same time as installed generating capacity more than doubles.
- Offshore wind and solar are the lowest cost low-carbon energy resources and will comprise the bulk of the Commonwealth's and the region's electricity generation in 2050; both must be deployed at scale (15-20 GW of each installed) in the Commonwealth over the next 30 years.
- A balanced range of complementary resources and technologies, including imported hydropower and additional high-voltage interstate transmission, is required to reliably operate a cost-effective, ultra-low emissions electricity grid based on variable renewable resources.
- Specific reliability resources (infrequently used thermal capacity without carbon capture, and/or new bulk storage) will be needed

Near Term Implications

- Decarbonization requires a comprehensive plan focused on a rapid deployment of renewables—the siting and construction of offshore wind and ground-mounted solar generation at scale, reliable balancing, and planning for limited land and bioenergy resources.
- Coordination across the Northeast will be necessary to transition to a clean, affordable, and reliable low-carbon, 21st century grid, including system planning and development of new markets by the grid operation

Near complete adoption of renewable electricity generation in 2050 would have public health benefits including an estimated annual impact of:

18

avoided deaths from cardiovascular and respiratory illness.

1,000

days of work absences avoided.

$190 MILLION

in total health benefits.

MORE THAN 10,000 JOBS

will have been created annually to support the development of a low carbon grid.

Non-Energy and Industry

Contributions to Massachusetts Emissions

The subsectors referred to as Non-Energy and Industrial emissions include:

- industrial energy and process emissions,
- fluorinated greenhouse gases (F-gases),
- solid waste management,
- wastewater treatment,
- natural gas transmission and distribution, and
- livestock and agricultural soils.

Non-energy and industrial emissions account for about 12.5% of statewide emissions.

Transition Needed for Decarbonization

- While a relatively small source of emissions collectively, emissions from industrial and non-energy sources are likely to be a significant portion of the Commonwealth's residual emissions in 2050 (3-5 $MMTCO_2e$ or about one-third of 2050 statewide emissions).
- These sources are among the most challenging to decarbonize and their emissions are intrinsically linked either to basic economic activity or to the population and are thus expected to remain in 2050.

Near Term Implications

- Despite the difficultly of emissions reductions in some of these subsectors, active management and best practices are necessary to achieve Net Zero.
- Phasing out high-global warming potential (GWP) fluorinated gases will reduce potential non-energy emissions substantially, but requires early action due to stock-turnover dynamics of equipment, particularly with increasing use of heat pumps.

Natural Carbon Sequestration

Contributions to Massachusetts Emissions

Massachusetts forests are projected to have the capacity to sequester about 5 $MMTCO_2e$ per year from now through 2050. This is equivalent to roughly 7% of the Commonwealth's current emissions and roughly half of allowable residual emissions in 2050.

Transition Needed for Decarbonization

- Ensuring the viability and health of the Commonwealth's existing 3.3 million acres of forested land is the primary strategy to ensure this sequestration potential is available in 2050.

Near Term Implications

- Encouraging dense development and best management practices for commercial timber harvesting can increase forest carbon sequestration, but only minimally; neither has the potential to significantly alter the 2050 sequestration potential of Massachusetts forests.

Continued Areas of Research and Further Investigation

1. Gaining a more complete accounting of land use impacts on human and natural systems to understand the long-term systemic effects and the balance of ecosystem benefits, and

2. Exploring the treatment of atmospheric carbon removals outside of Massachusetts' borders.

Additional Carbon Dioxide Removal

Contributions to Massachusetts Emissions

- By 2050, Massachusetts will need to have developed and secured at least 4-9 $MMTCO_2e$ of annual sequestration services beyond those that can be provided by the Commonwealth's own natural and working lands.

Transition Needed for Decarbonization

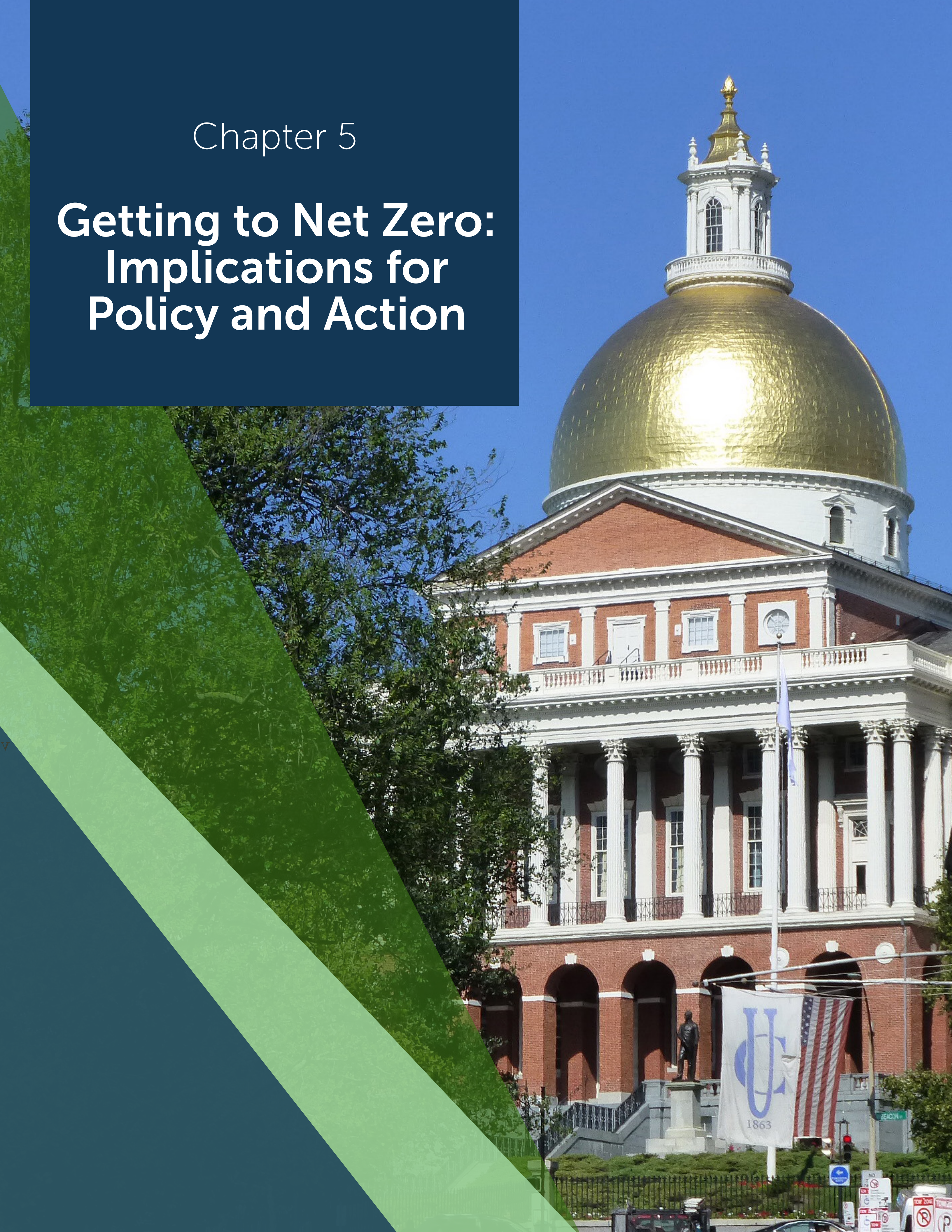
- Although mechanical and other carbon dioxide removal technologies are likely needed, the bulk of the Commonwealth's required sequestration could likely be provided at low cost by neighboring states and provinces pursuant to a regional effort to protect and enhance natural carbon stocks and sinks.

Continued Areas of Research and Further Investigation

1. Better understanding of forest carbon storage and improved measurement techniques, and
2. Further assessment of carbon dioxide removal strategies and their broader impacts.

Chapter 5

Getting to Net Zero: Implications for Policy and Action



Achieving Net Zero by 2050 will require significant transformations across the Commonwealth. The strategies and findings described in this Roadmap Report illustrate that Massachusetts has a robust, though not unlimited, range of viable options for deep decarbonization which will allow us to achieve our climate change mitigation goals at reasonable costs and using technologies and solutions that are known and, for the most part, available today. Importantly, these findings also demonstrate that working to achieve Net Zero will also provide broad and substantial economic opportunity and public health benefits to everyone in Massachusetts. In particular, transitioning away from the use of fossil fuels across the economy promises to deliver significant improvements in air quality and health benefits to overburdened Environmental Justice populations and communities of color.

As discussed herein, there are distinct tradeoffs in terms of costs, co-benefits, and risks among and between decarbonization pathways more broadly, and specific implementation actions more narrowly. But across pathways, certain strategies emerge as, essentially, "no regrets" near-term opportunities that can deliver required emissions reductions while maintaining future optionality and reducing future risk. Key among those opportunities is beginning to leverage stock roll-over, and its inherent cost-savings, immediately by accelerating the deployment of 2050-compliant solutions today across the buildings, transportation, and electricity sectors. The most cost-effective (and perhaps the only feasible) ways for Massachusetts to achieve our required near-term emissions reductions include increased regional coordination – particularly regarding transportation fuels and energy system planning – and the electrification of residential and small business building heating and of passenger cars and trucks. These near-term actions also set the Commonwealth up to achieve the much deeper reductions and carbon removal that Net Zero requires in the longer-term.

> We have decided not to aim for what we know to be possible, but what we know to be necessary. Our task is now to make the necessary possible.
>
> **Dan Jørgensen, Danish Minister for Climate, Energy and Utilities**

New, transformed, and expanded markets will play a critical role in achieving Net Zero. Many, if not most, of the Commonwealth's and the region's existing energy-related markets will need to be reshaped either directly through intentional redesign or indirectly in response to increasingly stringent, mandatory emissions limits. Investments made today in new, innovative technologies and approaches to decarbonization – particularly in the transportation and buildings sectors, where success depends upon millions of individual transactions – can help the Commonwealth achieve our Net Zero emissions goal at a faster pace and at a lower cost. Continued active leadership from the Commonwealth in this respect will be instrumental in achieving Net Zero by 2050 and doing so affordably; but it appears practically, if not technically, impossible for Massachusetts to reach that overall goal in isolation or through state-level policies alone. Federal policies that actively support state decarbonization efforts, as well as strong regional coordination, are necessary for the Commonwealth's ultimate success.

The pace and scale of transformation that will be required to achieve Net Zero demands that close attention and vigilant care is given to mitigate any undue or avoidable impact or burden on Massachusetts' residents across the Commonwealth's entire economic, social, and geographic diversity. While similar care and attention must also be paid to potential impacts and burdens on the Commonwealth's natural resources and on our economy-sustaining business community, the greatest concern and urgency pertains to the Commonwealth's disproportionately over-burdened EJ populations. It is a top priority to ensure that the benefits from climate mitigation actions are realized by those who have borne the disproportionate burden of historic and current fossil fuel pollution.

Despite the clarity that the Roadmap Study has provided regarding the main strategies and dynamics that will shape the Commonwealth's achievement of Net Zero in 2050, many details of this major, long-term transition must still be carefully and thoughtfully determined with widespread, active public engagement. However, with a sincere commitment to on-time, near-term action and sustained collaboration, the Commonwealth can and will achieve Net Zero and the widespread environmental, economic, and health benefits it will deliver.