MASSACHUSETTS 2050
DECARBONIZATION ROADMAP

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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Acronyms

°C	Degrees Celsius
°F	Degrees Fahrenheit
ASHP	Air-Source Heat Pump
BEV	Battery Electric Vehicle
CCS	Carbon Capture and Storage
CDR	Carbon Dioxide Removal
CES	Clean Energy Standard
CH_4	Methane
CO_2	Carbon Dioxide
DER	Distributed Energy Resources
EEA	Massachusetts Executive Office of Energy and Environmental Affairs
EJ	Environmental Justice
EV	Electric Vehicle
GHG	Greenhouse Gas
GSHP	Ground-Source Heat Pump
GWP	Global Warming Potential
GWSA	Global Warming Solutions Act
ICE	Internal Combustion Engine
LDV	Light-Duty Vehicle
MDHDV	Medium- and Heavy-Duty Vehicle
$MMTCO_2e$	Million Metric ton (tonne) of CO_2e
N_2O	Nitrous Oxide
$PM_{2.5}$	Particulate Matter (2.5 micrometers or less)
PV	Photovoltaic
RPS	Renewable Portfolio Standard
VMT	Vehicle Miles Traveled
W	Watt
Wh	Watt-hour
ZEV	Zero Emissions Vehicle

Letter from the Secretary

From coast to coast, the impacts of a changing climate are already on full display in the United States. Here in Massachusetts, climate change presents unique challenges, from intense heat waves and droughts, storm surges and flooding, to increases in insect-related diseases such as Eastern Equine Encephalitis and West Nile Virus. The climate crisis is a generational challenge that, without decisive action, leaves residents and communities across the state on the front lines. Recognizing the urgency of this crisis, the Baker-Polito Administration listened to the science, and set Massachusetts on an aggressive path to Net Zero greenhouse gas emissions by 2050

Reducing emissions to achieve Net Zero by 2050 is the Commonwealth's primary and most important line of defense in preventing the significant threats presented by a changing climate. To achieve this target in a cost-effective and equitable manner, the Baker-Polito Administration launched a comprehensive process to chart pathways and strategies to meet this ambitious commitment. The resulting process, culminating in the 2050 Decarbonization Roadmap, included significant stakeholder engagement, science-based analysis, and a focus on reducing costs for residents and businesses while maintaining a healthy, thriving economy.

Addressing climate change will also protect the Massachusetts economy, as analysis from the U.S. Environmental Protection Agency in 2015 found that reducing emissions will save the Northeast region at least $3 billion per year by 2050 and $42 billion per year by 2090. The 2050 Decarbonization Roadmap also makes clear that achieving Net Zero emissions will lead to the creation of thousands of local jobs while dramatically improving air quality and public health.

At a time when the nation and the world are grappling with a global pandemic, we are reminded that climate change presents a still greater long-term threat, and one for which there will be no vaccine. Achieving Net Zero by 2050 will require deep change and out-of-the-box thinking, and this report underscores the importance of local and regional partnerships to build stronger, more resilient communities, nation-leading clean energy jobs, and a vibrant economy.

Sincerely,

Kathleen Theoharides
Secretary of Energy and Environmental Affairs

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Reliability Resources

Although highly reliable and predictable on a daily and seasonal basis, renewable resources such as wind and solar power must be complemented by a range of resources both on the demand-side and on the supply-side, due to their inherent variability and in order to ensure the reliability of the electricity grid in every hour of the year.

A variety of different demand-side technologies – many in use today – can help to manage hourly and daily flows and peaks in electricity demand. Flexible loads improve system-wide performance by shifting the time of energy demand from periods with low electricity supply to periods of higher supply. Notably, buildings with tighter envelopes allow for more flexibility in space heating while maintaining indoor comfort due to lower levels of thermal losses. Many flexible loads are enabled by small-scale battery storage, such as those found in EVs, which can shift charging from the early evening to later at night. Load shifting flexibility is already offered in many high-efficiency electric end uses, but it requires deployment of millions of devices in order to aggregate to a useful grid asset. In general, with flexible end uses widely deployed, these resources will enable power grid operators to compensate for short periods – a few minutes or hours at a time – in which electricity demand exceeds renewable supply.

Sometimes renewable supply may be far greater than electricity demand, especially at night when most household and business energy use is dormant, but wind is still blowing steadily off the coast. Industrial electric conversion loads are large, flexible sources of electricity demand which are connected to the electricity system and operate when renewable generation is abundant. While flexible loads play a role when supply is insufficient to meet demand and electricity prices are high, electric conversion loads operate when supply is consistently greater than demand. They help optimize the energy system so that renewable production exceeding demand can be harnessed for useful purposes, rather than being curtailed (wasted). Examples of such loads include hydrogen electrolysis (the process of making hydrogen using electricity), and other innovative solutions like using electricity instead of fuel in dual-fueled boilers for industrial applications.[42] Note that electric conversion technologies do not need to run at any specific time but can be dispatched on an as-needed basis.

The University of Massachusetts Amherst Central Heating Plant, pictured above, provides 70% of the campus' electricity and 100% of its steam needs from natural gas. In the future, district heat systems such as this could operate using the dual-fuel approach that leverages electric boilers when renewable energy is abundant and low-carbon gas at other times. Photo credit: UMass Amherst

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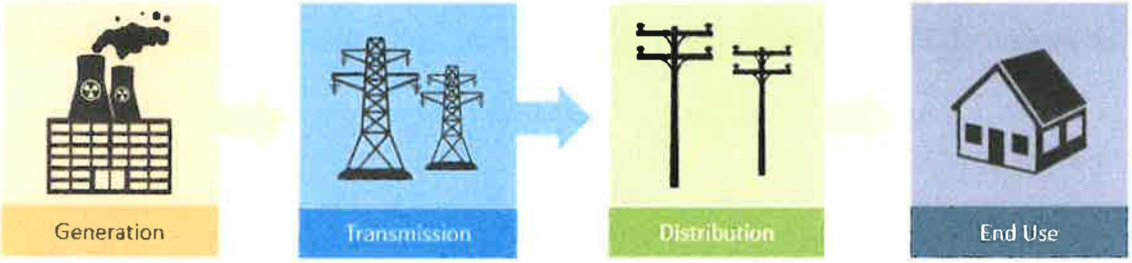
[44] *The Commonwealth supports development of both technologies through grant programs at MassCEC.*

Shifting from a Fossil Fuel Grid to a Renewable Energy Grid

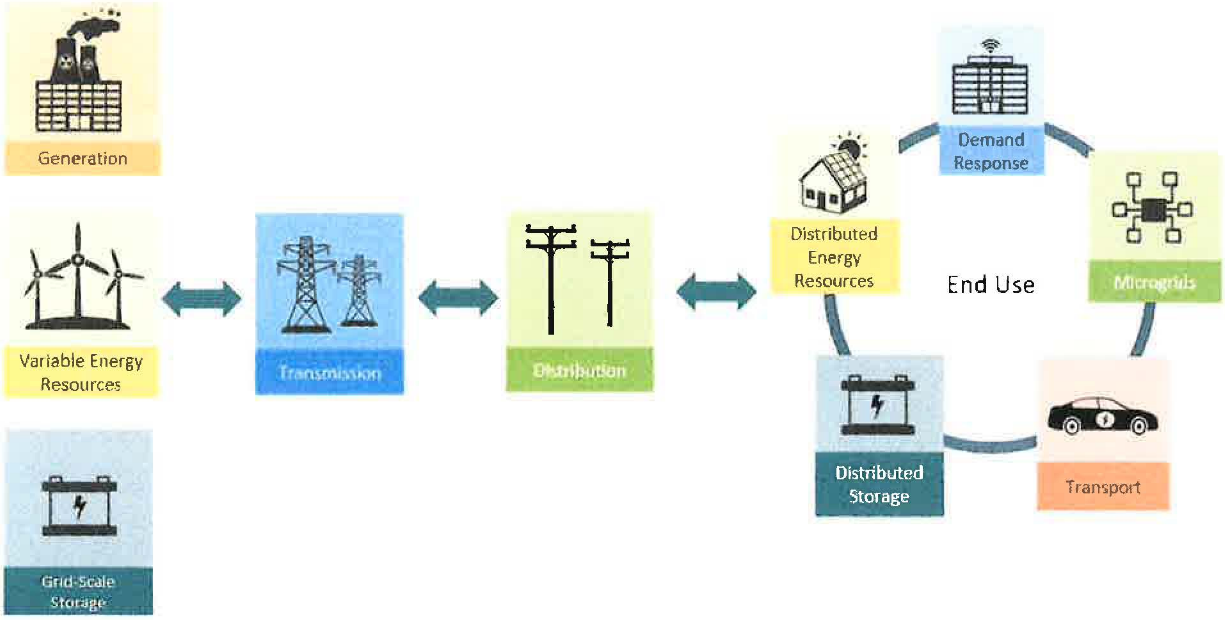
The Northeast electricity system today has been designed to balance electricity demand with centralized large-scale fossil fuel, hydropower, and nuclear resources. Traditionally, the flow of electricity has gone one-way, from the generation source to the customer (Figure 14).

Figure 14. Traditional flow of electricity, from generation to end use.



In order to meet future decarbonization goals, the electricity system will need significantly more renewable resources. As renewables, new energy resources, technologies, microgrids, and end uses interact with the electricity system, we will need to adapt the grid. Electricity system components of the 21st century grid, like two-way flows of power and variable renewable resources, require a more dynamic grid to respond to electricity supply and demand in real-time (Figure 15).

Figure 15. Components of a decarbonized electricity system



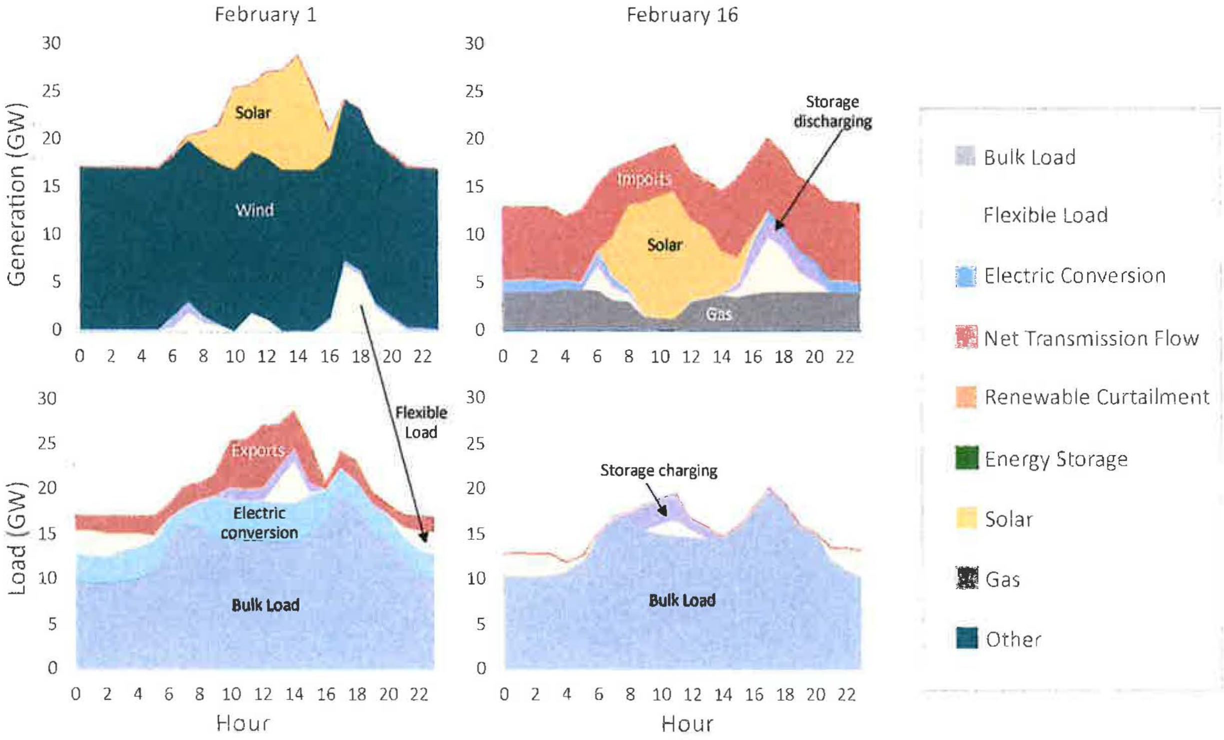
There is no single solution for decarbonizing energy supplies; decarbonization requires a comprehensive plan focused on a rapid deployment of renewables, reliable balancing, and planning for limited land and bioenergy resources

Two Days In February 2050: An Illustration Of Reliable Low-Carbon Electricity Supply In An Electrified Future

Figure 16 illustrates how an integrated portfolio of clean energy, flexibility, and other reliability resources are used to meet electricity demand with an electricity grid dominated by variable renewable generation. Two example days in 2050 are shown, February 1 and February 16, with the generation mix for each day in the top row and the overall demand in the bottom row. These generation mixes illustrate the performance and operation of a Net Zero-compliant 2050 generation fleet using actual New England weather data from 2012. The key difference between the two days is that there is ample wind resource available on February 1 and nearly none on February 16, as was the case in February 2012 and can be expected normally around a dozen times a year, for up to several days at a time.

The system that results from a lack of offshore wind generation is illustrated on the right-hand side of Figure 16. Resources needed to ensure a reliable electricity supply during such a sustained low-wind period include clean electricity imported over interstate transmission lines, wholesale "bulk" energy storage, flexible demand-side load (including from EV charging and other distributed batteries and resources), and gas-fired thermal generation. For the vast majority (~95%) of hours and days, renewable generation either meets or exceeds the bulk of Massachusetts' demand – as shown by the February 1 day – facilitated by shifting flexible loads, like EV charging, to late-evening hours. Note the significantly different role transmission imports and gas generation play to meet demand across these two days.

Figure 16. Example days illustrating the variability of renewables and the need for balancing resources. Data from the All Options pathway in the Energy Pathways Report.



Longer periods of low renewable generation require a different scale of resources to help maintain the reliability of the grid. Although offshore wind represents a rich renewable resource for New England, episodically throughout the year (a total of about 12 days during the 2012 data year used for the Roadmap Study), the wind can be expected to "die down" for as many as 36 hours at a time.[45] A variety of resources is expected to be the most economical solution to provide the large-scale, long-duration reliability services necessary to complement offshore wind.

Particularly in this respect, the abundant hydropower available in New England, New York, Quebec, and New Brunswick represents a valuable resource for New England. The cumulative quantity of stored energy in dammed reservoirs is a key solution to balance and manage a regional electricity system with high penetrations of renewable generation. Unlike most traditional dispatchable generation resources, such as coal power, gas generators, and oil plants, hydropower is a clean generation resource that is nevertheless highly controllable and effectively dispatchable at-will. The New England Clean Energy Connect 100% Hydro project[46] will provide 9.5 Terawatt-hours of clean hydropower and increase regional transmission capacity by more than 1 GW.[47] Because renewable generation variability is rooted in geographically distinct zones, transmission capacity can be used to optimize systemwide efficiency across broader geographies. Since, on any given day, it might be sunny in Rhode Island, but cloudy in New Hampshire – or perhaps windy off Long Island but calm in the Gulf of Maine – intrastate and intraregional transmission can be used to export excess generation during times of high renewables and import external resources during times of low renewables.

With the closure of Pilgrim Nuclear Power Station in Plymouth in 2019, New England currently has two nuclear generating facilities – in Seabrook, NH, and Millstone, CT – supplying about 20% of load in New England.[48] However, nuclear reactors take considerable time to heat up and cool down, meaning that these resources cannot easily respond to fluctuations in electricity demand. Further, the high construction costs of nuclear make it a very expensive resource to use only intermittently. If offshore wind resources cannot be fully realized, new nuclear resources would be an economically viable alternative for supplying low-carbon electricity, but concerns about safety and the disposal of radioactive waste make it unlikely that new nuclear resources would be sited in New England in the future. Future breakthroughs in small modular reactor technology or even fusion technology could change both of these dynamics, but neither technology has been, or appears likely to be, commercialized and affordably deployable during the timeframe of the Roadmap Study.

Currently, the lowest cost method for maintaining reliability on the few days each year with very low renewable energy production is the intermittent use of thermal power plants, primarily gas-fired power plants. Due to the low capital costs associated with gas-fired electricity, their relatively low emissions profile, and because of the speed with which a gas plant can be turned on to produce electricity, these already-existing resources are compatible with providing electricity when wind power is unavailable. As the quantity of renewables on the system grows, Massachusetts' use of, and reliance on, gas-fired generation will decline precipitously; these units could continue to be both useful and valuable but serve in a new role as a long-duration reliability resource. In such a role, the use of gas-fired generation in 2050 would be minimal and fully consistent with achieving

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[45] *Solar has a more variable daily and seasonal production potential but is not as abundant of a resource in New England as in other parts of the country with much greater average solar irradiance.*

[46] *Awarded under the charge of Section 83D of the Massachusetts Green Communities Act.*

[47] *Green Communities Act, Ch. 169 of the Acts of 2008, §83D, as amended by the Act to Promote Energy Diversity, Ch. 188 of the Acts of 2016, §12. https://malegislature.gov/Laws/SessionLaws/Acts/2016/Chapter188.*

[48] *ISO New England. Resource Mix (2020). https://www.iso-ne.com/about/key-stats/resource-mix/.*

Cost And Land Implications Of Retiring All Thermal Generation

Based on the best available information today, Massachusetts' existing gas thermal capacity, combined with an expansion of regional transmission to tap into clean imports from across the region, can provide required stability on the grid during periods with very low offshore wind production at least-cost, while still achieving a 99% abatement of the electricity system's total annual carbon emissions. Restricting either regional transmission buildout or retiring existing thermal capacity – in the absence of a technological, cost, and commercialization breakthrough in long-duration energy storage or another dispatchable resource – could have significant cost and resource tradeoffs.

The *Energy Pathways Report* analyzed a case where all thermal generation in New England was fully retired by 2050. In the absence of these units operating as a low-cost reliability resource, the analysis indicated the need for deploying a large quantity of novel and likely expensive, long-duration, grid-scale battery storage as well as a significant increase in new clean generation – mainly low-cost ground-mounted solar – needed to charge it. This new and unique large scale storage requirement added a 15% increase in overall system costs (about $4 billion dollars a year by 2050) which would be expected to be passed onto Massachusetts residents and businesses through utility bills (Figure 17). This scenario with No Thermal generation also increased costs because it required nearly 40 GW of ground-mounted solar in Massachusetts alone, likely consuming about 158,000 acres of land – or about 3% of Massachusetts' total land area – and more than double the land use requirements of other pathways analyzed (Figure 18).

Figure 17. Average societal electricity rate ($2018) by component, across years and between pathways.

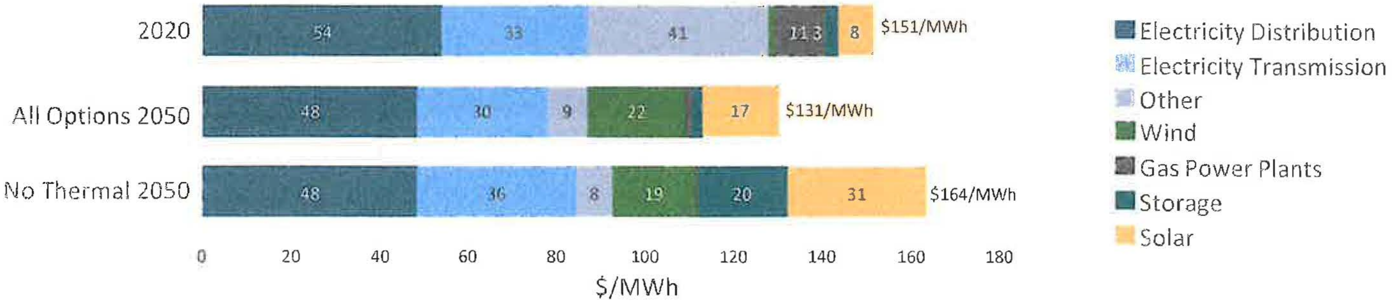
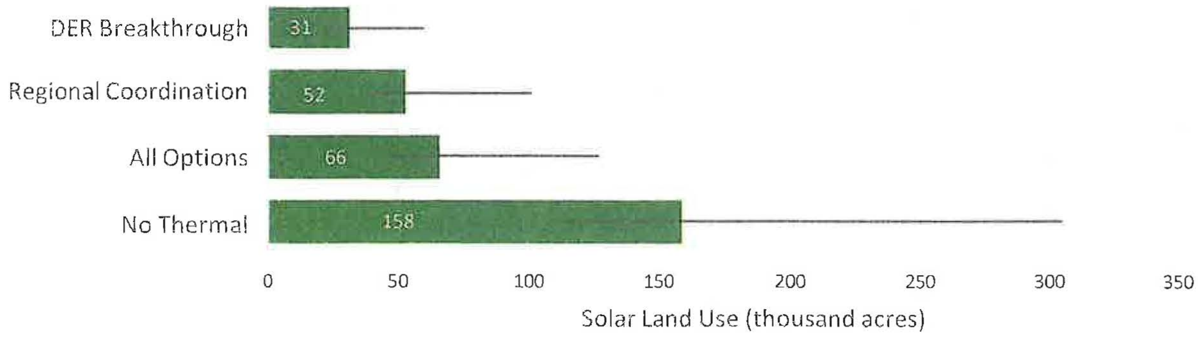


Figure 18. Ground-mounted solar PV land use estimates across pathways. Error bars show high and low land use estimates based on project design and technology progression. Fifty thousand acres represents approximately 1% of Commonwealth land area. Refer to Table 1 for a description of pathways.

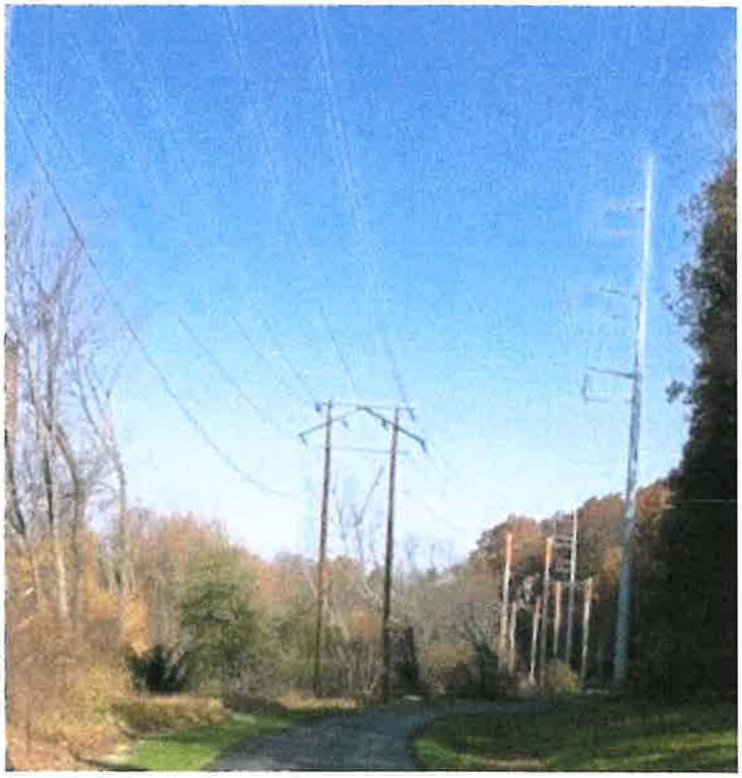


Net Zero emissions statewide. Electricity-sector emissions with infrequent gas generation used only for system balance would closely approach, but not reach, zero by 2050. Blending hydrogen produced from excess renewables during periods of high production and low demand could further reduce those residual electricity sector emissions, as could deploying zero-carbon fuels or employing carbon capture (although carbon storage is extremely limited in New England).

Implications and Policy Context

The deployment of renewable energy resources is the foundational step in developing a low-cost and largely decarbonized energy supply for Massachusetts. The development of offshore wind not only provides an affordable, clean energy resource for the Commonwealth, but also the region more broadly. Offshore wind development at the scale forecasted by the *Energy Pathways Report* will allow Massachusetts to become an energy exporter during many high-generation hours of the year. This is particularly valuable for neighboring states and provinces, which may not have as direct access to or the ability to actively develop large offshore wind resources. Further, the ability to export offshore wind power to Quebec can enable the optimal use of hydropower and offshore wind resources across the broader Northeastern region, with Canadian hydropower serving effectively as a regional storage resource for hours when wind is less abundant in New England. This sharing of resources has an added benefit of reducing costs for ratepayers in the Commonwealth and across the Northeast. Massachusetts' commitment to the responsible development of local renewable offshore wind resources off the New England coast not only helps to facilitate decarbonization in the Commonwealth, but also helps to drive down emissions and costs across the Northeast.

In order to support decarbonization across the economy in the timeframe required to achieve Net Zero by 2050, new renewable generation and necessary supporting infrastructure must be sited and placed in operation at a pace that is much faster than historic or current levels. Under all scenarios examined, several new, large transmission lines (to the North and to the West) – each of which will take almost a decade to plan, site, and construct – are required in order for Massachusetts to have access to sufficient clean electricity and to maintain system reliability. At the same time, Massachusetts and the region must site and construct offshore wind and ground-mounted solar generation at scale,[49] installing on average about 1 GW each year, from 2030 to 2050, regionwide.



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[49] *As explored in detail in the Energy Pathways Report, even if every rooftop with solar access in Massachusetts was covered in solar panels, some 30,000 - 40,000 acres of ground-mounted solar installed in the Commonwealth would still be required to achieve Net Zero.*

New England States' Vision For A Clean, Affordable, And Reliable 21st Century Regional Electric Grid

In light of the technical analysis presented in the *Energy Pathways Report* and similar decarbonization studies underway in other New England states, and pursuant to a shared understanding of the "need for a decarbonized regional grid capable of supporting the accelerated adoption of more sustainable electric, heating, and transportation solutions for families and businesses," Massachusetts, Connecticut, Maine, Rhode Island, and Vermont released a statement of their vision and requirements for a clean, affordable, and reliable 21st century regional electric grid on October 16, 2020.[50]

Agreeing that "a clean, affordable, and reliable regional electric grid – together with transparent decision-making processes and competitive market outcomes that fully support clean energy laws – is foundational to achieving our shared clean energy future," the five states, representing more than 90% of all energy system users and purchasers in New England, specified their need for "a regional electricity system operator and planner that is a committed partner" in the states' decarbonization efforts, that will:

1. Proactively develop market-based mechanisms, in concert with state policymakers, that facilitate growth in clean energy resources and enabling services, while fully accounting for ongoing renewable energy investments made pursuant to enacted state laws;
2. Conduct best-in-class system planning activities that proactively address the states' clean energy needs;
3. Ensure grid resiliency and reliability at least cost in a manner that is responsive to state and consumer needs; and
4. Adopt an organizational mission and structure to reflect the states' required energy transition and establish a higher degree of accountability and transparency to the participating states and other stakeholders.

Maintaining high levels of year-round system reliability on a grid dominated by renewable generation resources presents several additional challenges, particularly when considered under today's approach to grid operations. Thermal generators that have traditionally operated by following electricity demand will need to shift to a "peaking" or "gap-filling" reliability role in the coming decades as they operate fewer and fewer hours and cease to be providers of bulk electricity. In the *Energy Pathways Report*, thermal generators operating 50% of the time today are projected to operate around 5% of the time in a decarbonized system. While breakthroughs in long duration storage technologies could replace the need for retaining thermal capacity for reliability, the technology has yet to be proven at scale and is not necessary in order to achieve Net Zero. Forcing the retirement of all thermal capacity in the electricity system, rather than capping or managing emissions and operational profiles as part of new reliability service markets, represents an unnecessary operational risk to the regional energy system that is likely to ultimately result in higher costs for consumers and higher environmental impact.

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[50] *Full text at: http://nescoe.com/resource-center/vision-stmt-oct2020/*