

Carbon Free Boston

Energy Technical Report 2019



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Carbon Free Boston: Energy Technical Report

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Carbon Free Boston: Summary Report

Carbon Free Boston: Social Equity Report

Carbon Free Boston: Technical Summary

Carbon Free Boston: Buildings Technical Report

Carbon Free Boston: Transportation Technical Report

Carbon Free Boston: Waste Technical Report

Carbon Free Boston: Offsets Technical Report

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1 SUMMARY OF KEY POINTS

1. Energy is delivered to the City of Boston via the electric power grid, the natural gas pipeline distribution system, the delivery of fuel oil and transportation fuels, and cross-boundary district energy systems. Each must be converted to clean energy to meet the City's GHG mitigation goal.
2. State law, the Massachusetts Clean Energy Standard, will require that retail electricity sales are less carbon intensive each year until 80 percent of all electricity sales are from clean energy sources in 2050.
3. The City can target a procurement date for 100 percent carbon free electricity as late as 2050 to meet its carbon neutrality commitment. Accelerating the procurement schedule to achieve 100 percent carbon free electricity as early as 2030 will likely be the most effective action to achieve its interim target of 50 percent reduction by 2030 and align itself with global deep decarbonization efforts.
4. There are three dimensions to the options for decarbonizing Boston's electricity supplies by 2050: the sources of carbon-free electricity to be purchased, the mechanism by which the supplies are purchased, and the timing or phasing of the purchases.
5. Electricity purchases in the near-term will probably consist of a portfolio of solar PV, onshore wind, and offshore wind. Additional sources of carbon free electricity (hydro or carbon capture and storage) could also be considered. The timing of procurement will greatly influence the cost of such a procurement
6. With respect to electricity procurement mechanisms, the three main, nonexclusive options are (1) buying MA Class I Renewable Energy Certificates (RECs), (2) purchasing carbon-free electricity directly from a producer via a local ISO-NE power purchase agreement (PPA), and (3) entering into a virtual power purchase agreement (VPPA) with verified additionality.
7. Any specific generation (e.g., PPA or VPPA) source options competitively sourced by the City should be evaluated in regard to cost to Boston electric customers, equity, economic development, and contribution to resilience.
8. Sustainably-sourced renewable fuels are likely to be in limited supply, but could power systems that are difficult to electrify. Hydrogen could play a role, but the costs of converting systems hydrogen are substantial.
9. District energy systems will need to be decarbonized. This will necessitate improving the efficiency of the district systems and identifying a carbon-free energy source.
10. Boston can accelerate the transition to carbon neutrality across the entire New England region while simultaneously setting an example for all global climate policy stakeholders. Boston's purchase of clean electricity will accelerate climate policy if it enables a new clean energy technology to achieve a market breakthrough it would otherwise not achieve.

2 INTRODUCTION

The adoption of clean energy in Boston's buildings and transportation systems will produce sweeping changes in the quantity and composition of the city's demand for fuel and electricity. The demand for electricity is expected to increase by 2050, while the demand for petroleum-based liquid fuels and natural gas within the city is projected to decline significantly. The city must meet future energy demand with clean energy sources in order to meet its carbon mitigation targets. That clean energy must be procured in a way that supports the City's goals for economic development, social equity, environmental sustainability, and overall quality of life. This chapter examines the strategies to accomplish these goals.

Improved energy efficiency, district energy, and in-boundary generation of clean energy (rooftop PV) will reduce net electric power and natural gas demand substantially, but these measures will not eliminate the need for electricity and gas (or its replacement fuel) delivered into Boston. Broadly speaking, to achieve carbon neutrality by 2050, the city must therefore (1) reduce its use of fossil fuels to heat and cool buildings through cost-effective energy efficiency measures and electrification of building thermal services where feasible; and (2) over time, increase the amount of carbon-free electricity delivered to the city. Reducing energy demand through cost effective energy conservation measures will be necessary to reduce the challenges associated with expanding the electricity delivery system and sustainably sourcing renewable fuels.

3 FUTURE DEMAND FOR ENERGY IN BOSTON

During the next 30 years, the demands for energy will be influenced by changes in the city's economic activities, demographics, weather patterns, transport infrastructure and travel patterns, building stock, and many other factors. Electrification of the transport sector and building thermal services will have significant impacts on the amount and time of use of electricity. Demand reduction in these sectors can moderate these impacts. Rooftop solar will provide a measurable portion of the city's electricity demand during the daytime. In addition, actions that change demand response and storage policies will also change the hourly and seasonal shape of power demand, which, in turn, will influence grid carbon emissions. Fuel use will decline substantially.

Table 1. Changes in energy use (TWh) across key sectors under alternative future scenarios

Other fuels include those used by the MRWA, MBTA and MASSPORT to provide backup, process, and off-road services. Levels for these are assumed to be the same in all future scenarios. TWh is used as a unit due to the future focus on system electrification. Source: Model calculations

Sector	Current Demand (2015)		2050 Baseline		2050 Demand Efficiency + Electrification		2050 Electrification Only	
	Electricity	Fuels	Electricity	Fuels	Electricity	Fuels	Electricity	Fuels
Transportation	0.1	7.3	0.4	4.0	0.9	0.4	1.0	0.4
Buildings	6.4	12.1	7.2	11.7	6.5	2.9	9.3	3.6
Other		0.4		0.1		0.1		0.1
Total	6.5	19.7	7.6	15.9	7.4	3.4	10.3	4.1

In the *Carbon Free Boston: Buildings and Transportation Technical Reports* we presented illustrative scenarios that coupled the actions of aggressive energy conservation and electrification. Here we combine the results of those sectors to further illustrate the impact on energy consumption both in aggregate (Table 1) and in an approximate hourly analysis. Our hourly analysis does not aggregate

hourly demand from other sectors such as street lighting, wastewater treatment or industrial due to lack of data. Despite these data deficiencies, this analysis is sufficient to frame the transitions and to evaluate the impacts of the two potential extreme pathways to carbon neutrality.

The combined effects of increased electricity use are shown below over the course of a year (Figure 1) and on selected seasonally-representative days (Figure 2). Currently, the peak demand for total energy in Boston occurs on very cold days in the winter when demand for heating energy is highest. That heat is currently supplied predominantly by natural gas, and to a lesser extent by heating oil and electricity. Peak demand for electricity occurs in the summer, often during the afternoon and early evening on very hot days when air conditioning consumes a lot of electricity. Electrification will shift peak demand from summer to winter, and if pursued without any demand reduction (in transportation and buildings) will also result in total annual demand to increase substantially. Aggressive demand reduction can significantly reduce electricity consumption to a degree that offsets the increasing demand of thermal and vehicle electrification. However, even under this situation, winter demand still increases significantly although summer demand drops.

Figure 3 contextualizes these changes in terms of the relationship between energy use and temperature. Currently, Boston's electricity demand peaks on the hottest days of the year as space cooling spikes. Energy conservation measures such as envelop improvements, reduces this demand for cooling, while thermal electrification increases electricity demand during the coldest hours of the year. Base load demand declines, while the number of peak hours and the magnitude of them increase significantly.

Changes in the quantity and time profile of Boston's demand for clean electricity will have ripple effects across the ISO-NE grid. These changes will require strategic management both at the grid and the local level. For example, the application of storage and demand response technologies at the local level will substantially change the shape of the future curves in Figures 1, 2 and 3. Onsite solar will depress mid-day demand, which does not often occur during peak hours. While these technologies can help to manage this transition, meeting the high peak demand with intermittent sources will require the development of significant generation capacity and grid management solutions. The ISO-NE Grid will need to adapt to this changing landscape as intermittent supply and demand grows.

While such issues may not be an issue in the near term, in the long-term Boston's procurement of renewable energy will need to take the time-value of generation and demand into account. For now, large purchases of additional clean electricity will move the entire system towards greater levels of clean energy regardless of whether the time patterns of Boston's purchase and use are exactly matched to the grid's supply. An early procurement of renewable energy by Boston alongside actions to promote electrification will signal the need to develop solutions to enable and accelerate this transition.

Figure 1. The Impacts of Energy Efficiency and Electrification.

Daily city-wide energy demand for natural gas and electricity in 2015 (left) and 2050 (middle and right). The values represent the maximum hourly quantity of electricity or gas consumed in a given day. The Electrification Only scenario reflects deep electrification of the buildings and transportation sectors, with no additional action by the City to improve energy efficiency in buildings, or to dampen the demand for travel in personal EVs. In the third scenario (far right), deep electrification is coupled with deep efficiency gains and demand reduction in the buildings and transportation sectors. Source: model calculations

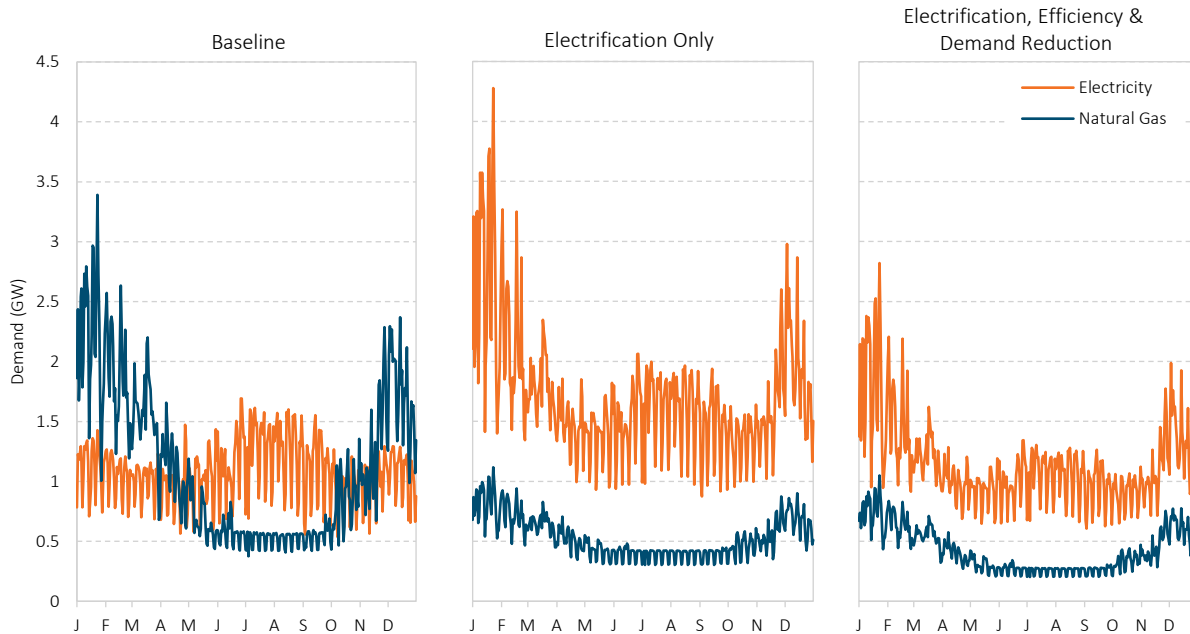


Figure 2. Hourly electricity demands for a current and Electrification plus Efficiency 2050 Scenario

Source: Model calculations

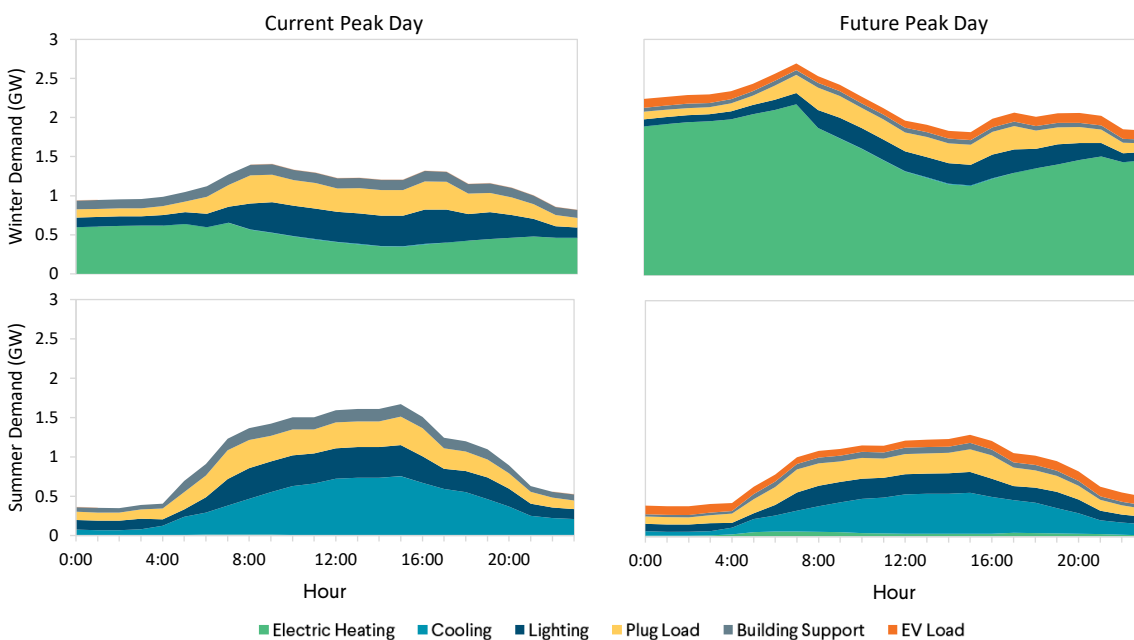
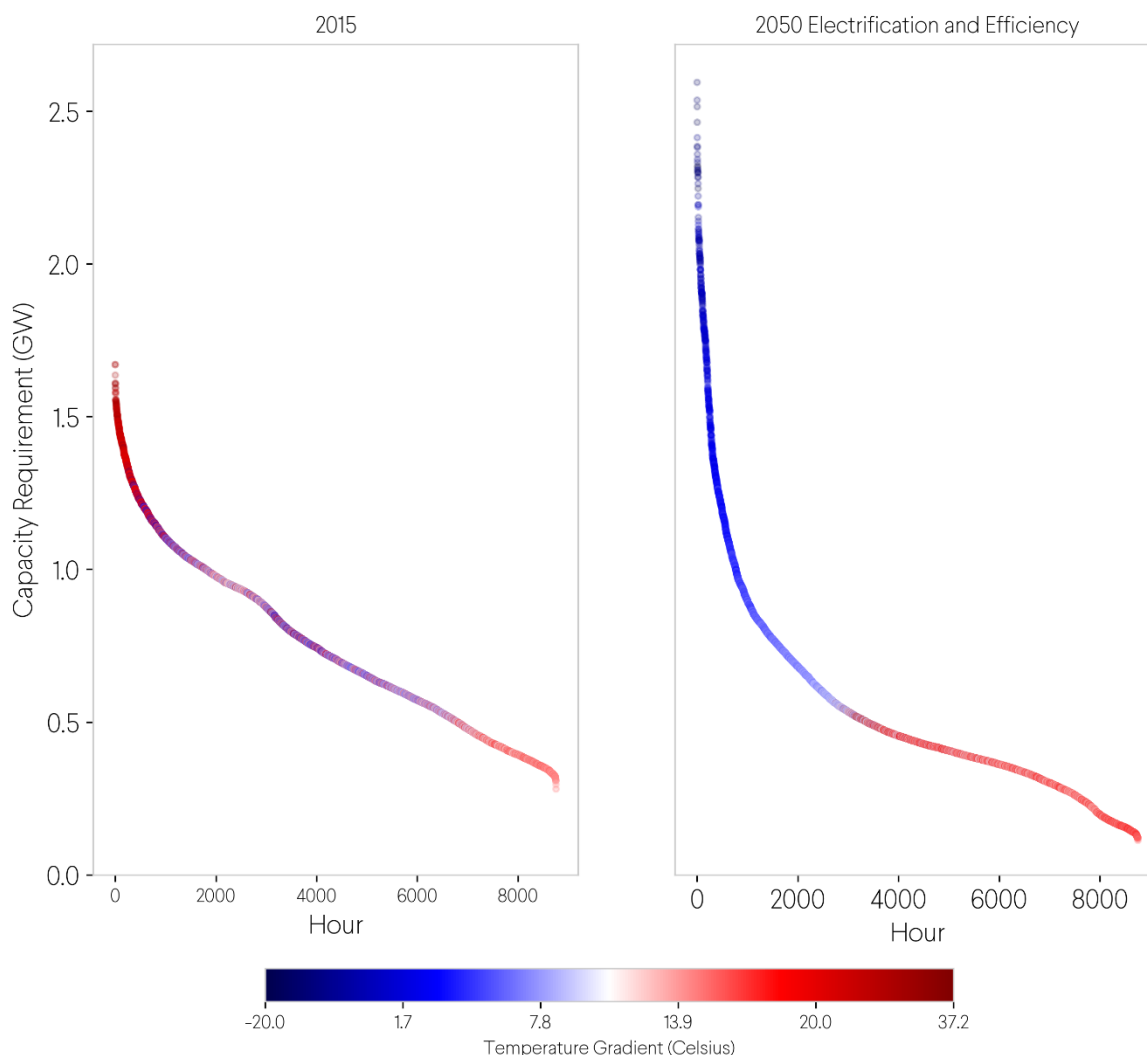


Figure 3. Temperature-colored Load Duration Curves under 2015 and a 2050 Electrification and Efficiency Scenario

Curves show 8760 hourly transportation and buildings electricity demand sorted from highest to lowest. Individual hours are colored by the outdoor temperature.



4 CURRENT ENERGY POLICIES

Federal, regional and state policies set the stage for city energy and climate planning. While cities can promote market transformation, states often have greater power to drive adoption of clean energy. States set building and energy codes, regulate utilities, and often run regional transportation systems. The Massachusetts Renewable Portfolio Standard (RPS) and Clean Energy Standard (CES) are examples of state policies that strongly impact City decision-making in regards to clean energy. Federal standards for vehicle fuel economy are a key ingredient in the assessment of clean energy options in transportation. The Regional Greenhouse Gas Initiative (RGGI) impacts energy and climate decision-making in Massachusetts and eight other Northeast and Mid-Atlantic States.

Under the current CES, 80 percent of retail electricity sales must be met by clean sources by 2050. The recent House Bill No. 4857: “An Act to advance clean energy” increased the RPS requirements so that 55 percent of retail electricity sales must be met by renewable energy in 2050. Despite these standards heading in the right direction, there is no absolute guarantee that the system as a whole will achieve complete carbon neutrality by any particular date.

Table 2 Summary of Policies that Set the Stage for Carbon Free Boston

Key Policies	Summary
Clean Power Plan (Federal)	Mandates emission reductions from electricity generation units by 32 percent, relative to 2005 levels, by 2030 across the US.
Regional Greenhouse Gas Initiative (Multi-state)	Establishes a regional cap on the amount of CO ₂ pollution that power plants can emit by issuing a limited number of tradable CO ₂ allowances through auctions.
Global Warming Solutions Act (Massachusetts)	Requires Massachusetts to achieve economy-wide GHG emissions reductions of 80 percent by 2050.
310 CMR 7.74: Reducing CO₂ Emissions from Electricity Generating Facilities (Massachusetts)	Set an annually declining limit on CO ₂ emissions from power plants in MA by creating a market for carbon allowances specific to the power sector.
310 CMR 7.75: Clean Energy Standard (Massachusetts)	Increases the percentage of electricity sales that retail suppliers must procure from clean sources (defined below) with the goal of reaching 80 percent by 2050.
225 CMR: Renewable Portfolio Standard (Massachusetts)	Requires a certain percentage of the state's electricity to come from renewable supply sources. Class I focuses on new electricity generation facilities, while Class II focuses on older facilities
HB 4857: "An Act to advance clean energy" (Massachusetts)	A recent house bill passed in August 2018 increasing the state RPS to require 35 percent renewables by 2035 and 55 percent by 2055, increasing the amount of offshore wind to be purchased by Massachusetts distribution utilities by up to 1,600 MW, establishing an energy storage target of 1,000 MW by 2025, and establishing a clean peak requirement

Of particular importance is the Massachusetts Global Warming Solutions Act (GWSA) adopted in 2008 that placed a declining cap on total carbon emissions from all state electric generating facilities connected to the Independent System Operator of New England (ISO-NE).¹ The GWSA combined with the CES (2017) set the policy foundation for the supply of clean electricity from the grid to the city, in the absence of any special supply policy adopted by the City. Throughout our analysis, we assume that this remains in force and is effective through 2050. Our analysis of options for energy supply will build upon, leverage, and ideally accelerate policies that are outside the City's direct control.

¹ The regulations apply to “a facility that includes one or more electricity generating units for which the owner or operator is required to report CO₂ emissions pursuant to the Massachusetts CO₂ Budget Trading Program at 310 CMR 7.70(8)” other than the MWRA Deer Island and MBTA South Boston Power plants.

4.1 POLICY DEFINITIONS

4.1.1 Clean Energy

Table 3. Clean electricity generation technologies that supply ISO-NE

Existing Clean Energy Sources	Potential Future Clean Energy Sources
Solar photovoltaic	Geothermal power
Solar thermal electric	Next-generation nuclear power
Small (≤ 30 MW) hydroelectric	Combustion-based electricity using carbon-free fuels or carbon capture and storage
Large (≥ 30 MW) hydroelectric [†]	
Wind energy	Marine or hydrokinetic energy
Landfill methane and anaerobic digester gas	Fuel cells fueled by carbon-free sources
Advanced biomass*	

*Generation units that meet emission limits for nitrogen oxides (NO_x) and particulate matter (PM)

[†] Must meet life cycle GHG emissions set by CES

The City will need to acquire significant quantities of clean electricity to address its Scope 2 emissions. We use the definitions for “clean energy” set in the Massachusetts RPS and CES. There are several initial, important points concerning the definition of clean energy. First, it is unquestionably valuable for the City to make the fastest possible transition to carbon-free electricity because cumulative emissions of carbon cause the impact, so earlier adoption will reduce the total emissions of carbon. Second, the City’s purchases can combine any of these sources into a portfolio each year to achieve a clean energy goal. Third, every carbon-free generation technology in Table 3 should be considered an option for inclusion in the City’s purchase portfolio, and those that may not be (e.g., biomass and renewable methane) be evaluated for their potential inclusion on a situational basis. Finally, the availability of these technologies and their cost will change over time. For example, it is possible that new geothermal, novel nuclear, or full carbon capture and storage technologies may become commercially available by 2050.

4.1.2 Carbon Offsets

A GHG offset, commonly referred to as a “carbon offset”, is a verified quantity of a GHG that is reduced, avoided, or permanently removed from the atmosphere (“sequestered”) through an action taken by the creator of the offset. Actions include modifying agricultural practices and industrial processes to reduce emissions, changing transportation modes, using cleaner and more efficient household devices, and generation of clean or renewable energy. After the action and the GHG reduction are verified, the creator is awarded a certificate showing the number of tons of carbon-dioxide equivalent (CO₂e) reduced. These certificates can be retired or sold by the creator. In the Global Protocol on Community Greenhouse Gas Emissions (GPC) [1], the GHG accounting system used by the City of Boston, the amount of GHGs on offset certificates held by entities within the city can be deducted from the city’s GHG emissions. More details are provided in the *Carbon Free Boston Offsets Technical Report*.

4.1.3 Additionality

One of the important steps to creating offsets is validation that the action taken that reduces, avoids or permanently removes emissions in the atmosphere would not have occurred if not for

the generation of the offset certificate and the market value of that certificate. This aspect of offset validation is known as additionality. For an offset project to be deemed “additional,” it must meet several stringent tests. First, the project cannot be common practice or required by regulation. Second, the reduction, avoidance, or sequestration of emissions must be “in addition to” a business-as-usual scenario. Third, the financial incentive from the offset market must be reasonably found to have enabled the project.

4.1.4 Renewable Energy Credits

A renewable energy credit (REC) certifies that electricity is indeed produced from a renewable source. Specifically, a REC is a tradeable certificate that represents the renewable attribute associated with one megawatt-hour (MWh) of electricity that was generated from a renewable energy source. In terms of carbon mitigation, this attribute can be extended to include the carbon-free aspect of the REC. In Massachusetts, RECs may be generated from solar, wind, tidal, small hydropower (<30 MW), landfill methane and anaerobic digester gas, marine or hydrokinetic energy, geothermal energy and eligible biomass fuels. The REC is distinct from the electricity bought or sold and can be sold separately from the electricity or bundled with it.

The Massachusetts RPS requires retail sellers of electricity to obtain a specified minimum percentage of their power supply from renewable power sources. In 2019, Massachusetts sellers must obtain 14 percent of their electric supply from renewable sources. Sellers prove compliance by self-creating or purchasing the necessary number of RECs. For example, if one seller’s total sales in 2018 are 100 MWh, that seller must create or buy 13 RECs and surrender them to regulators at the end of the year to prove that 13 percent of their supply came from renewables. A seller’s ability to purchase RECs means that they themselves need not generate the necessary fraction of renewables from their own facilities; instead, the purchase of RECs allows them to claim the renewable aspect of generation from a third party as their own. The creation and subsequent retirement of a REC certificate for each MWh generated ensures that a renewable MWh cannot be double-counted. Only the party holding *and* retiring the REC can claim to have generated one renewable MWh and the lower emissions associated with the generated unit of electricity.

4.1.5 Comparing RECs and Offsets

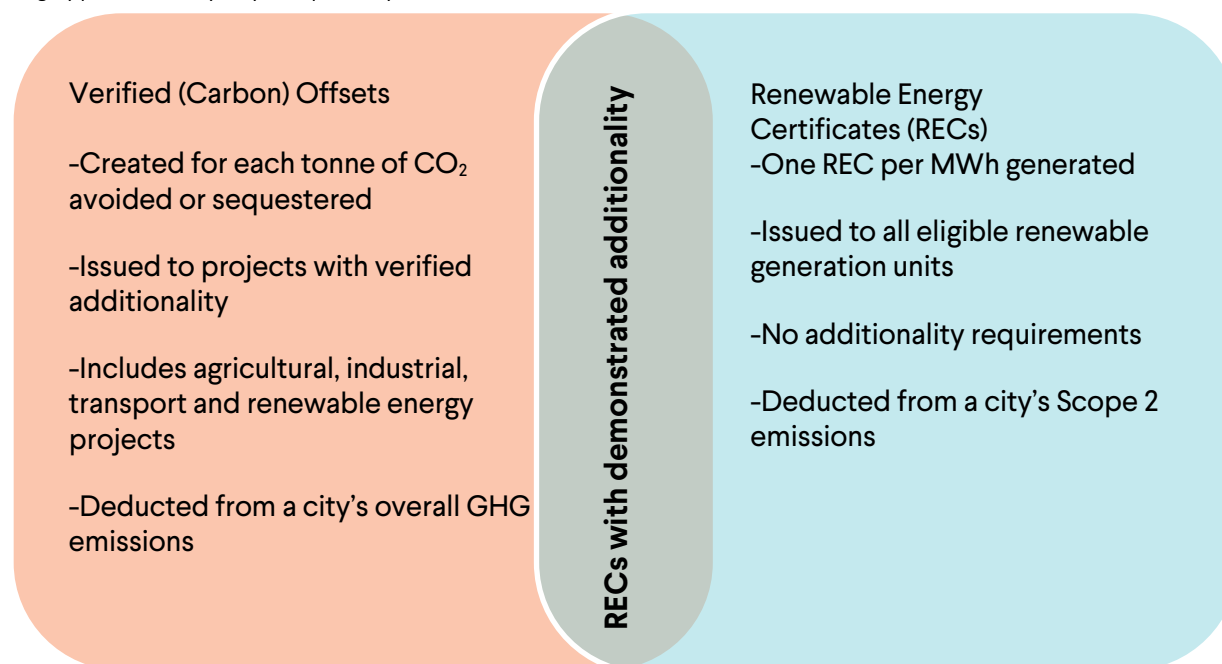
The accounting conventions for RECs under RPS rules are similar in some respects to the accounting conventions for offsets in GHG emissions inventories. The holder of a carbon offset can deduct the equivalent number of tons of GHGs from any scope of their GHG emissions inventory as they are reported for policy purposes. The holder of RECs can deduct the MWhs, and there for the equivalent GHGs from their Scope 2 emissions.

However, there are some important differences between the two instruments (Figure 6). First, the measurement processes for RECs and offsets are quite different. One REC is automatically given to every eligible renewable generator for every MWh generated. The process of verifying the correct number of RECs to issue a facility simply requires accurately measuring its electrical output over a year, which already occurs routinely. RECs purchased by an entity are later

converted to GHG emissions reductions when the RECs are used in the REC purchasers GHG inventory to quantify electricity emissions. In contrast, an offset is measured in tons, and an offset certificate is granted only after a somewhat complex examination of additionality, i.e., whether the creator of the offset took action they would not otherwise have taken in the absence of the offset. Note that there is no examination of additionality in the issuance of a REC. In developing a procurement strategy that includes RECs or some similar mechanism the City of Boston may want to incorporate a requirement for additionality.

Figure 4. Relationship between offsets and RECs

Renewable electricity generation facilities could undergo additional verification requirements to also receive offsets. However, due to the lengthy process, usually they will opt to only receive RECs.



A renewable energy facility is eligible to apply to obtain tradeable offset certificates – but only if it can successfully pass the validation procedure demonstrating that its renewable generation satisfies additionality. This is a much longer and costly process than the automatic receipt of RECs, so almost no renewable power generators in the U.S. bother to apply to receive offsets. Instead, they receive RECs.

So, do RECs satisfy an additionality criterion analogous to a carbon offset such that a city can justify the deduction of the GHG associated with an MWh from their emissions inventory? The short answer is that most types of RECs do *not* generate additionality, while a few types may do so such as MA Class I RECs.

Examination of electricity and REC markets indicate that in some cases a generator would have acted exactly the same whether or not it received REC certificates—no additionality. In other cases, the issuance of RECs caused renewable power developers to construct new generators, so that the RECs did qualify as additional. In other words, in some cases the financial incentives

created by RECs serve the same critical function as the financial incentives created by certified carbon offsets. In these cases, the RECs have played the same role as an offset even though the renewable energy facility has not gone through the process of receiving a tradeable offset. In this report, we refer to these RECs as “RECs for which additionality has been demonstrated.”

4.2 CLEAN POWER PLAN (CPP)

Under the authority of Clean Air Act the EPA established CO₂ emission guidelines for existing fossil fuel-fired electric generating units. The CPP² aims to reduce emissions from electricity generation units by 32 percent, relative to 2005 levels, by 2030. States and utilities have substantial flexibility and latitude in achieving these reductions since they can work independently or cooperatively to achieve these goals.

This policy established state-specific rate-based and mass-based goals that reflect the subcategory-specific CO₂ emission performance rates and each state’s mix of affected generation units. This rule establishes the first federal regulation of CO₂ emissions from existing power plants. Concurrent with this action, the EPA also issued a final rule that establishes CO₂ emission standards of performance for new, modified, and reconstructed power plants.

4.3 REGIONAL GREENHOUSE GAS INITIATIVE (RGGI)

In January 2007, Massachusetts joined RGGI, a cooperative effort by nine Northeast and Mid-Atlantic States to reduce CO₂ emissions from large fossil-fueled power plants. RGGI is a regulatory program that uses market incentives instead of top-down legislation to combat climate change. Together, these states planned to reduce CO₂ emissions from the power sector by 10 percent by 2018.

RGGI establishes a regional cap on the amount of CO₂ pollution that power plants can emit by issuing a limited number of tradable CO₂ allowances. Each allowance represents an authorization for a regulated power plant to emit one short ton of CO₂. Individual CO₂ budget trading programs in each RGGI state together create a regional market for CO₂ allowances.

The RGGI states distribute over 90 percent of allowances through quarterly auctions. These allowance auctions generate proceeds, which participating states are able to invest in strategic energy and consumer benefit programs. Programs funded through RGGI have included energy efficiency, clean and renewable energy, greenhouse gas abatement, and direct bill assistance.

On December 6, 2013, the State finalized amendments to the RGGI program by reducing the regional cap to 91 million tons per year, and implementing programmatic changes, including the auction process, consistent with a model rule developed by the nine RGGI states.

² The CCP has effectively been suspended by the Trump administration, but CPP targets are still in effect as part of Massachusetts’ participation in the United States Climate Alliance (which includes four other New England states).

4.4 GLOBAL WARMING SOLUTIONS ACT (GWSA)

The GWSA, signed in 2008, requires Massachusetts to achieve economy-wide GHG emissions reductions of 10-25 percent below 1990 emissions levels by 2020 and a reduction of at least 80 percent by 2050. It was the first piece in establishing Massachusetts as one of the leaders in developing a comprehensive program to address climate change.

As a first step, it required legislation to be established the required the reporting of GHG emissions. It also allowed departments across the Commonwealth to establish target emissions reduction and plans for achieving them. Additionally, it required the Mass DEP to establish a 1990 baseline GHG emissions case and a 2020 “business as usual” projection. The 2020 projection assumes that no government action is implemented to require emission reductions and is used to analyze options for future emissions reductions to meet the GWSA. The GWSA is the basis for CMR 7.74 and 7.75 discussed below.

4.5 225 CMR: MASSACHUSETTS RENEWABLE PORTFOLIO STANDARD (RPS)

The RPS was one of the first regulations in the nation that required a certain percentage of the state's electricity to come from renewable supply sources. The RPS established two separate renewable standards and an Alternative Energy Portfolio Standard (APS). RPS Class I focuses on new electricity generation units built after December 31, 1997 and Class II focuses on existing facilities in operation prior to January 1, 1998. The APS aims to incentive the use other technologies such as Combined Heat and Power (CHP), flywheel storage, some bioenergy applications, heat pumps, and fuel cells.

4.5.1 225 CMR 14.00: Renewable Energy Portfolio Standard – Class I

Under RPS Class I, all retail electricity suppliers must provide a minimum percentage of their electricity sales to customers in Massachusetts from eligible renewable energy resources. As the current legislation stands, this is set to increase 1 percent each year. Retail electricity suppliers can meet their requirement through some combination of producing electricity from a qualified generation unit, purchasing the Class 1 RECs or paying an alternative compliance payment. Note that the Class 1 RECs must be retired for it to count towards compliance.

Generally speaking, these RPS Class I generation units must be located within the ISO-NE Control Area. There are additional provisions for any RPS Class I Renewable Generation Unit in a region adjacent to ISO-NE. Eligible RPS Class I Renewable Generation Units include:

1. Solar photovoltaics or solar thermal electric energy.
2. Wind energy.
3. Ocean thermal, wave, or tidal energy.
4. Fuel cells utilizing eligible biomass fuels, landfill methane gas or hydrogen derived from said renewable fuels.
5. Landfill methane gas if the gas.

6. Hydroelectric facilities with a capacity under 30MW. Older units, prior to December 31, 1997, may qualify if additional capacity was installed or efficiency improvements made as long as the capacity does not exceed 30 MW.
7. Low-emission advanced biomass power conversion technologies utilizing eligible biomass fuels.
8. Marine or hydrokinetic energy.
9. Geothermal energy.

4.5.2 225 CMR 15.00: Renewable Energy Portfolio Standard – Class II

Similar to RPS Class I, RPS Class II requires suppliers to provide a percentage of sales from Class II renewables. The Class II standard was designed to provide financial incentive for the continued operations of older renewable generation units. Eligible facilities generate Class II RECs and the annual percentage requirement that suppliers have to meet varies from year to year per a formula in regulation. Eligible Class II Renewable Generation Units include older implementations of units listed under Class I RECs and some waste-to-energy facilities.

4.6 HOUSE BILL NO. 4857: AN ACT TO ADVANCE CLEAN ENERGY

As of August 2018, Governor Baker signed Bill Number 4857 “An Act to advance clean energy” into law. This bill is intended to further promote clean energy in the Commonwealth and bundles various pieces supporting clean energy. Specific to the RPS Class I and the discussions in this chapter, the law changes the minimum percent requirement of increasing 1 percent annually to increasing 2 percent annually between January 1, 2020 and December 31, 2029. After this period, the requirement falls back to increasing 1 percent annually. As a result, electricity suppliers in the Commonwealth are now required to supply 35 percent of the electricity sold from RPS Class 1 eligible renewable supply sources in 2030 (as opposed to 25 percent under the original RPS Class 1).

4.7 310 CMR 7.74: REDUCING CO₂ EMISSIONS FROM ELECTRICITY GENERATING FACILITIES

Section 7.74 establishes an annually declining limit on carbon dioxide emissions from power plants in Massachusetts. It does this by creating a market for carbon emissions allowances, specific to the power sector in Massachusetts. Allowances are issued and administered by the Mass DEP and each allowance allows the power plant to emit one tonne of CO₂. These allowances are only to be used to comply with 310 CMR 7.74.

The carbon allowances for 2018 were directly allocated by the Commonwealth. However, moving forward, they will be auctioned quarterly. Only owners or operators of electricity generating facilities can purchase these and may trade amongst themselves. Every year, the number of allowances up for auction decrease in line with the declining limit on carbon dioxide emission from power plants. The Mass DEP is also not obligated to sell these allowances if a reserve price is not met. The funds from the auctions are to be used to further to goals of the Climate Protection and Green Economy Act (Chapter 21N) by supporting programs or projects to reduce GHG emissions in order to mitigate the impacts of climate change.

Currently, there are 21 fossil fuel plants that fall under this regulation's jurisdiction with the goal of reducing aggregate CO₂ emissions from 9.15 Mt in 2018 to 1.8 Mt by 2050. The program and its requirements are set to be reviewed no later than December 31, 2021 and every ten years thereafter.

4.8 310 CMR 7.75: CLEAN ENERGY STANDARD (CES)

Section 7.75 establishes an annually increasing minimum percentage of electricity sales that retail suppliers must procure from clean energy sources, similar to the RPS. The minimum percentage of electricity sales required begins at 16 percent in 2018 and increases 2 percent per year until 2050, when it reaches 80 percent. Similar to satisfying the RPS requirements, a retail supplier may use clean energy credits or alternative compliance payments to meet the minimum. Note that the CES does not currently apply to municipally-owned utilities. The funds from any compliance payments or credits are to be used to further to goals of the Climate Protection and Green Economy Act (Chapter 21N) by supporting programs or projects to reduce GHG emissions in order to mitigate the impacts of climate change.

In order for a generation unit to be classified as clean under the CES, it must be built after December 31, 2010 and demonstrate that it is either: 1) an RPS Class I generation facility or 2) has net lifecycle GHG emissions, over 20 years, that are at least a 50 percent reduction of GHG emissions per unit of useful energy relative to the lifecycle emissions from a new combined cycle natural gas electric generation unit using the most efficient commercially available technology. Hydroelectricity generators over 30 MW may also qualify if it satisfies certain emissions criteria.

The CES was designed to be compatible and complementary to the RPS. However, a major difference between the two are the qualifying technologies. Most notably, the CES uses carbon emissions-based performance metrics to define eligible technologies. While all RPS Class I technologies are eligible for the CES, other technologies that are eligible may include nuclear, large hydroelectricity and fossil-fuel with carbon capture and sequestration. For example, RPS Class I RECs would also comply with CES requirements, but a CES approved-technology may not necessarily generate Class I RECs.

5 REPRESENTATION OF POLICY AND PROCUREMENT IN THE CARBON FREE BOSTON STUDY

Figure 5. Emissions intensities used to evaluate various scenarios in Carbon Free Boston

The orange line represents our interpretation of the Massachusetts Clean Energy Standard which would result in a grid that is 80% supplied by carbon free electricity with the balance being generated by natural gas combined cycle. The two blue lines represent linear trajectories to 100% carbon free electricity by 2050 (dark blue) and 2030 (light blue).

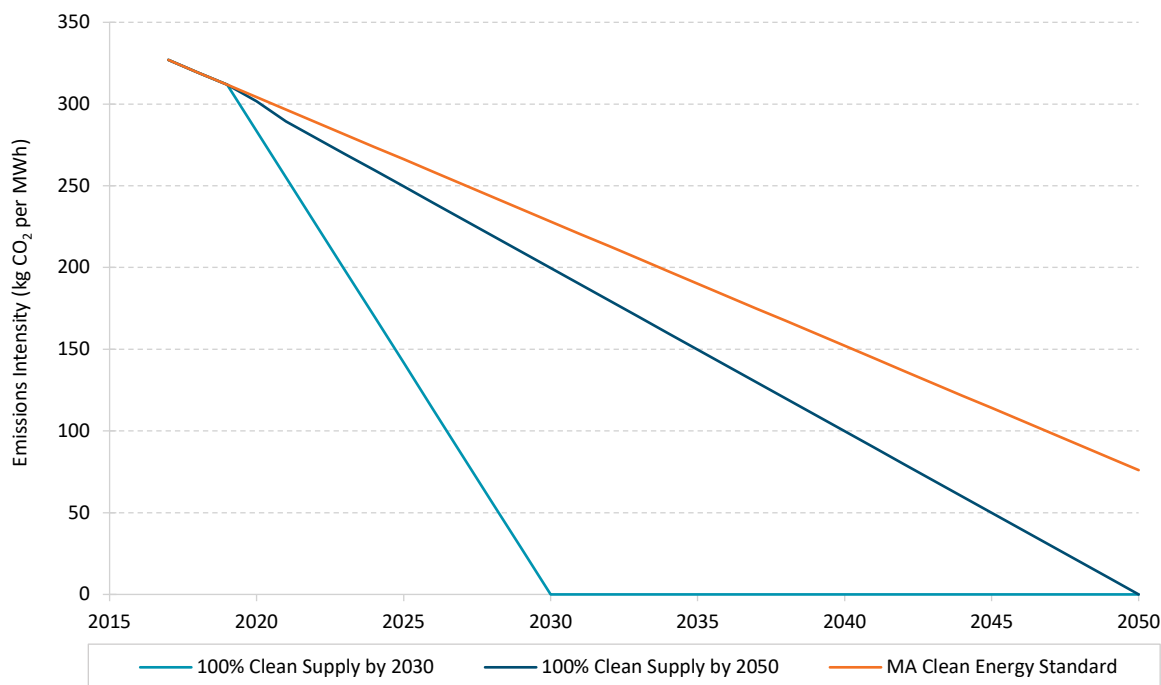


Figure 6 shows carbon intensities for various electricity supply scenarios for the City of Boston used in this study for analysis. The Massachusetts Clean Energy Standard described above is assumed to define the carbon intensity of Boston's electricity supply through 2050, assuming no additional procurement is made. The City could lower the emission intensity of supplied electricity through an accelerated procurement policy that aims for 100 percent carbon free electricity by 2050 at the latest – which is assumed to be a necessary action for the City's goal of carbon neutrality. In addition to a 100% Clean Supply by 2050 trajectory, this study also looked at the impact of a 100% Clean Supply by 2030 trajectory that would likely be necessary for achieving the City's interim target. The following section explores several options for such procurement strategies.

The use of steadily declining trajectories in each of the two procurement strategies, rather than by a specific time point reflects two key elements. The first is the need for the decarbonization of electricity supplies to progress starting now. Second it can reflect the use of individual tranches of clean energy procurement rather than a single large bulk purchase. The use of such tranches allows the City to mitigate the risk of high prices. The city would not be locked in to a single, potentially high electricity price, but would have the opportunity to negotiate for its desired procurement size on an annual basis that best meet its financial and mitigation objectives.

6 PROCURING CARBON FREE ELECTRICITY

Boston receives its electric power from the electricity grid that is managed by the ISO-NE, a system that spans the six New England states and includes imports from and exports to the adjacent electric grids in New York and Canada. The city's electricity supply is delivered within the city entirely by Eversource, which owns the local distribution system. Customers within the city used a total of about 6,500 GWh of electricity in 2016, four-fifths of which was consumed by commercial and industrial customers and about one-fifth by residential customers. Municipal use for buildings and street lights accounts for about 2.2 percent of all use. Over two-thirds of all power sales within the city were made by competitive retailers, with the remaining one-third supplied by Eversource in the form of "basic service."³

Boston has options to reduce GHG emissions in its buildings, transportation systems, and waste streams. One avenue is to dramatically improve the efficiency of all major energy services: mobility, illumination, and thermal comfort. The other major avenue is to electrify energy services, especially transportation and the heating of buildings. The success of deep electrification hinges on a clean supply of electricity. The Massachusetts Clean Energy Standard will result in an increasingly clean supply of electricity, but it alone will not supply the city with 100% Carbon Free Electricity.

The City has three main options to acquire the clean electricity needed to reduce its emissions from electricity consumption:

Option 1: Purchase RECs that have demonstrated additionality.

Option 2: Physical purchase of zero-carbon electricity (100 percent renewable power) from a local source that can deliver to the ISO-NE grid.

Option 3: Purchase and resale of power from a distant source that is not able to deliver to ISO-NE, also referred to as a virtual power purchase agreement (VPPA).

In all options, the RECs associated with the power are also purchased and retired. All options would be implemented by the issuance of an RFP and the City's usual methods of competitive bid evaluation, selection, and contracting. The City could also allow for private entities to pursue procurements independently, as long as such procurements met standards consistent with the policy objectives. The City could conceivably combine the use of the options in any combination yielding carbon neutrality by 2050 or sooner, or pursue these options at different time points to achieve certain objectives as discussed below.

6.1 OPTION 1: PURCHASING RENEWABLE ENERGY CERTIFICATES (REC AGGREGATION)

A wide variety of RECs are available, including RECs from renewable projects anywhere in the United States. Massachusetts issues a special REC known as a Massachusetts Class I REC for projects that it certifies are new all-renewable energy sources that deliver clean power to the ISO-NE system. MA Class I RECs are associated with the state's RPS regulation.

³ In Boston, electricity customers who do not buy power from a third-party licensed retail supplier receive "basic service" electricity supply from Eversource. In Massachusetts, all electricity bills have three supply cost components: supply costs, RPS compliance costs, and administrative costs.

Our assessment is that MA Class I RECs satisfy the essential spirit of the additionality requirement due to the structure of the Massachusetts RPS regulations. Utilities must purchase Class I RECs in the compliance market to meet their RPS obligations. Boston's purchase of Class I RECs in the voluntary market reduces the supply to utilities, which in principle stimulates new investment in clean generation capacity to meet the RPS requirements. However, this is by definition an indirect relationship, and the existence of the ACP pathway for utilities means that additionality impact of voluntary REC purchases remains uncertain. Renewable resources that produce RECs outside the ISO-NE region are ineligible for Massachusetts RPS compliance.

Thus, if the City chooses RECs to purchase clean electricity, then MA Class I RECs are the best option. There is generally no simple way to determine whether RECs that are not MA Class I have additionality, i.e. lead to the creation of an additional MWh of renewable power that displaces one MWh of non-renewable power. Without this assurance, if the City buys non-MA-Class-I RECs it may not be reducing total GHG emissions below the level that existed without its purchase of such RECs.

6.2 OPTION 2: PHYSICAL PURCHASE OF ISO-NE SYSTEM RENEWABLE POWER (PPA)

An alternative option for decarbonizing Boston's power supply is purchasing 100 percent clean power and reselling the power immediately to in-city customers. Alternatively, instead of purchasing the power outright and then having to resell it to city residents, the City (or its designated entity) could act as a purchasing agent on behalf of its customers, pooling customer demand and then purchasing supplies to meet this demand. The City or its designated entity would retire the RECs generated in this PPA. This approach to purchasing an aggregated demand for carbon-free power is known as Community Choice Aggregation.

Power is routinely purchased by large energy users, municipal utilities, and load aggregators from the competitive wholesale power markets via a power purchase agreement (PPA). These agreements specify the type and amount of power to be produced, the delivery point, the term of the sale, and other standard contractual terms. The price at which power is sold under the PPA is a critical term, and may vary from a single fixed price per MWh delivered over the life of the contract to a price that changes based on power spot markets.

In order for this power to be deemed carbon-free and delivered to Boston, a PPA would need to specify that the power purchased comes from a clean generation unit connected to the ISO-NE grid or delivered to ISO-NE by using firm, contracted transmission capacity. Delivery costs increase with the distance to the source as do line losses, and at very large distances, delivery becomes infeasible. PPAs can specifically designate the generation sources, and that source can be a new clean generator built to satisfy the contract. This creates additionality.⁴ Generation-specific renewable PPAs normally have long terms of between 10 and 20 years; other clean generation sources may require other terms.

If the City acts as a buyer or reseller, the City must resell the power it has purchased to the citizens and businesses of Boston, or perhaps customers outside the city. There are several policy and financial mechanisms by which this sale could occur. One option is for the City or its representative to purchase power on behalf of all citizens and then make arrangements for Eversource to deliver it to citizens, much like current retail electric power suppliers. This is a municipal or community choice aggregation. The City

⁴ Additionality also requires that the PPA award all RECs produced to the buyer, who retires them all, assumed here.

would need either to (1) mandate full participation in the aggregation in order to have enough customer load to absorb the power it has purchased, requiring a change in law; or (2) resell its unsold purchase surplus into the ISO market. Another similar alternative would be to require that any power supplier serving Boston load buy this power from the City and offer it for resale, almost certainly requiring an amendment to state laws. Finally, the City could opt to resell the power into the ISO-NE market while retiring the associated RECs.

6.3 OPTION 3: VIRTUAL POWER PURCHASE AGREEMENT (VPPA)

VPPAs are best understood as the physical purchase of power from a carbon-free generation unit that is too far away to deliver the power to Boston.⁵ In this case, Boston would purchase the renewable power from a generation unit elsewhere in the country and must resell the power that market, since it cannot take physical delivery.⁶ The City pays the contract price to the generator for the power it generates, and receives the spot market price for the power it resells. In some hours, the City may receive more than it is paying, while in other hours it may receive less.

Other than the immediate resale of the power purchased under the VPPA, most other terms of the contract are similar to a local physical PPA. In both cases the contractual price must be sufficient to convince a competitive power plant developer to build and operate a new plant for a period long enough for the developer to obtain financing (usually 10 years or more), thus achieving additionality.

As with RECs, a VPPA does not require the City or other buyers of VPPA power to arrange to take delivery of any electricity. The City buys and instantly resells power in order to ensure that more clean power is produced than would otherwise be the case, but the City does not physically receive any power. Thus, the City itself and all its residents would continue to buy and pay for their actual power service in New England. A VPPA would simply give Boston “credit” for having created clean power outside the ISO-NE service area whose carbon savings is designed to equal the carbon emissions resulting from its actual power use in New England. The City or its designated entity would retire the regional equivalent of RECs generated in this VPPA. Under GHG accounting conventions, this is a fully legitimate clean energy option. With respect to many other criteria, however, VPPAs differ significantly from PPAs.

The main driver of the cost of a VPPA to a buyer is the payment obligation of the buyer under the contract minus the revenues received for the immediate resale of purchased power at the specified grid. The net present value of this quantity can be calculated only when the payment price is known and future spot prices at the point of resale can be forecasted for the duration of the VPPA, typically at least ten years. The NPV of this stream of revenue amounts, which may be positive or negative, represents the NPV cost of this option to the buyer. As noted above, a difficult element of VPPA cost is the need to forecast the revenues earned from the immediate resale, as this varies with spot and capacity prices at the point of resale. Forecasting electricity prices over a decade or longer is difficult. Evaluation of forecasts of projected resale revenues is part of the solicitation and evaluation process of a VPPA, but it cannot be done generically.

⁵ See https://www.epa.gov/sites/production/files/2016-09/documents/webinar_kent_20160928.pdf for a short, clear visual explanation of how VPPAs work. Useful information is also found in <https://3degreesinc.com/ppas-power-purchase-agreements/>

⁶ The City could retain the services of an agent who administers the VPPA, but this would not change its financial obligations as described here. Also, the City could join with other buyers to be a joint VPPA; this does not change the option significantly from the discussion in this section.

The City's options for effectuating a VPPA primarily revolve around different options for financing a source of money to pay the net cost of the VPPA including any net losses on the resale of power and the lost revenues from retiring, instead of selling, the RECs:

Option 1: Pay the net cost from City revenues, funded by any revenue source chosen by the City.

Option 2: Allocate the net costs of the VPPA to all power suppliers on a sales pro-rata basis. (This may require changes in state law)

A VPPA provides an additional option for achieving net carbon free generation by allowing for the creation of additional renewable generation in areas outside New England. In regions with more carbon intensive grids than NE-ISO this may enable a larger value in terms of dollars spent per carbon emission displaced.

6.4 POTENTIAL OF IN-CITY DISTRIBUTED ELECTRIC GENERATION

The City also has the opportunity to foster up to approximately 1.3 TWh/yr [1] of rooftop solar potential through a combination of building owner mandates and incentives. These installations can also generate MA Class I RECs which can be integrated into a REC aggregation program. Rooftop solar tends to be one of the costlier renewable energy sources due to high installation costs. Further, protecting and prioritizing foliage is necessary to preserve and enhance the urban ecosystem and air quality. Still, where advantageous the deployment of local solar can promote local economic activity and resiliency. The City could issue a "carve out" for such local solar RECs in its municipal aggregation program that would help to incentivize the deployment of rooftop solar.

6.5 COST CONSIDERATIONS

6.5.1 Cost Trends in Renewable Power

The marketplace for solar and wind power is highly diverse and competitive, with a variety of for-profit, cooperative, and non-profit developers all offering high-quality projects. In evaluating the cost of renewables, levelized costs of electricity (LCOE) are assumed to be reasonable proxies for offers the City would receive for a long-term renewable power purchase.

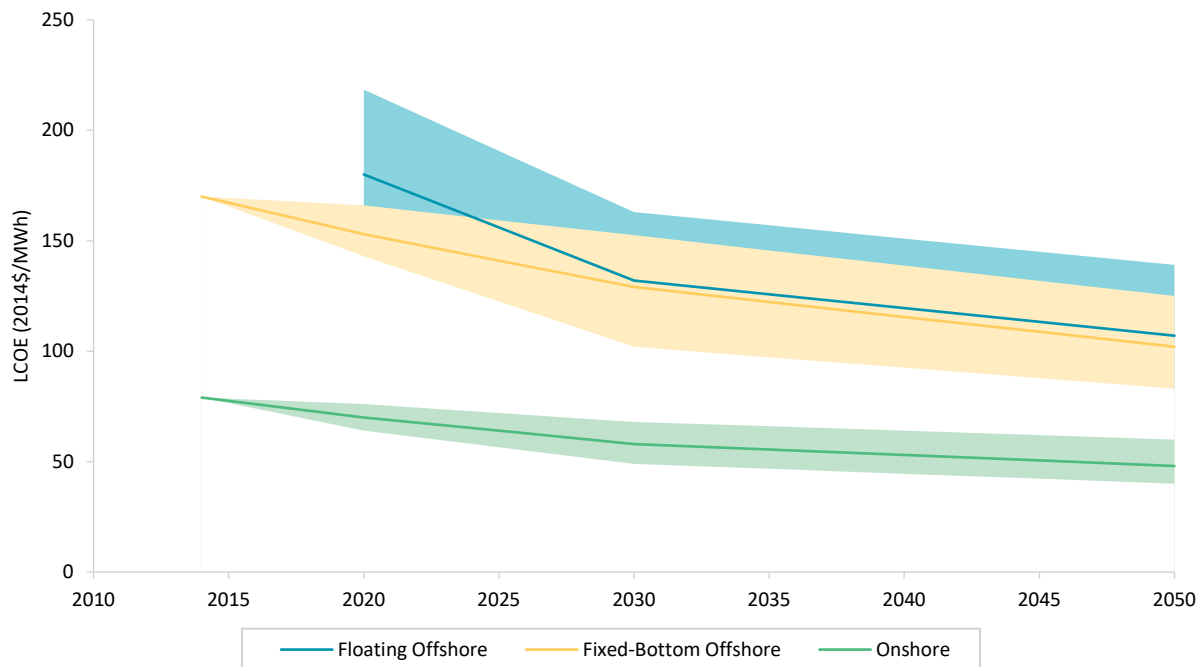
The prices of onshore wind and utility-scale PV solar have declined substantially in the past decade and are projected to continue to decline at a more moderate pace through 2050 [2] (Figure 7 & Figure 8). In recent years, the average reported price of onshore wind power in the U.S. has been about \$0.05 per kWh, although in regions with high average wind speeds and low construction costs, prices are as low as \$0.02 per kWh. Current estimates on the LCOE of current offshore wind power ranges from \$0.08 to \$0.27 per kWh, [3], but note that Massachusetts utilities recently filed for approval of a contract with an offshore Massachusetts windfarm with a levelized bid price of only \$0.065 per MWh [4].

The price of electricity from solar PV is forecast to continue a downward trend. The decline in cost is expected to slow down after 2020 and especially after 2030, though cost declines continue steadily and significantly through 2050. By 2030, these forecasted costs are in the range of \$0.03 to \$0.04, the same range as current wholesale average electricity costs in ISO-NE [5].

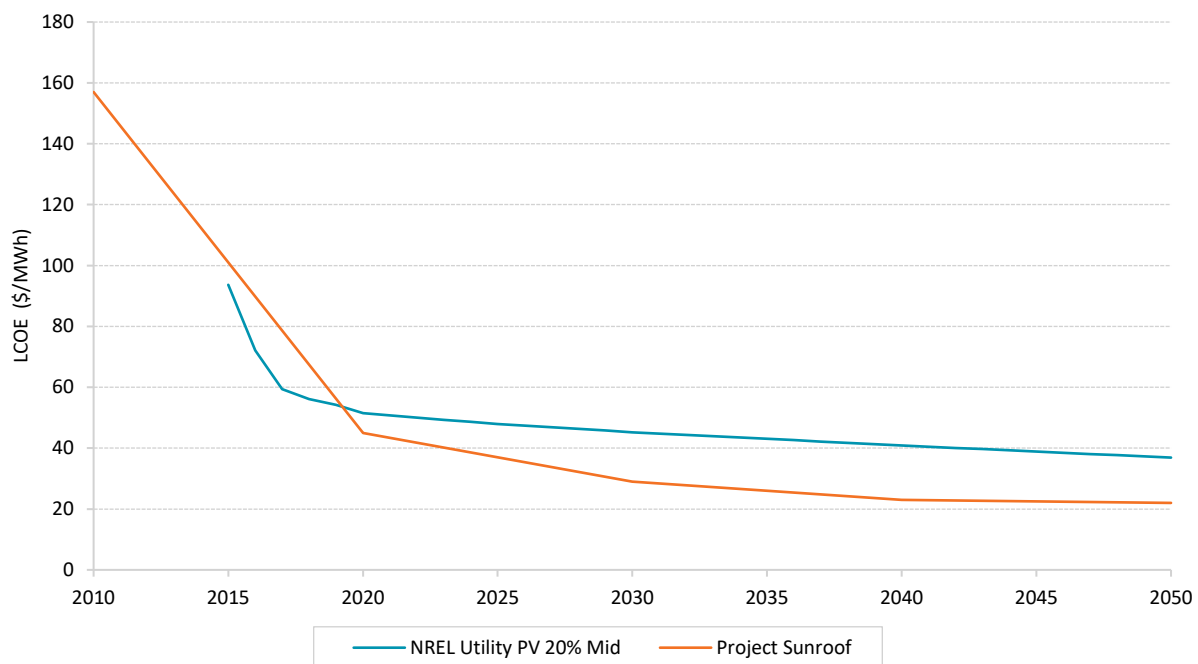
Figure 6. Summary of the Levelized Cost of Electricity for Onshore and Offshore Wind

Shaded areas represent first and third quantiles of forecasts.

Source: [6]

**Figure 7. Cost of Utility-Scale Solar Photovoltaic**

Sources: [1], [6]



6.5.2 Massachusetts Class I REC Prices

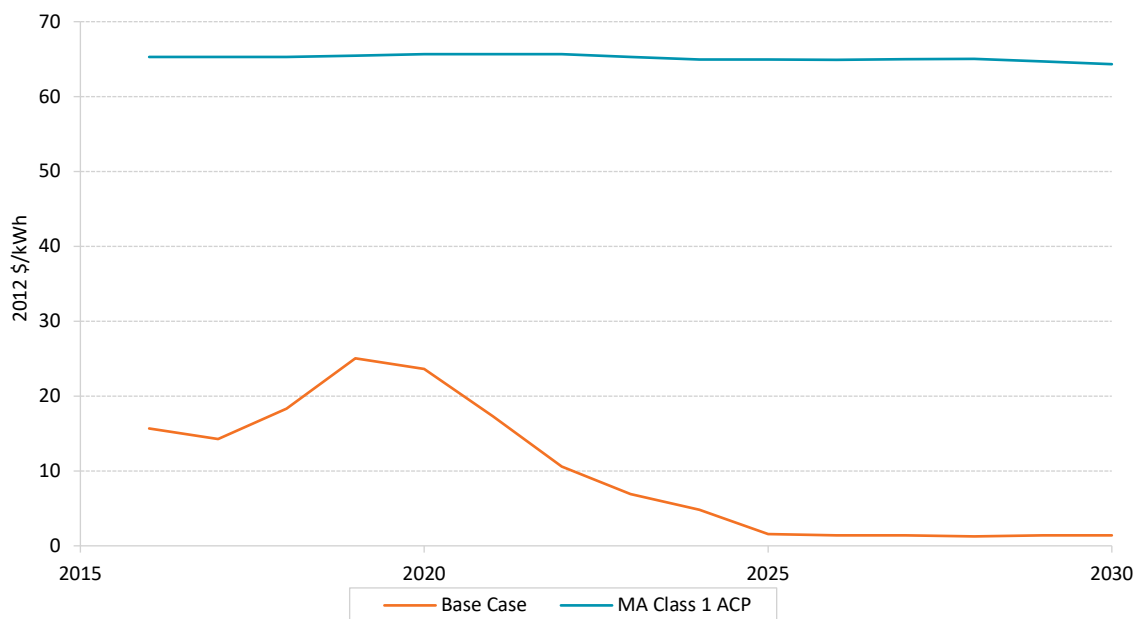
The price of Massachusetts Class I RECs is key to their acceptability as a mitigation option. Additionality requires that the price of a REC must be sufficient to prompt a wind or solar developer to break ground on a facility they would otherwise not build. A complete analysis of this degree of causality or attribution, which is at the core of the additionality concept, is quite difficult. A simple rule-of-thumb for additionality is that the REC price equals the difference between revenues a renewable energy developer can obtain from the bulk power market and the revenues required to meet their investment hurdle rate. At present, this is estimated to be approximately \$0.01 to \$0.025 per kWh.

Alternatively, the developers of clean power sources may go through additionality verification processes such as the Verified Carbon Standard. If this occurs, the City can further guarantee its REC purchase is additional by also purchasing and retiring the facility's offsets. However, renewable energy generation units usually do not go through the lengthy and expensive process that enables them to receive offsets and are not eligible to do so in the RGGI region, so RECs are the only attribute besides electricity these facilities can usually offer.

A study that predates the passage of HB 4857 suggests that MA Class I REC prices could drop precipitously in the future [7] (Figure 9). A price collapse for RECs threatens their additionality function. If this occurs, REC purchase is not a feasible option for the City. If prices remain in the band predicted between 2016 and 2022, prompted in part by the implementation of HB 4857, MA Class I RECs may be additional. It is also possible that the City's decision to purchase RECs will, in turn, influence the Massachusetts state government to change the RPS market such that Boston's REC purchase will ensure additionality by increasing the required fraction of renewables all vendors must offer. In this way, Boston's actions will create a positive climate policy feedback loop with state climate policies that helps decarbonize the entire Massachusetts (and undoubtedly, New England) grid faster than the current GWSA trajectory.

Figure 8. Historic and Projected Massachusetts Class 1 REC Prices and the ACP

Source: [7]



The following options can be combined to yield a total REC purchase of the required size:

Option 1: A REC purchase from City revenues, funded by any revenue source chosen by the City.

Option 2: A mandate that each city electric customer purchase RECs to offset their own carbon emissions from power consumption, possibly exempting small and/or low-income customers.

Option 3: A mandate that every supplier of power selling power to Boston residents offer only clean power after a specified date. (This option may require state permission under public utility laws or a change in law.

6.5.3 Cost Considerations across the Three Options

The total cost of electricity supply to Bostonians under each of the three purchase approaches can potentially vary. In the case of a PPA, all customers must pay for electricity. In the case of a VPPA or REC purchase, customers must continue to pay their electricity supply costs as before.

The full cost of these options is explained more completely in Table 4. Under the first option, REC purchase, Bostonians continue to purchase their own grid power from the supplier of their choice but are also allocated, in one form or another (e.g. a tax increase), the cost of REC purchases. While RECs may not be high in price, the total cost of power under this approach will exceed Bostonians' cost of buying power alone.

Table 4. Cost Details for Three Electric Purchase Options

Option	Elements of Electricity Costs	Form of Total Cost Each Boston Inhabitant Pays
REC Purchase	In addition to paying for RECs, all Boston citizens continue to purchase marketplace power	Allocated cost of RECs and cost of self-selected power
Local Power Purchase	Recipients have their power "purchased for them" and it is carbon-free	Allocated cost of local power purchase
VPPA Purchase	In addition to paying or receiving the net cost of VPPA, all Boston citizens continue to purchase market place power	Allocated cost or credit from VPPA and cost of self-selected power

The second option is the local power purchase of renewables allocated to all consumers via PPAs that the City has negotiated. In this case there is no additional cost for RECs or VPPA costs beyond the cost of power supply itself.

The third option, VPPA purchase, presents similar economic characteristics as the option of REC purchases. Bostonians continue to buy their own power supplies, but are allocated the net costs of the VPPA. These costs may be small, and conceivably they could be a net credit to consumers, but the highest likelihood is that a small cost would be incurred by the VPPA.

6.5.4 Variability in Costs

Regardless of the specific mixture of clean power purchased, the purchase mechanisms dictate the degree to which payments are predictable, and whether the purchase options should be considered capital outlays versus operating costs.

The purchase of RECs is typically done on a short-term (one to two-year) basis via solicitation. This would ordinarily be considered an approach that is entirely operating expenses. During each purchase period the price of RECs would be known and probably fixed, but it would be necessary to predict future REC prices for future solicitations, and these could vary considerably, as shown in Figure 9.

For PPAs, payments will largely be on an ongoing basis as power is delivered, which in most cases would be viewed as an operating expense to the City, or to customers if the City has simply acted as an aggregator or agent. Most PPAs with wind or solar producers have specified prices for the duration of the contract, making these payment streams the most predictable and least volatile option. As future clean power technologies become available, PPAs with these technologies may have variable payment elements.

VPPAs are also contracts with periodic payments that are typically considered operating rather than capital outlays. The volatility inherent in a VPPA because of the potential differences between the contract purchase price and the spot market resale price might trigger a need for the City to set aside a pool of working capital to protect against payment changes. Determining the magnitude of the risk can be a challenge.

6.6 EQUITY AND ECONOMIC DEVELOPMENT CRITERIA

The discussion thus far has focused rather narrowly on the costs of electricity. But there are additional social and economic considerations that are part of a complete assessment of the city's clean energy options. For this generic evaluation discussion, we group them into several categories, recognizing each criterion is specific to the type and location of a project and the terms under which the project is financed, built and operated.

Economic development benefits are readily evaluated for a project once these project attributes are known. Most major utility and infrastructure programs are now accompanied by economic development evaluations, which include the calculation of job creation, economic stimulus via the multiplier effect, and other attributes [8]. The results of this type of study are relevant to assessment of equity considerations as well.

A purchase of power from an ISO-NE generation unit or MA Class I RECs will generally have an incrementally better local economic development effect than a VPPA because, by definition, a VPPA is not located in New England. Most of the economic development benefits of such a facility go to the locality where the facility resides. This point was emphasized in the City of Atlanta's recent Clean Energy Atlanta plan, which noted that the purchase of out-of-state RECs "provides no benefits to equitable clean energy access, economic development, public health, utility bills or water consumption [9]." The only exception to this would occur if the VPPA option's total impact on Boston electricity bills was smaller than the same decarbonization achieved through a PPA or REC purchase, in which case the power cost savings would create added local economic activity. This can be evaluated when specific alternatives are identified.

The first group of equity criteria involve communication and decision-making. This includes the specific criteria of how stakeholders are informed of potential action, how well communication is maintained, whether affected parties are adequately consulted, and related issues. There is no *a priori* reason why

any of the electric supply options would tend to score better or worse on these criteria, but the City should nonetheless evaluate this dimension of its electric purchase.

The next set of equity criteria involves what economists call the “incidence of costs” or “who pays”. The magnitude and distribution of this impact is a direct function of how the City funds the option. There are a variety of ways in which the City can structure the recoupment of funds required to pay for clean electricity, each of which will impact different customer groups differently. There is no reason to think that this will vary by the composition of the portfolio selected for purchase, or by the type of purchase.

The next set of criteria about “who benefits?” When examining economic development, it is important to go beyond the aggregate effects on the city or region and examine the communities, companies, and laborers who will benefit. Where they are located and whether and how these benefits can be directed towards under-represented communities. Once again, these criteria are tied more to the mechanism and details of the implementation of specific projects, and not to the type of clean power option.

The environmental impacts of clean electricity are strongly tied to the type and location of specific projects. There are well-developed techniques for measuring both the environmental and human impacts. The City can assess the environmental and health impacts of its options using existing studies and techniques as it evaluates the facilities that have offered to sell it power, virtual power, or RECs.

A VPPA is an outlier in regards to how its health and environmental impacts are assessed. Since a VPPA does not affect the regional power grid, or the operation of any facilities in the city, there is no change to the business-as-usual environmental and health impacts. The only exception may be benefits from the reduction of airborne fossil fuel pollutants that migrate from the region holding the VPPA facility into New England. Otherwise, the environmental and health impacts (positive as well as negative) will be more local with the PPA and REC approaches.

The final evaluative criterion is resilience benefits. This category is affected by both the type and location of the clean electricity portfolio options selected. One can estimate the resilience benefits of specific types of investments in specific location once they are identified. The VPPA purchase option will provide no local resilience benefits, as it does not act on the local electrical system. The resilience benefits of projects stimulated by RECs or PPAs will depend on their size, type, location, interconnection and control features, degree of physical and cyber hardening, and a number of other factors the City can evaluate upon receiving proposals from developers.

6.7 REGIONAL AND GLOBAL CLIMATE POLICY ACCELERATION LEADERSHIP

Boston can accelerate the transition to carbon neutrality across the entire New England region while simultaneously setting an example for all global climate policy stakeholders. Boston’s purchase of clean electricity will accelerate climate policy if it enables a new clean energy technology to achieve a market breakthrough it would otherwise not achieve. For example, a purchase of offshore wind could help further establish this sector and help it achieve scale and learning effects that lower costs and benefit all energy buyers in New England. These regional accelerator effects will be time- and technology-specific, but the City should be attentive to them. A VPPA purchase provides no intra-regional acceleration.

VPPAs also raise a global policy tradeoff for which there is no easy answer. The City could choose to enter into a VPPA in another part of the country whose grid has higher GHG emissions intensity than

New England. One could argue that from a global perspective, such action is more powerful than buying within ISO-NE.⁷ Others would argue that global leadership is best demonstrated when New England makes the fastest, deepest progress towards complete carbon neutrality, sourcing its carbon-free energy within ISO-NE as much as possible. Both points of view have merit that Boston should be attentive to when selecting its clean electricity supply options.

6.8 CONCLUSIONS ON CLEAN ELECTRICITY OPTIONS

The City has good and improving opportunities to obtain clean electricity that score well against all the various evaluation criteria as summarized in Table 5. As the price of renewables declines, the cost of the purchase of 100 percent renewable power will also decline. However, after the point at which these cost curves plateau the cost savings from waiting diminish greatly. For example, both onshore wind price projections show that, after 2030, inflation-adjusted prices will decline less than one percent per year. At this point, from the standpoint of the going-forward cost of power there is little to gain by waiting to make an all-renewable purchase.⁸ In view of all this, policy actions include:

1. Adopt policies that ensure that every rooftop that can cost-effectively host solar PV panels within the city install PV systems by 2050.
2. Hold competitive solicitations leading to the purchase of Mass Class I RECs or carbon-free electricity (directly or “virtually”) on behalf of all Bostonians who do not voluntarily purchase 100 percent carbon-free power.
3. Require energy users to procure zero carbon energy sources.
4. Hold these solicitations every two years, purchasing a portion of the total required to decarbonize all power use within the city in each solicitation. Purchase the balance required to reach 100 percent carbon-free electricity use in 2030.
5. Select specific offers from the solicitation based on an evaluation of the tradeoffs (if any) between the NPV of offer prices and the economic development, equity, and resilience benefits of each offer, as illustrated in the example.

In view of all these considerations, procurements should be made from a portfolio selected by the evaluation bids for all the technologies and purchase options against our criteria. Recognizing that purchases occur in ten- or fifteen-year contracts whose prices are typically fixed for the duration of the contract, the logical phasing of this policy would be to begin purchasing as soon as possible, but purchase added supplies every year or two such that the total percentage of clean power increases cumulatively until it reaches 100 percent by approximately 2030. The initial purchases can represent smaller fractions of the cumulative required purchase, than fractions purchased in later years, when costs are lower. This would cumulate carbon savings year after year towards the goal of carbon neutrality, while taking advantage of future lower prices and the likely availability of new carbon-free options.

⁷ There is no global policy benefit to doing a VPPA in an area with a grid less carbon intensive than the ISO-NE grid.

⁸ Note that the total cost of supplying Boston with carbon-free power may include costs from transitioning between power suppliers and supply arrangements, administrative costs, and other cost elements not reflected here. These costs can be estimated after the City chooses its procurement approach and other elements of its purchase policy. The measurement of costs should include all costs ultimately born by Bostonians as the result of these changes.

Table 5. Summary of Illustrative Criteria Evaluation for Generalized Carbon-Free Electric Supply Options for Boston

Option	Required Approx. MWh Purchase Size	Predictability/ Volatility in Annual Costs*	Allocation of Financial Risks	Local Economic Benefits	Additionality	Resilience Benefits	Regional Acceleration
1A. REC Purchase Recouped via City Collections	Equal to Boston power use in target year for zero-carbon	Uncertain predictability and medium volatility	City assumes risks from purchase; ultimately pass through to citizens	Yes	Good for certified Class I RECs	Medium	Yes
1B – REC Purchase Recouped via Power Suppliers	Equal to Boston power use in target year for zero-carbon	Uncertain predictability and medium volatility	City's price risk passed on to suppliers and ultimately to customers	Yes	Good for certified Class I RECs	Medium	Yes
2A. Local Physical Purchase Resold via CCA	Equal to Boston power use in target year for zero-carbon	Good predictability and low volatility	City assumes take-or-pay (quantity risk) and possibly price risk	Yes	Certain	Medium	Yes
2B. Physical Purchase Resold via Supplier Mandate	Equal to Boston power use in target year for zero-carbon	Good predictability and low volatility	City's price risk passed on to suppliers and ultimately to customers	Yes	Certain	Medium	Yes
3A. VPP Recouped via City's Collections	Fewer MWhs purchased if bought from market where carbon intensity exceeds ISO-NE	Good predictability and high volatility	City assumes price basis risk only. Passed on to citizens	Negative	Certain	Low	No
3B. VPP Recouped via Supplier Mandate	Fewer MWhs purchased if bought from market where carbon intensity exceeds ISO-NE	Good predictability and high volatility	Passed onto suppliers, who may or may not pass onto customers	Negative	Certain	Low	No

Notes: costs include total monetized cost, excluding transfer payments.

*Assumes all options are triggered with similar start dates. Absent changes to the MA RPS law, a recent Synapse/SEA study (Knight et al. (2017)) predicts that MA Class I REC prices will fall to approximately \$1/MWh due to oversupply.

7 SUSTAINABLY SOURCING LOW-CARBON FUELS

The combustion of natural gas, diesel, fuel oil,⁹ and gasoline accounts for approximately 60 percent of Boston's GHG emissions [2]. Natural gas is used predominantly for building heating services, and to a lesser extent used in the cogeneration of electricity (Table 7). This gas is delivered to customers primarily by National Grid, with a small amount delivered to mostly residential neighborhoods in southwest Boston by Eversource. A small amount of natural gas is used for transportation services. Less information is available for the consumption and delivery of liquid fuels in the city because they are delivered by a large number of small distributors rather than a single dedicated utility. Residential consumption of liquid fuel, other than gasoline, is predominately for household heating, while commercial use is likely a mix of heating and backup generation. About 36 million gallons of fuel oil were consumed in 2016. Most fuel oil contains about 5 percent biodiesel. Gasoline (163 million gallons) and diesel fuel (39 million gallons) dominated liquid fuel use in transportation in 2016. Gasoline is blended with 10 percent corn-ethanol to meet air quality and renewable fuel standards (US EPA, 2015). Biodiesel or biodiesel blends are used in a small segment of vehicles.

This section evaluates potential options for sustainably sourcing low-carbon fuels for services within the city. Our review below identifies substantial challenges and promising opportunities in this space. We have hesitated to explicitly represent these technologies in our illustrative pathway in the Summary and Technical reports even though this pathway still exhibits a significant demand (~25 percent of 2015) for methane. This is due to the hazier technological pathway associated with renewable fuels. Bioenergy technologies are challenged by poor lifecycle performance. Waste-based energy resources have promise, but are potentially limited. Renewable hydrogen is effectively a storage mechanism for renewable electricity that could materialize in the long run. More analysis is needed in the latter two cases before we would feel comfortable including them in a decarbonization pathway for Boston. As such, the City may need to be prepared to offset systems that are difficult to decarbonize.

Finally, it is important to recognize that if methane remains a fuel, it is still a greenhouse gas that is 28 to 100 times more potent than carbon dioxide, regardless of whether it is biogenic or fossil-sourced. As methane moves through the pipeline system, emissions occur through intentional venting and unintentional leaks; together these are called "fugitive emissions." Eliminating these emissions is essential to reaching carbon neutrality. There is considerable uncertainty regarding the rate of fugitive emissions, but it appears that the Boston metro region is characterized by rates of fugitive emissions that are consistent with the most recent national estimates of one to three percent of gas supply. National Grid, the city's supplier of natural gas, replaced about 550 miles of leak prone pipe (LPP) from 2013 to 2017 in its Boston gas territory, and set a goal of 100 percent replacement of pipeline in less than 25 years. The City should continue work with the state, National Grid, and other stakeholders to hasten the elimination of pipeline leaks as a critical ingredient of a carbon-neutral city.

⁹ Diesel fuel and fuel oil (#2) are compositionally similar and are sometimes used interchangeably.

7.1 BIOENERGY

The sustainability and carbon emissions associated with bioenergy are challenging to assess. The carbon intensity of a biofuel depends on the fuel type, its feedstock, cultivation, and processing; how it is transported; and its method of consumption. The bioenergy supply chain is a complex network of agricultural and forest ecosystems, agricultural supply chains, regionally heterogeneous biomass feedstocks, and multiple potential conversion pathways. The costs and benefits of bioenergy vary with the time horizon and regional scope of the assessment [10]. While some biofuel supply chains have the potential to sequester carbon (e.g. biochar [11]), others have GHG emissions greater than that of fossil fuels [10].

Bioenergy can be derived from a spectrum of sources ranging from intentionally cultivated bioenergy crops to waste biomass that would have otherwise decomposed with little realized value. Large-scale use of the former can drive land use change and emissions from land use change [12], consume water resources [13], promote nutrient overuse [14], and compete with food crops for these resources raising the price of food [15]. Alternatively, waste biomass can provide sustainable solutions both as an energy source [15], [16] as well as the reduction and valorization of waste streams that may otherwise end up in landfills [17].

Waste bioenergy has the potential to lower the carbon emissions associated with fuel consumption without straining natural systems. Some organic waste streams are locally available, such as food waste, municipal wastewater, and animal waste. The Deer Island Wastewater Water Treatment Plant is, to a large degree, self-powered on the wastewater that it is treating (see Carbon Free Boston Waste Technical Report). Reclaiming organic waste for energy from Boston's commercial and residential waste streams could generate 618 TJ of methane, meeting approximately 13 percent of the fuel demand in 2050. Peri-urban agriculture in the metro-region and other industries within New England may also provide sustainable waste streams for the city. Utilization of local organic wastes to generate energy could enhance regional economic development and provide a cost-effective disposal solution. Nationally, the energetic technical potential of organic waste streams is estimated to be approximately 1 EJ [18] which could meet much of the country's fuel needs in a highly electrified future.

7.1.1 Liquid Biofuels

The climate benefits of biofuels are challenged by the sustainable sourcing of feedstocks and highly energetic conversion processes, both of which can significantly influence lifecycle GHG emissions [19]. Ethanol from corn offers little if any carbon benefit due the intensive use of fossil fuels in its supply chain, and to the land use changes it can drive. On the other hand, liquid biofuels, in particular, biodiesel, are viable substitutes for liquid fossil fuels in vehicular (e.g., heavy duty trucks and ferries). Biodiesel can be rendered from various bio-oils (e.g. vegetable oils, animal fats), and the biocrude product of the thermal conversion of various organic waste stocks [20].

Most diesel and fuel oil already include approximately 5 percent biodiesel, and blends of approximately 20 percent can be used without stressing existing equipment. One hundred percent biodiesel has been demonstrated in vehicles and backup generation systems. Higher concentrations of biodiesel may require adjustments to storage and combustion equipment, primarily due to the fuel's potential to corrode and degrade engine materials.

7.1.2 Renewable natural gas

Renewable natural gas can be dropped-in to existing supply and use systems with no change to existing equipment. This makes it a strong candidate for urban carbon mitigation strategies, especially for decarbonizing systems that are reliant on natural gas. The important caveat here is that gas produced from some biological sources have life cycle energy cost and land use impacts that limit their climate and other environmental benefits [21].

A common pathway for the production of renewable natural gas is the anaerobic digestion of organic wastes such as manure, sewage, food waste, and other biological material. Anaerobic digestion is a relatively mature technology that also generates a nutrient rich solid in addition to methane gas. Regional organic waste streams (food and agriculture) could be used as a feedstock for the production of renewable natural gas [22]. The solid nutrient rich residues could replace synthetic fertilizers manufactured from fossil fuels. The production of renewable natural gas is an area of significant market growth, both nationally [23] and locally.

Thermal gasification is a less common, but emerging, technology that can convert biomass or plastic wastes to natural gas. This process has been widely used for coal in the past to generate methane but could be used on waste biomass to generate renewable gas. The conversion of plastics would result in a fossil-carbon fuel. The air quality impacts of thermal gasification would be influenced by facility design.

A review [16] by the World Resources Institute found that renewable natural gas could deliver carbon reductions if it is produced from waste, and that its use lowers overall methane emissions into the atmosphere. Resource assessments for anaerobic digestion in Massachusetts range from 5,100 TJ [24] for anaerobic digestion of organic municipal solid waste and agricultural wastes, to 31,600 TJ if thermal gasification of solid wastes was included [25].

The Anaerobic Digester up the Road

In 2017 Crescent Farm and Vanguard Renewables came to an agreement with the City of Haverhill to build a 100-ton anaerobic digester. By using methanogenic bacteria to break down organic waste, it can produce up to 7,700MWh of electricity annually in the form of combustible biogas. It is the first of its kind for the city of Haverhill and the sixth of its kind in the State. The digester produces excess electricity, which is sold back to the City of Haverhill in the form of credits. The agreement saves the City \$0.05/kWh for the amount generated. The digester provides enough to power 950 homes in the nearby area.

The digester is fed a total of 30 tons per day (TPD) of manure from 200 cows, 20 TPD from Crescent Farm and 10 TPD from the neighboring Shaw Farm. The manure is mixed with pre-consumer organic waste and heated to 104 degrees F for 30 days. During the month, methanogens will break down the mixture, creating natural gas in the process. At the end of the process, the methane is harvested and used to produce electricity. Leftover is an organic liquid fertilizer and solid materials that can be dried and used for cattle bedding.

In addition to financial benefits, the installation of the digester yields sustainability and environmental benefits as well. Michael Davidowicz, the owner of Crescent Farm, no longer spreads as much manure on his land, which reduces costs and the smell for nearby residents. Local businesses can divert their organic waste to Crescent Farms for digestion, which works in tandem with the state law that bans certain organics diversion to landfills. This helps the environment in turn by reducing the nitrogen and phosphorous loads in the surrounding ecosystem.

7.1.3 Solid Biomass

Biomass combustion can generate electricity and/or heat from the burning of solid organic matter such as wood pellets. However, the use of dedicated crops or forest material face the same challenges of biofuels: their dedicated cultivation can drive unwanted land use change and competition with food crops and other land uses. The carbon emissions associated with consuming dedicated woody biomass for example may be substantial due to the decomposition of residual biomass (stumps and roots) and soil disturbance, both of which can release CO₂ to the atmosphere after harvest [26]. While this carbon is of biogenic in nature, this biomass is a temporary store of carbon, that if released on a large scale could cause a net increase in atmospheric emissions if biological uptake was too slow to replace the released carbon [27]. Waste wood products may be able to demonstrate carbon reductions, but their use may come at an opportunity cost of long-term sequestration potential if the biomass could be incorporated into a product such as particle board [28].

Unlike renewable natural gas, biomass would not be a “drop-in” solution for current energy systems in Boston. Switching existing energy plants to biomass would require new systems for boilers, emissions control, transport, and storage. Such a transition will likely have substantial costs and ultimately may not deliver the requisite carbon reductions in the absence of a sustainable source of biomass.

7.2 RENEWABLE HYDROGEN

Hydrogen is a versatile synthetic fuel that burns at high temperatures with no CO₂ emissions at the point of combustion. Hydrogen has a very low volumetric energy density (energy per unit of volume), but its mass energy density (joules per kilogram) is very high. The dominant methods of producing hydrogen

today uses natural gas in a process that emits CO₂, or as a byproduct of petroleum refining. But hydrogen can be produced with no GHGs by electrolyzing water with renewable electricity. Other carbonless production pathways, including the use of carbon capture and storage (CCS), are possible. Hydrogen's versatility lies in the fact that it can directly generate electricity via a fuel cell, or release heat through combustion. Its ability to be stored at high volumes makes it a suitable long-term storage medium for surplus electric power.

This versatility and storage potential could position hydrogen as an ideal fuel to deliver thermal and backup energy services. Hydrogen could be blended into existing natural gas distribution systems to approximately 5 to 15 percent under current distribution and end use technologies [16]. Hydrogen blending would not alone decarbonize the gas system, but it would significantly lower the emissions intensity of gas use, and augment renewable natural gas resources.

A major barrier to hydrogen is cost. Current delivered hydrogen costs are approximately 15-25 times that of natural gas. The cost of developing a delivery infrastructure for hydrogen is large. Hydrogen can be transported under pressure via pipeline or truck, liquefied by refrigeration, or by using ammonia as a carrier. There are many large dedicated hydrogen pipelines already working around the world, generally associated with chemical plants or refineries, but these are mainly individual pipelines. Northern Gas Networks of the United Kingdom has drafted a plan developed a hydrogen-fueled infrastructure in Leeds UK [29], but this project is still in the planning phase.

To launch hydrogen as a potential solution, small demonstration scale projects are needed to show that hydrogen can be generated on or near-site and be stored or used to support building thermal demand. For this to be feasible renewable electricity costs will likely need to decline significantly. As such, hydrogen would likely evolve as a long-term solution to thermal decarbonization, servicing buildings or processes that need a combustion-based source of fuel.

7.3 SYNTHETIC NATURAL GAS AND LIQUID FUELS (ELECTROFUELS)

Synthetic natural gas (SNG) can be generated using the Sabiter reaction of hydrogen and CO₂ performed at high temperatures. For this process to generate a low-carbon synthetic natural gas, renewable hydrogen would need to be reacted with a source of CO₂. Such CO₂ streams currently are limitedly available from ethanol production and some industrial processes, future streams could include a fossil fuel plant, or Direct Air Capture of CO₂. The extra production step and utilization of captured carbon would incur an additional energy penalty on top of that incurred by the production of feedstock hydrogen.

SNG has potential as long-term storage mechanisms that exceed both the size and charge-durations of batteries. Such fuels could be generated from surplus renewable energy during periods of high generation and low prices, and subsequently discharged to generate electricity at periods of higher demand and low supply. The deployment of these technologies could enable the grid to meet the increased load due to electrification.

The potential of synthetic fuels as a thermal commodity fuel alternative to current fossil natural gas use is less likely. Becker et al. [30] performed a technoeconomic analysis on SNG as part of a power-to-gas strategy. The most optimistic case using the U.S. DOE's target hydrogen production costs (2.2 \$/kg) found a production cost of \$2.9 per therm of SNG. Current production prices of natural gas range from

(\$0.3-\$0.5 per therm). Approximately \$0.25 of the cost of SNG can be attributed to the sourced captured carbon, which was assumed to cost \$40 per tonne, a standard estimate of the cost and delivery associated with captured carbon.

Deep decarbonization efforts imply a high value to sequestering carbon in the ground. The use of captured carbon to create a commodity fuel would thus incur an opportunity cost compared to sequestering the same carbon. The implied cost of captured carbon would thus be higher as carbon sequestration would likely incur a subsidy. Lehtevier et al. [31] demonstrated this dynamic with synthetic liquid fuels, showing a negligible likelihood of adoption under scenarios that included carbon capture and storage (CCS), and modest adoption (~15 percent of market share) under a no-CCS scenario, with the limiting factor being the cost of production.

Given the higher costs associated with SNG, additional value in its application would likely be needed to justify its high cost. These are likely to come from time and location. For example, SNG could be used as a low-carbon seasonal peaking fuel enabling the grid to meet the higher demand levied by electrification. It is not clear what advantage SNG may have over hydrogen in this regard, other than a potentially longer geologic storage potential.

Searle et al. [32] suggested that liquid synthetic fuels may be “more economical and have a greater potential market share than gaseous fuels”. Thus, given the high costs of producing carbon fuels it might make sense to focus on liquid fuels that could provide time and locational value by supporting on-site generation during periods of high demand. Lehtevier et al. [31] did not assess this case in their analysis.

7.4 THE ROLE OF LOW CARBON FUELS IN REDUCING BOSTON’S EMISSIONS

In recent years decarbonization of fuels has been viewed as a secondary strategy to efforts to generate renewable electricity and electrify services that have historically been reliant on fuels. One reason for this has been differing pace of reduction in cost and carbon intensity in the technologies in the renewable fuel and renewable electricity sectors. Costs of renewable electricity generation and electrification (batteries, heat pumps and EV’s) have declined rapidly over the past decade while renewable fuels have struggled to show material reductions in cost and carbon intensity. Bioenergy in particular has had significant challenges due to concerns of the environmental impacts of energy crop cultivation and land use change. Generating renewable, low carbon fuels generally requires substantial energy inputs yielding large efficiency losses across the production chain compared to fossil fuels; while site-based electrification of cars and shifting to electric heat pumps increases efficiency. Still, low-carbon fuels can still play a role in decarbonization emissions by providing energy for systems that are difficult to electrify or in peak demand events where the cost of delivering carbon-free electricity may be high. Ensuring that low-carbon fuels can play a role will require an acceleration their development.

The current market for renewable fuels is not as well established as that for renewable electricity. The federal Renewable Fuel Standard (RFS) [17], however, does establish a market for the renewable attribute of various liquid biofuels for transportation, including biomethane from anaerobic digestion. The program establishes the *renewable identification number* as a credit mechanism similar to a RECs. RINs can be traded and ultimately retired by an obligated party or voluntarily. RINs encapsulate the statutorily defined renewable attribute of the fuel, *but* do not necessarily imply low-carbon status. As noted above corn ethanol produced to meet the RFS generates substantial life cycle GHG emissions.

The RFS has had challenges meeting mandated production levels, notably in its cellulosic and advanced fuels requirements. Starting in 2022 the RFS will be no longer subject to the renewable statutorily defined production levels. This has left its status uncertain, but it will likely continue on in some form until a clear mandate from Congress is set. Given the limited application the RFS to transportation fuels, its challenges, and future regulatory uncertainty, Boston should look beyond it to focus on demonstrating the utility of waste bioenergy and advanced alternative fuels in urban climate mitigation.

For renewable fuels to play a role in decarbonizing the thermal sector, a more nutritive policy regime must develop. Across the states, there have been several attempts to integrate a renewable thermal standard alongside state renewable portfolio standards [33]. In Massachusetts, this has taken the form of the Alternative Portfolio Standard which includes provisions for biogas and biomass alongside solar thermal, heat pumps and geothermal [34]. The program is linked to the state's RPS, but has been escalated at a slower rate than the RPS. Separating out a distinct standard and increasing the required generation amount could help to spur the deployment of renewable fuels. However, the life cycle emissions of many renewable fuels are uncertain, and can vary substantially depending on production site design, fuel feedstock source, delivery logistics, and other factors. The California Air Resources Board publishes a list of emissions coefficients for a number of renewable fuels [21]: the large diversity of potential calculated values for a given fuel demonstrates that linking renewable fuels into carbon reduction efforts is a challenge. The City could advocate for additional development of a thermal standard given the requirements of its building stock on a variety of thermal systems. This could promote a variety of renewable fuel technologies in the region.

The City can also foster an innovative ecosystem to promote the transformation of its diverse thermal systems that can leverage renewable fuels smartly. Near-term retrofits or new building projects where full electrification may face challenges should incorporate the use of renewable or low carbon fuels to provide peak demand support. Local development of anaerobic digestion to process food and other organic wastes could supply a stream of renewable natural gas. Such digesters could incorporate renewable hydrogen generation to generate feedstock H_2 that can be used to improve the methane yield from biogas to improve via the Sabatier process [35]. Large scale local renewable hydrogen generation could be implemented in or near the city, but will likely not be a practical pathway until costs decline and more renewable electricity becomes available.

While renewable fuels can help to facilitate Boston's decarbonization, they should not be viewed as an alternative option to electrification. Future cost and carbon intensity reductions are too uncertain to defer action on electrification and efficiency. Renewable fuels are likely to play a role in Boston's decarbonization efforts but should be prioritized to be used:

1. In end uses that are difficult to electrify or are reliant on combustion;
2. In applications that provide location and time-based energy generation value
3. Only when the sources are certified as wastes or certified as part of a sustainable and low-carbon supply chain.

8 DISTRICT ENERGY

District or distributed thermal energy systems have been a part of Boston's energy infrastructure for over a century. In 2017, large-scale district systems provided heating to approximately 70 million square feet of floorspace in offices, hospitals, laboratories, hotels, and residences (approximately 10 percent of

the city's built environment). These systems range in age, efficiencies and technologies, from steam generation and delivery to state-of-the-art trigeneration systems integrated with microgrids. All of these systems are currently dependent on fossil fuels.

As Boston grows it will have a number of opportunities to smartly plan future developments. Boston's New Smart Utilities Policy calls for large developments to consider the use of district systems. Such systems further aim to provide in-city generation of electricity, which supports local resiliency efforts to protect critical services in the city from climate-related or other disasters. Further, new systems can enhance their overall efficiency by integrating with thermal storage and demand management technologies.

Ultimately, even the most efficient of these systems rely on the combustion of a fuel. Right now, natural gas is the predominant fuel with oil providing some backup and peak services. Electrified district-scale heat pumps may be practical in some situations but may lack resiliency benefits and flexibility. The resiliency predicate would likely require systems to be reliant on combustion or provide sufficient storage.

Boston's future carbon-free district energy systems may integrate several different technological and carbon abatement options that reflect the situational changes that need to be made to current systems as well as future ones. Ultimately the City and its constituents need to find a balance and accept tradeoffs between the need for local, resilient energy generation and the goal of carbon neutrality.

8.1 THE VALUE OF DISTRICT ENERGY AND ITS USE IN BOSTON

Space heating and cooling needs can be satisfied by using low-temperature heat sources. District systems can be used to distribute low-grade energy which can be obtained directly from combustion or a byproduct of other processes. Combined heat and power (CHP) district systems are seen as highly efficient because they utilize both the high-grade and low-grade heat produced from combustion. The generation of electricity from high-grade heat results in the creation of significant amounts of low-grade heat. Many extra-urban electric generation plants dump this low-grade energy using large cooling towers or natural water resources. The proximity of buildings in an urban environment creates the opportunity to use this low-grade energy for space heating via a pipeline distribution network. The sale of this waste heat can be used as a second revenue stream for the generator, leading to more favorable economics in addition to the higher overall efficiency of energy use in the system. Table 8 lists additional associated benefits of district energy systems.

Table 6. Summary of benefits from district energy systems

Benefits	Description
<i>Operational Efficiency Gains</i>	Combined heat and power and trigeneration plants (to be discussed later) operate at much higher efficiencies, up to 90 percent [36]. In comparison, if these services were provided separately with fossil fuels, overall efficiency would only be around 50 percent [37].
<i>Utilization of Local Renewable Resources</i>	Allows different local resources streams such as waste heat, water bodies and renewable energy that are unique to each city to be utilized. With urban densification and population growth, the inclination to adapt and integrate these local streams is essential to sustainability and the future.

Benefits	Description
<i>Reduced Greenhouse Gas Emissions</i>	Reduced Greenhouse Gas Emissions due to fuel switching from harnessing more local renewables and improved operational efficiency, leads to decreases in primary energy consumption of 30-50 percent [38].
<i>Air Quality Improvements</i>	Improvements from reduced fossil fuel consumption lead to additional co-benefits from associated health impacts.
<i>Resiliency Improvements</i>	Improvements from reduced reliance on imports, fossil fuel price volatility and utilization of local renewable resources. District energy systems also allow for local management of electricity demand reducing the risk of brownouts. Storage allows for continued electric and thermal energy in the event of a blackout or supply cutoff.
<i>Equal Energy Access</i>	Access from utilizing more local resources and a reduced reliance on fossil fuel leads to less energy price volatility. Under the proper oversight, this provides more equitable access for all households to keep the heat on. Space heating has historically made up the highest percentage, 59 percent, of a Massachusetts household's energy expenditure [39].
<i>Flexibility</i>	Buildings connected to a district system share a central plant. This approach allows for flexibility in the design, operation and improvement of that central plant. This could include switching the central plant from a carbon emitting fuel to a low-to-zero carbon fuel and using thermal storage.
<i>Green Economic Development</i>	Development from local employment in the design, construction, operations and maintenance of district energy systems. Investments in peak generation infrastructure are deferred or avoided, allowing for cost savings.

District energy systems provide distributed thermal energy regulation from a central plant. Typically, thermal energy is generated through a combustion process at a centralized plant. The thermal energy is delivered to consumers through the circulation of a fluid, such as steam, hot water, chilled water or some combination thereof. Once the thermal service has been delivered, the fluid is returned to the central plant in a loop. District energy systems remove the need for decentralized onsite thermal systems, allowing for centralized operation and maintenance of these systems. These properties position district energy systems as more energy efficient, resilient, easier to maintain and have reduced operational and maintenance costs when compared to individual building systems. While these efficiencies are substantial, most thermal district systems are still reliant on the combustion of fossil fuels, which may conflict with carbon neutrality goals.

The first generation of district energy systems emerged in the late 1800s to provide heating to nearby buildings in the form of steam. Although outdated, these types of heating systems are still common in older cities, including Boston. In the mid-1900s new district systems became more efficient by abandoning steam in favor of pressurized hot water (100°C). These systems were sometimes coupled with large mechanical chillers to provide cooling services using the same or a parallel fluid loop.

Many modern systems take advantage of cogenerating heat and electricity as described above to maximize the energy obtained from combustion processes. In these systems, steam is used to drive an electric generation turbine and then condensed water is used to deliver heat, often at lower temperatures (< 100°C) than older systems [40]. Trigeneration involves using this heat to power an absorption chiller to provide cold water for cooling at much higher efficiencies than conventional air

conditioning. Additional efficiency gains have been achieved by coupling these systems with waste heat or local renewable energy sources.

Boston's systems span most of these technologies (Table 9, Figure 10). The foundation of these systems were laid over a century ago as central plants in the downtown area serviced nearby buildings through a network of underground pipes. Systems at Boston's universities and hospitals were laid down as these institutions experienced periods of rapid expansion. Central plants came and went, but these pipe networks remained largely intact and expanded as growth continued. The Charles River wasn't a barrier as Harvard expanded its campus to North Allston and piped over steam from the Blackstone Street plant. The downtown steam loop was eventually linked up with the Kendall Plant in Cambridge. As Boston became a medical research and care powerhouse, Harvard's medical schools and hospitals in Longwood outgrew their turn-of-the-century facility and required a *total energy* solution that produced heat, chilled water and on-site electricity for backup purposes. Despite its promised high efficiencies, the Medical Area Total Energy Plant (MATEP) project, was met with opposition from residents and regulatory challenges. Its cost ballooned from a budgeted \$40 million to \$350 million, and was eventually sold at a loss. Recent upgrades to its combined heat and power turbines have increased its efficiencies.

Most of the plants listed in Table 9 generate steam, despite the fact that they were built long after hot water became a preferred heat transfer fluid. Hot water is preferred due to the high energy demand associated with the phase change of liquid water to steam, leading to lower efficiencies with steam. This legacy is problematic because it has locked in this less efficient heat transfer medium as steam pipes and water pipes are usually incompatible. Converting the 22 miles of the downtown network to hot water would ultimately be expensive and disruptive. This limits the potential efficiency gains associated with Boston's existing systems.

Table 7. Summary characteristics of existing district energy plants and systems in Boston.

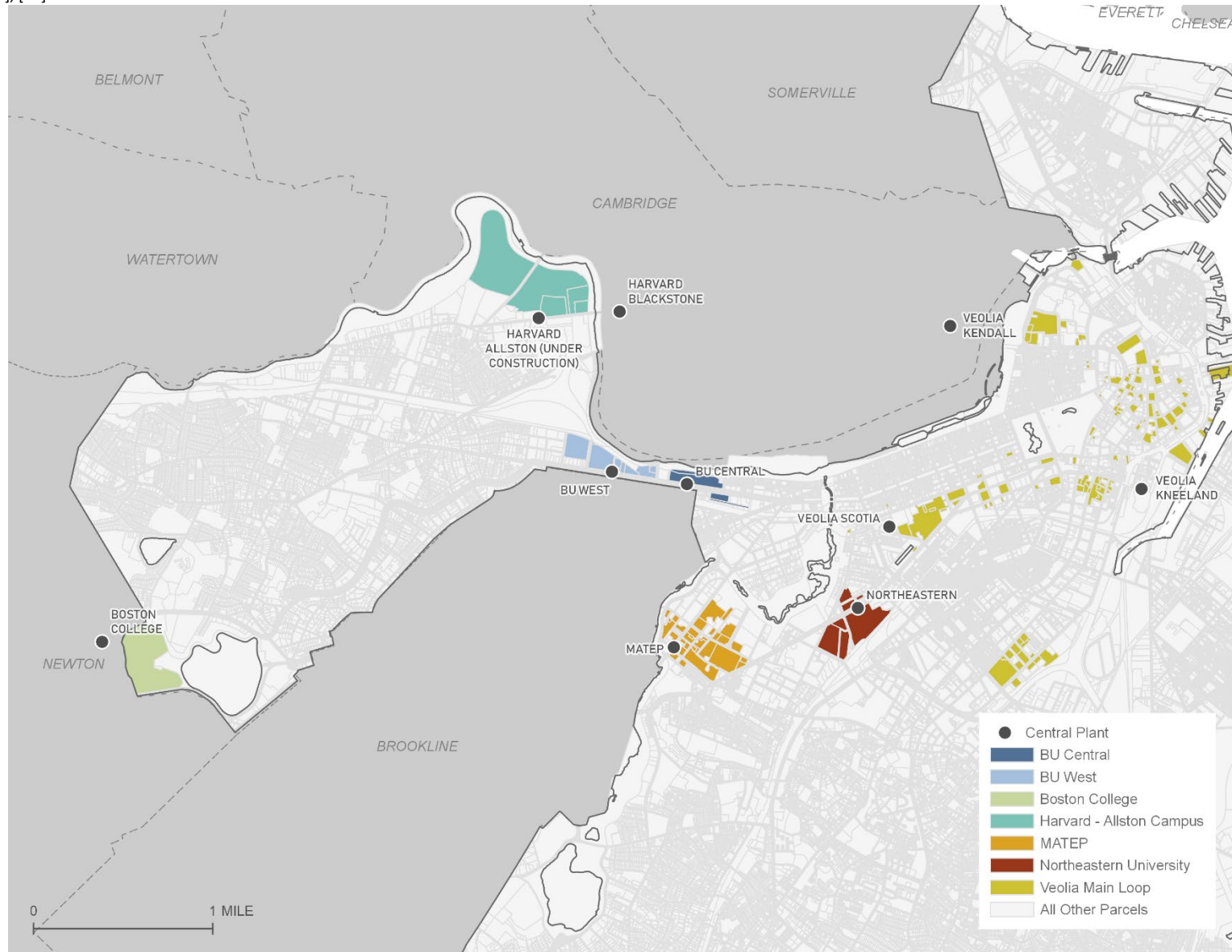
Year Commissioned indicates year of central plant construction or conversion to district energy. Associated distribution systems may be older.

Central Plant <i>Linked-System</i>	Year Commissioned	Technology (Transfer fluid)	Approximate Million Sq. Ft. Served [41], [42]	Max Steam Capacity (Mlbs per Hour)	CHP Electricity Capacity (MW)	2015 CO ₂ Emissions (t) [43]
Kendall* <i>Downtown</i> [44]	1949	CHP Cogeneration (Steam)		1,200	253.6	797,969
Kneeland <i>Downtown</i> [44]	1928	Large Boilers (Seasonal & Peak Steam)	38.9		N/A for Kneeland and Scotia	108,736 (Kneeland and Scotia)
Scotia <i>Downtown</i> [44]	1930	Large Boilers (Seasonal & Peak Steam)				
MATEP [44]	1986	Trigeneration (Steam and Chilled Water)	12.7	1,000	84	236,651
Boston College* [45]	1948	Large Boilers (Steam)	2.2	370	N/A	21,403
BU Central	1964	Large Boilers and Chillers (Steam and Chilled Water)	3.2	-	N/A	51,611
BU West	2000	Large Boilers and Chillers (Steam and Chilled Water)	3.4	-	N/A	
Harvard* [46]	1930's	CHP Cogeneration (Steam)	3.2	-	12.5	71,028
Northeastern [47]	1890s-1900s	Large Boilers (Low Pressure Steam and Hot Water)	4.8	145	N/A	31,967

*These plants are located outside the City of Boston. The service area reflects only the buildings served within the City of Boston. The capacities and emissions represent the entire facilities.

Figure 9. Location and parcels served by district energy systems.

Source: [41], [42]



Emergent district systems operate at lower temperatures which allow for increased efficiencies and the ability to provide service to a larger range of low density areas. Enhanced control systems, monitoring and dispatchability enables improved integration of district technologies with service demands and electricity delivery. Thermal storage and microgrids, can further enhance the reliability, resiliency and efficiency delivered by district systems. Such systems would allow district systems to take advantage of temporal differences in energy demand and supply. Conceivably district systems can reduce their reliance on fossil fuels or completely decouple from them. This could be achieved by using geothermal or other natural heat sources such as waterbodies by concentrating and transporting heat energy from these sources. These tend to come at higher costs and are of limited availability.

Due to their efficiency gains, multiple product streams, and economics of scale, district energy systems can be financially attractive. The large capital expense of constructing a central plant and distribution system, however, can be a barrier to its implementation. Effective urban and district planning coupled with favorable regulations is necessary to overcome this hurdle. Ultimately this requires some involvement of local governments in facilitating the deployment of district systems.

8.2 TECHNOLOGICAL PATHWAYS TO DECARBONIZING DISTRICT SYSTEMS

Prior carbon reduction targets, such as 80 percent emissions reductions by 2050 relative to a base year, positioned district cogeneration as potential sustainable solutions as such systems deliver high levels of efficiency of fossil fuel use. More ambitious carbon-neutral goals effectively proscribe the use of fossil fuels, necessitating either:

- decommissioning of district energy systems and replace building thermal service with on-site electrified thermal generation; or,
- Switching systems fuels to a sustainable zero-to-low carbon fuel source (bioenergy, H₂).

The former option precludes the ability to generate electricity to support local resilient microgrid systems. Further, decommissioning with a 2050 goal would imply the formation of numerous stranded assets, including facilities currently in the development pipeline, before they reach their expected end of life. This option may evolve out of economic necessity especially under scenarios that involve carbon prices. Or it may stem from institutional climate goals, such as those outlined in Boston University's Climate Action Plan, which anticipates electrification of buildings as a replacement of its aging district steam systems. While planning for and implementing such a transition may be more feasible for single-customer campus systems, there are examples of multi-customer steam systems shutting down. Decommissioning of such systems will necessitate regulatory oversight by the City to ensure that users transition to low-to-zero carbon thermal services.

If district energy systems are to remain a part of Boston's energy landscape they will need to demonstrate a path to carbon neutrality via efficiency gains and the adoption of alternative fuels. Efficiency gains could be attained through:

1. *Converting from steam to hot water distribution to attain higher efficiencies:* Such an approach would require a complete system rebuilding of both the central plant and the conversion of the distribution pipes as current steam pipes cannot deliver hot water. For larger systems this would be problematic, but this is possible for smaller systems operated by local universities. Such a

conversion could also preclude the use of steam for sterilization service in Boston's district energy-linked hospitals.

2. *Replacing thermal-only systems to co-generation or trigeneration systems:* This step would enhance local resiliency through the ability to generate electricity on-site.
3. *Implementing thermal storage technologies:* Storage in the form of hot water, cold water, or ice enables heating and cooling production to continue throughout the year. Systems can vary in size from large centralized storage near a district energy facility or decentralized in individual buildings. Depending on the type of technology used, storage periods can range from a few hours to months, and reduce the peak capacity of a system. First, thermal storage helps district systems reduce their demand on backup oil combustion which is more carbon intensive than gas. Thermal storage also allows for peak shaving and shifting, which can help to address intermittency issues associated with renewables and limiting the impact of electrification. When there is cheap or excess electricity, it can be converted to thermal energy and stored for use during peak periods.

A plan for the integration of low-to-zero carbon fuels into the facility will be necessary and a part of planning for in addition to these efficiency steps with existing systems, and for the deployment of new systems. Harvard University's new plant in Allston was designed to be able to accommodate a fuel switch in the future. The simplest fuel switch for most systems would be procurement of biomethane generated from a local agricultural or organic waste stream.

District scale heat pumps or electric boilers could also be used to provide thermal service. If these technologies were to be used, they would require a hot water circulation system, and greatly benefit from thermal storage. Air-, water- and ground-source heat pumps could conceivably be used, but would require a large thermal source/sink. Construction of ground source systems in the city would be costly. Water source heat pumps may be viable given the city's proximity to various waterbodies.

Alternative sources of low-grade heat were considered by Boston's neighbor in Cambridge's *2018 Low Carbon Energy Supply Strategy*. Most of these sources could be utilized, but are likely to be costly:

- Deep geothermal
- Waste heat from sewers
- Waste heat from the MBTA
- Heat recovery from substations
- Industrial heat recovery

There may be specific instances where one or a combination of these sources may be employed by certain projects within in the city. Opportunities to take advantage of such sources often arises if new systems (e.g. large developments) are being put into place or existing systems are being deeply retrofitted (e.g. sewer and MBTA repairs). The permitting process for project development should seek to identify such opportunities.

The Newest District System on the Block

In September of 2017, Harvard University finalized plans to build a 58,000 square foot district energy facility on their Allston Campus (DEF). Designed by Leers Weinzapfel Associates, the facility highlights flexibility in energy supply and resiliency in the face of climate change, critical to meeting Harvard's goals of becoming fossil fuel-neutral by 2026 and fossil fuel-free by 2050. By employing a wide range of technologies, the DEF can optimize the heating, cooling and electricity mix from both an efficiency and cost perspective depending on demand and external conditions.

The DEF will feature a 2.5MW cogeneration plant to supply electricity, heat and hot water to the campus. As the campus grows, the DEF was designed with the ability to expand the capacity of the cogeneration plant. The DEF will utilize a heat-recovery chiller and low-temperature hot water system, both of which further improve efficiencies. A low temperature hot water loop for a district energy system, as opposed to steam, is the first of its kind in Boston. By opting for low temperature hot water (140°F) rather than steam, the system is much more efficient and provides additional opportunities to capture waste heat from any future technologies. While the facility will still rely on natural gas, as more zero-carbon district energy technologies are tested and proven, the flexible design allows for easy incorporation.

Perhaps the most significant technology is a 1.3-million-gallon thermal storage tank that will hold excess chilled water, which can be used to cool buildings. The total storage capacity of the tank is equivalent to about 9 MWh of capacity and will be the largest of its kind in the Commonwealth. Chilled water will be produced during off-peak hours when electricity is cheaper and less-polluting and used during the day allowing for peak shaving. Construction of the DEF is expected to be completed in June 2019.

The DEF is also designed with resiliency as a focus. The original site of the facility was found to be vulnerable to flooding. The DEF will have no basement and the infrastructure throughout it will be elevated. Combined with its portfolio approach means that it is more resilient than conventional steam distribution systems. The innovative design sets an example for future district energy systems. Considering future expansion and taking a portfolio approach to district energy supply not only allows for resiliency benefits and GHG reductions but mitigates financial risk as well.

"The DEF sets a high standard of quality and resilient design, creating a visible demonstration of innovative practice in building, landscape, and stormwater management" - Jane Weinzapfel, Founding Principal at Leers Weinzapfel Associates

8.3 POLICY OPTIONS FOR DISTRICT ENERGY

The City of Boston has already begun taking the initiative on district energy through the Boston Public Development Authority (BPDA)'s Smart Utility Policy [48]. Part of the two-year pilot requires a district energy and microgrid feasibility assessment for Article 80 projects over 1.5 million square feet. Based on the analysis, a more detailed Master Plan and proposed development must be prepared and approved by a Licensed Professional Engineer. Storage and CHP are just two of the technologies that synergize well in a district energy system considered under the Smart Utility Policy and its Standards.

The City of Boston can also implement specific policies to promote district energy. The degree to which the City could force existing buildings onto an existing district energy system is limited. However, they can provide financial assistance in the form of loans, subsidies and other incentives to connect. It is worth noting that hot or chilled water district systems are currently not regulated through the Massachusetts Department of Public Utilities, whereas steam systems are.

In addition, the following policies would greatly support the development of district energy within the city by helping to ensure load certainty:

1. In addition to requiring existing boilers to switch to a carbon-neutral fuel, simultaneously also require new district systems to have a decarbonization strategy.
2. Incentivize carbon-neutral district energy systems in high density areas, where it can reach its fullest potential.
3. Simplify the development and permitting processes to provide access right away. Waive development, planning, or other fees if a new building connects to a carbon-neutral district system.

Ultimately decarbonizing district energy will require a mixture of efficiency gains, strategic electrification, and fuel decarbonization. This is consistent with those sectors of Boston's economy that are not connected to such systems. Achieving these goals will require an integrated, holistic planning process that examines the least-cost system for meeting electric and thermal loads within the city by 2050 and with zero carbon.

9 INTEGRATED LEAST COST CITY ENERGY PLANNING

9.1 WHY ENERGY SYSTEMS REQUIRE AN INTEGRATED APPROACH

The great majority of options considered in this report can be viewed independently of their delivery infrastructure. The adoption of energy efficiency measures, for example, properly assumes that the gas and electric utility systems continue to play their delivery role and that the costs of delivery do not change as energy efficiency adoption increases.

This assumption does not hold for major changes to the city's energy systems. Systemic choices involve changes to three stages of the energy system: the end use equipment inside buildings or other parts of the city, the local delivery infrastructure, and the production of the energy carrier wherever it occurs. As an example, a policy changing all district energy boilers to hydrogen would require three parts, each with its own cost: altering the boilers themselves to burn a new fuel, creating a new hydrogen delivery system within the city (pipelines or trucks), and sourcing the hydrogen from a carbon-free process. That energy system must be built in a technically coordinated manner; the technical capacity to deliver hydrogen is negated if there is no commercially viable, low-carbon source of hydrogen.

New energy systems are highly scale-dependent. A change to hydrogen boiler fuel is likely to be economical in the future only if there are many other users of hydrogen in the city, so that the production and delivery systems can attain a scale that justifies a large fixed investment. Of course, these are the same economic factors that caused the gas and electric systems to function as natural

monopoly utilities early in the 20th century. When a City action alters the economics of these systems, or adds possible new energy utility systems, a more complete policy analysis is needed.

Geography plays an important role in energy systems planning. Many of the policies in this report can be applied to all parts of the city, or only to whichever parts of the city make them most effective. Many energy efficiency measures are applicable throughout the city, while the equitable and effective expansion of mass transit involves examining the region beyond Boston to optimize any policies. In contrast, new district energy systems may be viable only in high-density neighborhoods. The research to determine the applicability of geographically-limited, scale-sensitive systemic options requires a district-by-district evaluation of the city.

The time dimension of systemic policies is also important. Infrastructure is financed over long periods of time, so policies that require new infrastructure must enable financing over a suitable period. While different forms of infrastructure take very different amounts of time to plan, permit, and build, the changes to create a new energy system must sync so that portions of the system do not sit unused for long periods of time. As noted above in regards to renewable electricity, the performance and cost of many system technologies in all three stages is improving, which makes selection of the policy implementation year an important choice.

The final unique challenge in evaluating energy system options is that they must be compared to other equally complex system changes. To build on the previous example, a policy that converts district energy boilers to hydrogen fuel should be compared to the option of changing the boiler to burn SNG (e.g. no change to the boiler but rather a question about the supply availability), or to its replacement with electric-based district scale heat pumps. Each option has its own scale-dependent system capital cost. In addition to possible boiler modifications, the alternate renewable gaseous fuel must be sourced in sufficient quantities and transported through a leak-free pipeline. In addition to new electric boilers or heat pumps, changing to an electric-based district energy system would involve large additional power demands that would undoubtedly require distribution system reinforcements as well as expanded carbon-free electric supplies to the city.

9.2 CATEGORIZING AND EVALUATING SYSTEM CHOICES

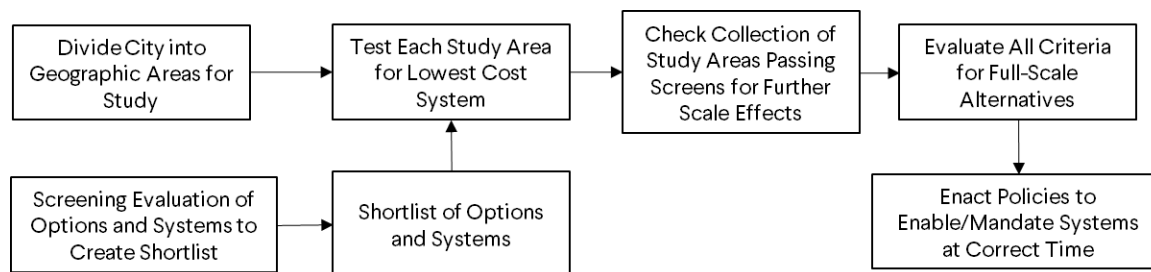
There are multiple pathways by which thermal and electric end uses can be served. Energy end uses can be supplied by direct solar or even wind energy, air or ground heat sources using electric heat pumps, waste heat from many processes, ecologically suitable water bodies, and renewable gaseous or liquid fuels. These diverse sources can deliver their energy via the power grid, gas grid, or a district energy system. Electric end uses can be served by generators fueled by every form of renewable energy, including fuel cells and/or CHP plants powered by renewable or decarbonized gases. If economical CCS becomes available before 2050, fossil-fueled sources of heat and electricity could be a part of Boston's GHG mitigation plan.

The multiplicity of pathways to provide decarbonized energy services makes it essential that Boston creates a manageable framework to evaluate the most likely systematic combinations of options that will yield affordable, equitable, and reliable clean energy services for the next three decades and beyond. Systemic choices and tradeoffs can be narrowed by examining three or four key alternative tradeoffs and options within a periodic evaluation process. One choice set is direct thermal service via district energy systems versus electrification served by the grid. This tradeoff applies only to thermal end

uses that have geographic density sufficient to allow aggregation to scale and thus service by district energy systems. One major alternative is to electrify each thermal use using the best feasible technology and then expand electric supply and delivery. Because electricity is typically more expensive to generate, deliver, and store, district energy with thermal storage may be cheaper, but may also involve much larger initial capital outlays and planning time. Other alternatives using new technologies may become available.

To evaluate these tradeoffs systematically, the City could conduct a periodic integrated analysis of its carbonless heat and power system options. Figure 12 shows one way such an integrated energy process could work. The process, which is largely an expansion of the process used by the City for its 2016 Boston Community Energy Study (BCES), begins by categorizing the City into logical districts that might be suitable for district energy using a screening tool that evaluates and aggregates cost-effective end uses. After creating a shortlist of end uses served and candidate cost-effective system and fuel combinations, one of which would often be electrification with an expanded grid, each district could be tested for lowest total energy service life cycle costs. The lowest-cost combinations from these districts would then be aggregated to the city or regional level to check projected future infrastructure costs at projected scale. Systems that passed cost-effectiveness screens would then be evaluated completely for equity, economic development, and other criteria. Systems that score well on these criteria should be considered for implementation by the City.

Figure 10. Proposed integrated energy systems planning and policy process



A process of this nature would require significant input from all stakeholder communities as well as specialized experts. The optimal process is open and transparent and recognize that technologies, costs, and other data are changing. The process would help spotlight the critical data and assumptions needed for system-level decisions, forcing greater attention to these critical inputs. For example, too little is currently known about the supply curve for renewable natural gas to determine whether this solution can be deployed at a scale that makes full decarbonization possible. Due to the extensive resources this process will require, it would be beneficial to conduct it every five years.

As noted, the proposed integrated energy systems evaluation process builds on the BCES. This study has already screened Boston communities to determine where expanded district energy systems might be cost-effective. The proposed new process would continue this work to examine specific alternative system expansion options and compare them to each other, including electrification of end uses and all economical, suitably large renewable heat sources. The process is also similar to the City of Cambridge's *Low Carbon Energy Supply Strategy* [49], studies by the National Renewable Energy Laboratory, and

studies performed by several EU cities. However, no city conducts this process completely, including consideration of all fuel options and accurate comparison to the cost of electric system expansion.

10 SUMMARY AND CONCLUSIONS

There are three main dimensions to the options for decarbonizing Boston's electricity supplies by 2050: the types or sources of carbon-free electricity to be purchased, the mechanism by which the supplies are purchased, and the timing or phasing of the purchases. The amount of clean power that Boston must purchase to reach carbon neutrality can differ based on its selection within these three dimensions, but that amount can be calculated for any particular combination of source, procurement mechanism, and timetable to full carbon neutrality.

The City already has several excellent options available for commercial clean electricity purchases, and more will become available in the future. Purchases during the next few years will probably consist of a portfolio of solar PV, onshore, and offshore wind. However, the City should allow any form of power recognized as a Massachusetts clean energy resource to participate in its purchase solicitations. As long as the required aggregate annual amount of carbon-free power is purchased, it is not necessary to match the time profile of purchased generation to the future demand profile of Boston.

The specific generation source options and procurement mechanisms that are competitively solicited by the City should be jointly evaluated according to cost to Boston electric customers, equity, economic development, contribution to resilience, and other criteria.

Because clean electricity is available now, the City can customize the time profile of procurements, leading to full carbon neutrality of the electricity supply well before 2050. The time profile chosen has important implications for customer costs, economic development, and many other criteria. Regardless of the portfolio of supply sources and procurement mechanism chosen, the City could choose a time profile that fully decarbonizes its electricity supply by approximately 2030. As noted earlier, forecasts of solar PV, onshore and offshore wind continue to decrease rapidly until 2030, when the costs declines begin to flatten. Additional electric needs resulting from decarbonization should also be sourced from clean resources.

The options for decarbonizing the portion of the city's direct energy use that will continue to rely on natural gas after all energy efficiency and electrification actions are less well-developed. Some gas demand can be transferred to electric technologies, which can be procured from a clean source. Renewable natural gas is technologically feasible, but is unlikely to be available in sufficient, economical quantities to fully supply the remaining gas demand. To contribute to a carbon-neutral energy supply, energy derived from biological sources must demonstrate certified sustainable and low- or zero-carbon supply chains within the same time frame. Some hydrogen use technologies are promising zero-carbon options for heating and cooling uses, but are not yet commercially viable.

Immediate actions involving natural gas and district energy systems should focus on advancing the City's understanding and use of the technologies that offer verifiably carbon-neutral alternatives to natural gas. A prudent option for the City is to perform integrated evaluation of-and immediate experimentation with-its future options for electrification and replacement of traditional natural gas or district energy with zero-carbon fuels.

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Peter Fox-Penner holds equity in Energy Impact Partners, a utility-backed energy investment and innovation firm, and consults for Energy Impact Partners and The Brattle Group on energy technologies. Dr. Fox-Penner also conducts research in areas of interest similar to the business interests of Energy impact Partners and The Brattle Group. The terms of this arrangement have been reviewed by Boston University in accordance with its financial conflicts of interest in research policies.

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ABBREVIATIONS

BCES	Boston Community Energy Study
BPDA	Boston Planning and Development Agency
CCA	Community Choice Aggregation
CCS	Carbon Capture and Storage
CES	Massachusetts Clean Energy Standard
CO₂	Carbon Dioxide
CO₂e	Carbon Dioxide Equivalent
CPP	Clean Power Plan
EV	Electric Vehicle
GHG	Greenhouse Gas
GPC	Global Protocol on Community Greenhouse Gas Emissions
GWSA	Massachusetts Global Warming Solutions Act
ISO-NE	Independent System Operator of New England
LCOE	Levelized Cost of Energy
MATEP	Medical Area Total Energy Plant
MBTA	Massachusetts Bay Transportation Authority
PPA	Power Purchase Agreement
PV	Photovoltaic
REC	Renewable Energy Credit (or Certificate)
RFS	Renewable Fuel Standard
RGGI	Regional Greenhouse Gas Initiative
RPS	Massachusetts Renewable Portfolio Standard
SNG	Synthetic Natural Gas
VPPA	Virtual Power Purchase Agreement
W	Watt
Wh	Watt-hour