ANALYSIS GROUP
ECONOMIC, FINANCIAL and STRATEGY CONSULTANTS

Wellesley Municipal Light Plant
Greenhouse Gas Emission Reduction Study

Phase II: Additional Considerations for a Low Carbon Transition through 2050

Paul J. Hibbard
Craig P. Aubuchon

Analysis Group Inc.
January 2019

Acknowledgments

This report reviews the implications of pursuing low-carbon energy supply and use strategies in the period 2030 - 2050, and how such strategies may affect the generation and consumption of electricity in the Town of Wellesley. It also reviews how a transition to decarbonization of energy use - in particular through electrification of transportation and heating sectors - would affect the provision of reliable electric service and recovery of associated costs by the Wellesley Municipal Light Plant (WMLP). Notably, it is at best difficult to understand how technological change will shape energy sector decarbonization over this longer-term period. With this in mind, the purpose of the report is to review potential paths to decarbonization, and consider ways in which the WMLP may anticipate, monitor, adapt to, and facilitate local, state and regional progress towards reducing greenhouse gases.

This is an independent report by Analysis Group, completed through a review of past and current data and research and analysis related to regional electricity market operations and technological and economic factors related to power sector greenhouse gas reduction options. Mr. Aubuchon contributed to this work as an independent consultant to the Analysis Group; Mr. Aubuchon also serves as an Asset Manager at U.S. Bancorp Community Development Corporation, where he manages a portfolio of more than 800 MW of renewable capacity representing more than $750 million of investment.

The report has benefitted from numerous discussions with staff and Board Members of the WMLP, an Ad-Goc group convened by the WMLP to provide input to and feedback on the report, staff of Energy New England (ENE), and other New England market participants. We wish to thank the WMLP, ENE, and the members of the Ad-Hoc group (listed below) for their assistance and input throughout the process. The report, however, reflects the judgment of the authors only, and does not necessarily reflect the opinions of U.S. Bancorp Community Development Corporation, WMLP, ENE, or the Ad-Hoc Group.

Paul L. Criswell, Esq.
David A.T. Donohue PhD, JD
James R. Gorman, MD, PhD
Ned Hall
Debra J. Healy
Richard F. Joyce
Robert D. Lampaa, PE, LEED AP
Donald H. Newell
Laura S. Olton, Esq.
John G. Tzimorangas

About Analysis Group

Analysis Group provides economic, financial, and business strategy consulting to leading law firms, corporations, and government agencies. The firm has more than 800 professionals, with offices in Boston, Chicago, Dallas, Denver, Los Angeles, Menlo Park, New York, San Francisco, Washington, D.C., Montreal, London, Brussels, Paris and Beijing. Analysis Group's energy and environment practice area is distinguished by expertise in economics, finance, market modeling and analysis, regulatory issues, and public policy, as well as significant experience in environmental economics and energy infrastructure development. The practice has worked for a wide variety of clients including but not limited to energy producers, suppliers and consumers; utilities; regulatory commissions and other public agencies; tribal governments; power system operators; foundations; financial institutions; and start-up companies.

Table of Contents

Executive Summary

Overview and Scope

In 2014, the Town of Wellesley Massachusetts established a goal to reduce its greenhouse gas (GHG) emissions from the electricity, transportation and building sectors 25 percent by 2020, relative to 2007 levels. This goal is similar to elements of the GHG reduction goals and binding requirements established for the Commonwealth of Massachusetts in the Global Warming Solutions Act (GWSA), as well as GHG reduction programs and priorities of other states. In addition, the WMLP has undertaken a number of measures to reduce the GHG emissions associated with the purchase and distribution of electricity to its approximately 10,000 customers. Notably, the WMLP has achieved reductions in total GHG emissions between 25 and 30 percent over the ten year period 2007 to 2017, depending on the quantity of existing renewable energy credits to be retired.[1] These reductions have occurred due to changes in the resources and operation of the regional power system, and through WMLP investments in energy efficiency, distributed renewable resources, and targeted long-term wholesale contracts for renewable resources.

The WMLP has supported the Town's efforts, and has evaluated its GHG emission portfolio and considered various ways to reduce the GHG profile of electricity purchased or generated to meet the needs of Town's residents and businesses. To aid this effort, the WMLP engaged Analysis Group to develop a comprehensive review of the feasibility for additional GHG reductions and the potential costs and benefits to the WMLP and its ratepayers of achieving such reductions.

A "Phase I" Study, based on current information and market expectations, presented and evaluated the suite of GHG emission reduction measures that are likely to be available to the WMLP in the near-term (that is, prior to 2030). The purpose of that Study was to provide the WMLP and its Board with data, information and insights that may be used to evaluate potential strategies for future GHG emission reductions, and to inform considerations related to the timing, measure, and scope of Wellesley's GHG reduction efforts. To inform near-term actions, that study primarily focused on measures that build from recent WMLP experience with demand side reductions in energy, supply side procurement of renewable energy, and the developing market for distributed energy resources. The Phase I Study also addressed the procurement of renewable energy credits (RECs) in proportion to GHG emission reduction goals. The Study outlined the market potential, costs and potential benefits from the purchase of RECs from existing projects in the secondary market, the direct purchase of energy, capacity, and/or RECs through long-term contracts with new or existing renewable resource projects, and reductions in total demand from energy efficiency or distributed energy resources. These strategies were not presented as

---

[1] The upper bound assumes the full REC retirement in 2018. See Energy New England, "Portfolio Emissions Evaluation", prepared for the Wellesley Municipal Light Plant, October 31, 2017 and subsequently updated in March 2018. (Hereafter, "ENE, 2018"). As of the writing of this Report, the WMLP was currently developing its strategy regarding existing RECs.

an either/or choice, but rather, a potentially diverse portfolio of strategies that could lead to the lowest cost and greatest flexibility for the WMLP and its customers.

This "Phase II" study complements the Phase I analysis with additional qualitative considerations that may inform WMLP actions in the context of broader energy system decarbonization strategies over a much longer - and far less certain - period: 2030 to 2050. These considerations include WMLP-specific impacts, but also how the actions and strategies undertaken by the WMLP interact with, and will be influenced by, broader regional efforts to reduce GHG emissions both within the electric power sector and the broader economy.[2]

We recognize that approaching very-low GHG emissions over the next few decades - beyond the measures identified in our Phase I Report - may only occur with a fairly dramatic transition in the electric sector combined with achieving substantial reductions in other energy sectors. Consequently, in this Report we consider (1) the potential of cross-sectoral GHG emission reductions - that is, using electrification to reduce transportation and building sector emissions - and what this does or should imply for the carbon intensity of the electric sector over time; (2) how the transition to a decarbonized electric sector could affect WMLP's operations and revenue recovery; and (3) what this implies for how customers are charged for electric service in the Town of Wellesley. As we discuss throughout, the answer to each of the questions depends on the other; how and how much customers are charged for electric service will affect how electricity is used in other sectors. The reverse is also true.

Setting aside for the moment what the specific pathway to decarbonization may be, there is a broad expectation (or assumption) that electrification – particularly of the building and transportation sectors – will play an important role in reducing GHG emissions outside the power sector. Indeed, The Phase I Report found that the total technical potential of GHG emission reductions in Wellesley associated with electrifying transportation and residential heating – *even assuming the carbon intensity of today's electricity generation portfolio* – could be on the order of 80,000 metric tons. This is greater than the total GHG emissions associated with the current use of electricity supplied by the WMLP. In fact, GHG reductions from transportation and building use could be even greater in the future, to the extent that

---

[2] The Massachusetts Global Warming Solutions Act (GWSA) requires an 80 percent reduction in economy wide GHG emissions, relative to 1990 levels, by 2050. For details on the MA GWSA, including policies and pathways for economy wide emission reductions, see: https://www.mass.gov/service-details/gwsa-implementation-overview.

Globally, the Paris Agreement set broad goals to balance GHG emission sources and sinks, with each country submitting its own "nationally determined contribution" (NDC) to GHG emission reductions. In 2009, the U.S. joined the Group of 8 nations calling for reductions of 80 percent or more by 2050. As part of the Paris Accord, the U.S. formally committed to a 26 to 28 percent reduction below 2005 levels by 2025, which is consistent with a straight line reduction to 2050 of 80 percent. In 2016, the U.S. released its Mid-Century Strategy Report (hereafter, "MCS, 2016") that outlined pathways to an 80 percent reduction in economy wide GHG emissions below 2005 levels by 2050.

On June 1, 2017, Donald Trump announced that the U.S. would exit the Paris Accord. That same week, 16 states (including Massachusetts) formed the United States Climate Alliance and pledged their commitment to meeting the U.S. obligations under the Treaty. Other cities (including Boston), states, businesses and organizations have joined a coalition "We are still in", affirming their local commitment to the U.S. goals.

the sources of electricity displacing fossil fuels for transportation and building use have a lower carbon intensity than the existing electricity supply portfolio. In this scenario, incremental reductions in GHG emissions from the building and transportation sectors through electrification could be a more valuable and cost effective approach to achieve GHG emission reductions than a more narrow focus on squeezing every last ton of reduction out of the electric sector.

A key observation is that in the context of decarbonization and electrification, maintaining the reliability of the electric grid – and managing the increasing variability of electric demand – will continue to be one of, if not the, vital task of the WMLP. Simply put, it will need to remain a core focus under any future decarbonization effort. This is an obvious statement, but one that takes on additional weight and complexity as total demand for electricity grows, and the supply of that electricity is increasingly provided by (a) variable resources like wind and solar, and (b) more widespread adoption of distributed resource and load management technologies and approaches. These decarbonization strategies require increasing visibility into, anticipation of, and response from power system planning, operational, and revenue recovery perspectives.

While electrification offers significant potential for future GHG emission reductions, it would also pose a new set of challenges and opportunities for both the WMLP and its customers. An increased use in electricity could benefit the WMLP in the form of additional revenues and revenue stability. An increase in revenues and sales could spread fixed charges over a wider base and offer additional funds for the WMLP to invest in programs to the benefit of its customers. Increased electrification could also open the door to increased innovation in energy use, through combined electricity-heating-transportation applications designed to create more flexibility for customers and enable more flexible response to changing price signals. On the flip side, an increase in electricity use, particularly during periods of high demand, could lead to an increase in ISO-NE energy, capacity, ancillary services, or transmission charges, or all of the above.

" ... how much electricity customers use will continue to matter, but *when* and *how* future electricity is consumed will begin to matter more..."

Under these conditions, how much electricity customers use will continue to matter, but *when* and *how* future electricity is consumed will begin to matter more, with important implications for the magnitude of associated GHG emission reductions, the reliability of WMLP operations, and the total cost to WMLP customers. And because the decision to electrify building or transportation uses will depend, in part, on the cost of electricity relative to other fuels, a focus on costs is critically important to assessing these future GHG emission reductions, and to developing efficient and lowest-cost pathways to meet decarbonization goals.

This interaction across energy sectors, time, cost and technologies makes it very difficult to forecast potential decarbonization pathways in the 2030-2050 period; however, in considering potential scenarios, it is possible to identify factors likely to be important, and steps WMLP may take to mitigate risks, address possible transitional issues, monitor changing circumstances, and be prepared to take GHG reduction steps if and when appropriate.

Based on our review, we come to the following observations:

- ***Uncertainties in the path for decarbonization increase dramatically in outer years:*** The path for GHG emission reductions for WMLP and the Town beyond 2030 can not be established with any certainty at this time. The path will depend on state and federal energy GHG emission policies and the pace of change affecting energy technology capabilities and costs over the next ten to twenty years.[3] Grid-connected and distributed low/zero-carbon resource costs and performance will continue to evolve rapidly; and pre-commercial distributed technologies - including battery storage, electric vehicles (EV), electric heat pumps, and microgrid technologies and configurations - could prompt discontinuous shifts in the industry. Evaluations of long-term (i.e., 2030 and beyond) GHG reduction technologies and approaches now are almost certain to be outdated by the time such investments would need to be made to achieve them.
- ***Nevertheless, it is useful to review the potential impact of current and emerging low-carbon technologies and demand side strategies on key WMLP responsibilities...*** Given these uncertainties, in this Phase II Report we review the characteristics of technologies that could soon become more widespread and contribute to decarbonization, and consider how a transition to them would affect WMLP planning, operations and cost recovery. From this vantage point, the Report evaluates the impact of potential decarbonization actions and technologies on customers' demand for electricity, WMLP's supply portfolio, and the implications these have for WMLP procurement, distribution infrastructure, and rate design. In particular, it is difficult to imagine decarbonization without significant shifting of generation to variable low-carbon resources, and without major changes in customer load shapes through electrification (electric vehicles, electric heat pumps) and more active management of customer load. Our focus, then, is on how a transition to such technologies and strategies may affect, and be influenced by actions of, WMLP.
- ***... And note that at the same time, changes in supply and demand will be intrinsically linked over time:*** The likely pace of change affecting WMLP in the coming decades suggests that it will be important to recognize that these changes in supply and demand may be intrinsically linked. For example, a new time of use (TOU) rate structure that increases the price of electricity during peak periods and decreases the price of electricity during off-peak periods would help shift system load from the late afternoon or evening into the night. This in turn might increase the value of wind resources that generate during off-peak periods or increase the need or magnitude of storage resources to be paired with solar generated during the day. Similarly, an increase in electricity prices during peak periods would raise questions about whether the retail rate remains the appropriate credit - if any - for distributed generation resources that provide net energy back to the grid.
- ***On the Supply Side, emerging technologies can exacerbate or help manage increasing load variability:*** On the supply side, challenges to power system operations can emerge with

[3] One need only look at the pace of change since 2007 in natural gas production capabilities and the price and performance of natural gas, wind, and solar technologies to understand how dramatically the industry may change - in ways not easy to anticipate - between now and 2050.

accelerated penetration of low/zero-carbon variable renewable technologies. Yet emerging and advancing technologies and strategies offer opportunities to more closely align low or no carbon generation with customer demand, including (for example) battery storage, new energy efficiency technologies, load management, and carbon capture. First, falling battery prices, changes in wholesale market rules, and state procurement targets could make battery storage increasingly economic for a wider range of uses and deployment scenarios. Battery storage currently can be used on short time scales to store excess renewable generation, but technological advances may improve opportunities for storage to help meet extended gaps in load and supply. Second, changing load shapes will likely change the relative costs and benefits of energy efficiency technologies, and could promote greater prioritization for programs that address future peak period needs. Grid facing investments will be needed to handle an increase in two-way power flows from distributed resources at peak periods, and customer facing investments in advanced meter infrastructure (AMI) could be helpful to provide greater insight and ability for customers and system operators to respond to changes in prices and intelligently control demand. And future advances in carbon capture and storage, particularly when combined with increasingly more efficient natural gas fired generation, could support an important source of dispatchable low- or no-carbon generation used to meet peak demand or other gaps in supply and demand.

- ***While on the demand side, WMLP will need to focus on strategies to harmonize customer use with the shape of low- and zero-carbon supply resources:*** On the demand side, it is likely that the path to 2050 will require the WMLP and its customers to be focused more on the shape of customers' loads, and better matching of the aggregate demand for electricity with the generation characteristics/timing of variable renewable generation. The focus of this Phase II Report addresses this broader question of how to more closely match the generation of low and no carbon electricity supply with the energy demand by WMLP customers, and how to best meet this goal in an era of changing load shapes as new sources of electricity demand are brought online.
- ***A key element of either approach will be the incentives built into rate design – which can help harness customer response and customer-sited technologies to help solve rather than worsen net load variability:*** For example, the WMLP can meet these "load matching" goals in part through tailored supply resource decision making; but it may also benefit from more active shaping of customer demand (or a combination of the two). Customer load can be affected by customer responses to changes in rates and rate structures that provide appropriate price signals, and incentives to shift demand to lower-cost periods or to periods of greatest renewable energy production. Customer demand can also be managed and optimized through "smart" devices that can support additional demand response programs controlled by the WMLP or the system operator. In this sense, future sources of customer load - such as EVs and appliances - could evolve to be more of a demand solution than a supply challenge. Yet rate design is by nature a slow-moving beast; in order to effectively harmonize supply and demand on the WMLP system under forward-looking decarbonization scenarios, it will make sense to identify and begin to transition rate designs sooner rather than later.

One factor bears repeating: the challenges and cost of WMLP distribution grid operations and investments will depend on the pace of changes in underlying supply and demand, and WMLP's ability to plan for and manage changes over time. As the WMLP looks out towards 2030 and beyond, it is important to recognize that there does not yet exist any single best solution to emerging challenges, or single best pathway to decarbonization. Instead, optimal solutions can not be anticipated over a very long time frame, and will surely change as the industry's structure, technologies, and relative costs evolve. In this context, monitoring, anticipating technological changes, and planning through scenario analyses are of heightened importance in a rapidly-changing regulatory and technology landscape. The WMLP will need to continue to develop and iterate on its regular planning processes, stay attuned to changing customer needs and uses, and monitor developments in the market.

The rest of this Report proceeds as follows. Section I provides context for the Report. Section II presents a broad overview of the existing decarbonization literature, with an eye towards what it means and implications for the WMLP. Section III reviews these issues in the WMLP context, considering current WMLP load profiles, the generation profiles of non-dispatchable solar and wind resources, and how system load might evolve in the future based on electrification of building and transportation policies. With this context in hand, Section IV presents our observations related to potential changes in the setting for WMLP operations, and potential responses, in the context of long-term, broad decarbonization efforts.

I. Context for and Approach to GHG Emission Reduction Pathway Analyses for WMLP

The Context for the Phase I and Phase II Studies

In 2014, the Town of Wellesley Massachusetts established a goal to reduce its greenhouse gas (GHG) emissions from the electricity, transportation and building sectors by 25 percent by 2020 relative to 2007, consistent with the broader goals and binding regulations laid out for the Commonwealth of Massachusetts in the Global Warming Solutions Act (GWSA). To help meet the Town's goals, the WMLP has undertaken a number of measures to reduce the GHG associated with the purchase and distribution of electricity to the approximately 10,000 customers in the Town. Notably, the WMLP has been able to reduce its total GHG emissions by between 25 and 31 percent (depending on REC retirement) over the period 2007 to 2018,[4] due to changes in both the broader regional electricity system and through investments in energy efficiency and additional long-term contracts for renewable resources. At the same time, the WMLP has continued to meet the reliability needs of its customers and provide power without interruption throughout the year. (See Figure 1, below).

Every state in New England is in the midst of developing its own plans and pathways towards greater decarbonization. Within the electric power sector, this has created important opportunities and also greater uncertainty in wholesale electricity markets and distribution system planning and management. Emissions continue to fall, driven by a wide mix of regional market based policies, such as the Regional Greenhouse Gas Initiative (RGGI) which puts a price on CO_2 emissions, and state based regulations and incentives that create demand for new renewables and clean energy through Renewable Portfolio Standards (RPS) and other procurement and solicitation policies that offer long-term supply contracts for new generation from off shore wind, large scale hydropower, and other renewables. All of these regional and state policies are overlaid by and operate within the regional wholesale electricity market administered by the Independent System Operator-New England (ISO-NE), tasked with market operations, scheduling and dispatching power supplies in every second of the year to meet the constantly changing system demand, and ensuring the fair and reliable operations of the transmission system to deliver that power.

Taken together, this suite of regional and state policies points to a continued decline in emissions from the electric power sector, through greater reductions in energy use and the increased deployment of renewable energy and other clean resources. Under the RGGI emission cap, total emissions are projected to decline from 75 million tons to 61 million tons by 2030. But there are challenges. While every state has set a goal or regulation towards greater decarbonization, differences in state policy and priorities have led to disagreements and tensions over the best path forward, increasing the difficulty to

[4] This assumes full REC retirement in 2018. Instead, if the WMLP retires only those RECs associated with customer demand in its voluntary renewable energy program, Energy New England estimated total reductions in GHG emissions of approximately 27 percent. See ENE (2018).

potentially site new infrastructure. And other goals hinge on the successful development and maturation of new offshore wind facilities, a continued decline in renewable energy prices, and/or a sustained commitment towards energy efficiency programs. Few of these actions can be guaranteed at this time.

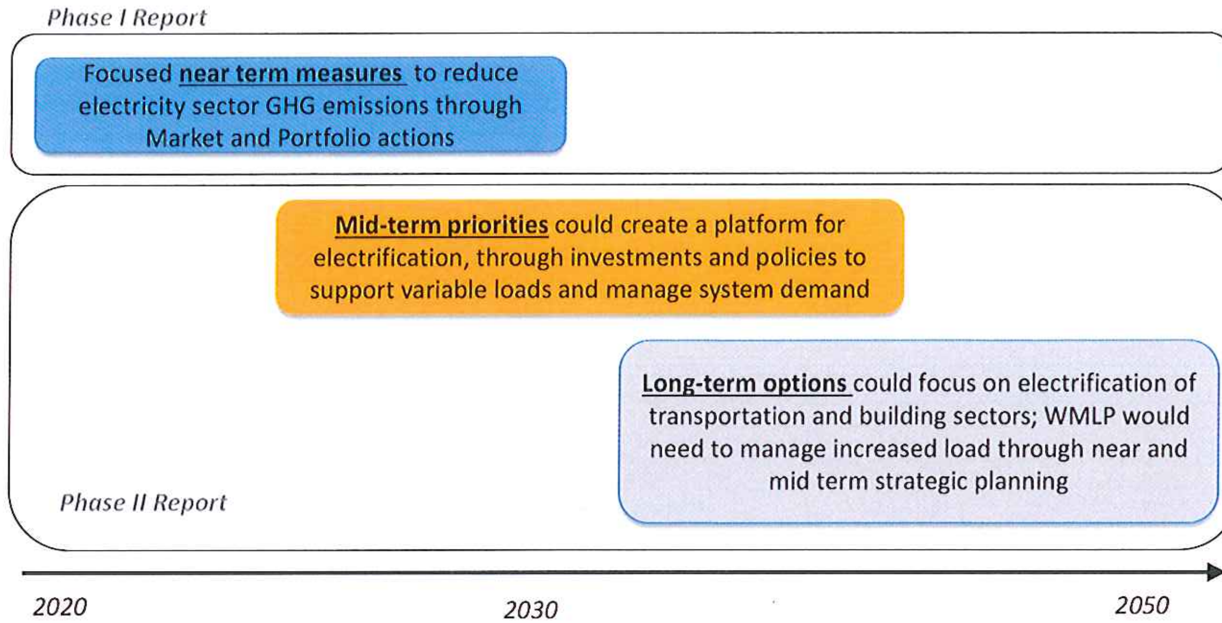
The immediate question, then, is what actions can or should the WMLP take within this broader context? And should the WMLP develop its own decarbonization pathway, in a way that provides for near-term reductions in GHG emissions while also creating a platform that could be scaled for greater change and potential electrification of the transportation and building sectors? To help in answering such questions, the WMLP engaged Analysis Group to develop two studies evaluating the context and feasibility for additional reductions and an assessment of the potential costs and benefits to the WMLP and its consumers.

In this manner, a Phase I Study was designed to provide input towards the Town's planning efforts vis-à-vis WMLP operations, and to help Wellesley consider a possible set of near-term actions to reduce GHG in the electric sector. This Phase II Report is necessarily more speculative and directional; it focuses on technology possibilities and transitional factors that should be considered, to the extent that the WMLP and the Town of Wellesley wish to evaluate longer-term goals toward a greater electrification and/or decarbonization of the transportation and building sectors.

This longer-term assessment is important even now, as the path is both challenging and complex. For example, a high level estimate suggests that the electrification of residential transportation and home heating could add on the order of an additional 160,000 MWh to WMLP load – an almost doubling of current non-GHG free demand. Doing so, however, could potentially reduce GHG emissions in those sectors by almost 60 percent (See Phase I Report). Future GHG reductions could be even greater than shown here if that future electrification is met from a portfolio of electricity resources with a lower carbon intensity than the current one. Yet achieving this requires careful longer-term planning, since it will require a mix of near- and longer-term GHG reduction strategies and goals that can be scaled alongside this potential growth in electricity demand.

Figure 1 depicts the need for mid-term priorities to support more variable load profiles and greater peak demand, should longer-term Town priorities require greater electrification. These changes will increase the importance and need for investments (including battery storage) that can provide peak capacity, investment in distribution infrastructure that can handle the two way flow of electricity, a utility business model that can potentially support higher fixed charges for infrastructure, and a regional electricity system served by high fixed cost, low variable cost resources such as nuclear, hydropower, wind, and solar. This Phase II Report presents these mid-term and longer-term concepts in more detail than the Phase I Report. Taken together, these two Reports aim to provide a broad lens for considering the near- and mid-term considerations that may be important to achieving significant CO_2 reductions over the long-term.

Figure 1: Near-Term, Mid-Term and Long-Term Perspectives



II. Decarbonization and Electrification

Achieving the GHG reductions necessary to meet the Paris Agreement atmospheric carbon dioxide target will require deep decarbonization of all forms of energy supply and use. In recent years, a wide literature has developed exploring various mechanisms or pathways to achieve this deep decarbonization. In particular, there is an ongoing debate around the costs and feasibility of different pathways focused on the electric grid as a whole. The Phase I Report noted that studies evaluating pathways based on costs or feasibility tend to find that a diverse mix of low and zero carbon resources offers the best opportunity to meet GHG reductions of 80 to 100 percent.[5] A diverse portfolio of resources would include variable renewable technologies, such as on and offshore wind, and solar located both behind and in front of the meter. Such a portfolio would also include dispatchable technologies including existing and new flexible nuclear, highly efficient natural gas generation with carbon capture and storage, biomass, and hydropower resources.[6] And to complete the variable and firm resources, system planners will still rely on flexible demand response.

In contrast, other studies ask a somewhat different question: namely, whether or not those same GHG reductions can be met through a narrow selection of renewable technologies only. Even with expanded investments in energy efficiency, a renewables-only pathway may be challenging and/or expensive. Given the lower capacity factors of renewable resources and intermittent generation profiles, a greater quantity of capacity will be needed to meet demand during periods of low generation or during periods of peak demand. This excess capacity can produce more electricity than is needed or can be used by the grid during other periods; this excess capability will likely be periodically "curtailed" or restricted from the grid, reducing the economic and operational benefits of renewable generation, as costs are spread over fewer hours of production

---

[5] A recent study by MIT energy economists reviewed more than 1000 cases, with various resource configurations and resource costs. Across all cases studied, the authors found that a diverse mix of resources led to a lower total cost of electricity than a narrow mix of variable renewables and storage only, ranging from 10 to 62 percent. This was true even under higher than expected costs for firm resources and rapidly falling costs for renewables and storage. See, Sepulveda, N.A. et al., "The Role of Firm Low-Carbon Electricity Resources in Deep Decarbonization," *Joule*, September 2018.

The Phase I Report also cited Roberts, D. "Is 100% Renewable Energy realistic? Here's what we know. Reasons for skepticism, reasons for optimism, and some tentative conclusions." VOX, Feb 7, 2018. That study provides a summary of both Jenkins and Thernstrom (2017) and Heard, Brook, Wigley, and Bradshaw (2017).

[6] In contrast to a typical focus on baseload and intermittent peak resources, Sepulvada et. al. (2018) propose a new classification of "fuel saving variable resources", "firm low carbon resources" and "fast burst balancing resources". They note that within each of these categories, there is competition among similar resource types. Nuclear or hydro or biomass or carbon capture and storage offer similar benefits as a firm low carbon resource. In contrast, between resource groups there is little competition or substation. Instead, each group of resources complement the needs of the others. It is this diversity that leads to lower total system costs.

It is not surprising then, that studies that focus on feasibility have found that a renewable only portfolio is technically feasible only if it is accompanied by a large expansion of the transmission grid, a substantial increase in total storage capability, or both.[7] In such a scenario, an increase in transmission infrastructure would almost certainly be needed with or without an increase in battery storage to help move renewable generation geographically from locations of high generation to high demand and to meet peak demand throughout the year more easily or economically through tapping into a geographically-diverse set of resources.[8]

---

[7] Several studies have reviewed the feasibility and challenges of a high renewable electricity grid. For a detailed literature review, see Jenkins and Thernstrom (2017), which is summarized in-line text box. We note the key conclusions of a few of those studies here.

The NREL RFES was one of the first studies to assess the operational considerations of the US bulk power system under a high renewable penetration. That study reviewed more than two dozen scenarios, including falling renewable costs, increased energy efficiency (a low demand case assumed that electric load would remain flat, even with the addition of new transportation and building energy use), and technological improvements in resource capacity. NREL RFES (2012), Researchers found that an 80 to 100 percent renewable energy future was technically feasible, but would require an approximate doubling of the U.S. transmission grid at penetrations above 80 percent. (See Figure ES-8); an increase in system capacity for reserves; a growth in storage (including pumped hydro and compressed air) from approximately 20 GW up to 150 GW; increased ramping of conventional power plant operations; and the potential curtailment of 8 to 10 percent of all renewable energy. Together, these constraints could pose important challenges on the regulatory framework used to recover system costs and incentivize new investments.

Similarly, Few et al (2016) reviewed various flexibility mechanisms that could be used to integrate increasing quantities of renewables. These mechanisms included geographic aggregation (through transmission); allowance for the over-generation (and curtailment) of renewables; the addition of storage; and the addition of flexible demand, in the form of electric vehicles. They reviewed six scenarios of different combinations of storage/curtailment/EVs, for renewable penetrations of 20 to 100 percent, for various geographies up to an including the U.S. They found that across all scenarios, geographic aggregation was the most cost effective form of flexibility, reducing costs by 5 to 50 percent. They also found that at multiple geographic scales (including the U.S.), moving from 80 percent to 100 percent renewables would approximately double costs and triple the quantity of over-generation/curtailment.

More recently, McDonald et al (2016) asked the same aggregation question a different way: the authors found that with a single, national HVDC transmission grid, the U.S. could achieve an 80 percent reduction in GHG emissions, without an increase in the levelized cost of electricity. In this scenario, total energy was met by wind (38%), natural gas (21%), solar (17%), nuclear (16%), and hydropower (8%). This included the cost of new transmission. Total costs and installed capacity of renewables were higher under all scenarios with smaller, more regional transmission systems.

[8] It is worth noting that the most recent meta-analysis of 100 percent renewable studies reached a different conclusion. Heard, Brook, Wigley and Bradshaw (2017) reviewed twenty four 100 percent renewable studies against four feasibility criteria, including a) demand projections b) simulations at a sufficient granular time scale c) identifying necessary transmission and d) meeting necessary ancillary services. That study noted that "none of the 24 studies provides convincing evidence that these basic feasibility conditions can be met" and that half of the studies relied on unrealistic forecasts of energy demand.

Additional Decarbonization Literature

Jenkins and Thernstrom (2017) provide one of the most current and thorough review of deep decarbonization studies. The authors reviewed 30 studies published since the most recent Intergovernmental Panel on Climate Change (IPCC) Report released in 2014. The 30 studies cover a wide range of geographic scopes, cost assumptions and research methods, with a focus on various technology pathways to meet GHG emission reduction goals of 80 to 100 percent. They reached seven direct conclusions: (directly quoted, below).

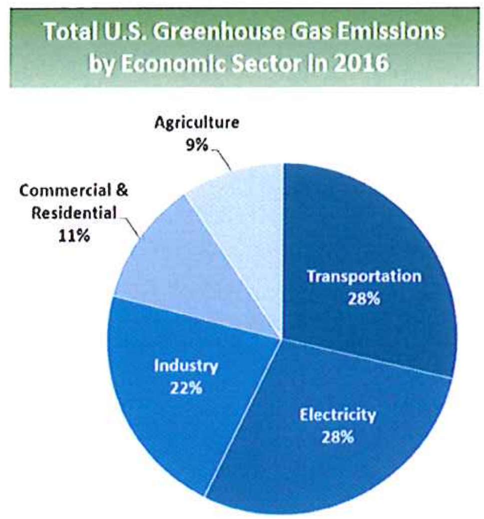
1) Power Sector CO2 emissions must fall nearly to zero by 2040 to achieve climate policy goals.
2) A low-carbon power sector must expand to electrify and decarbonize greater shares of transportation, heating, and industrial energy demand as part of a strategy for economy-wide emissions reductions.
3) Deep decarbonization of the power sector is significantly more difficult than more modest emissions reductions.
4) Deep decarbonization may require a significantly different mix of resources than more modest goals; long-term planning is important to avoid lock-in of suboptimal resources.
5) Achieving deep decarbonization primarily (or entirely) with renewable energy may be theoretically possible but it would be significantly more challenging and costly than pathways employing a diverse portfolio of low-carbon resources.
   - Decarbonized power systems dominated by variable renewables such as wind and solar energy are physically larger, requiring much greater total installed capacity.
   - Wind and solar-heavy power systems require substantial dispatchable power capacity to ensure demand can be met at all times. This amounts to a shadow system of conventional generation to back up intermittent renewables.
   - Without a fleet of reliable, dispatchable resources able to step in when wind and solar output fade, scenarios with very high renewable energy shares must rely on long-duration seasonal energy storage.
   - Very high shares of wind and solar entail significant curtailment – even with energy storage, transmission, or demand response.
   - High renewable energy scenarios also envision a significant expansion of long-distance transmission grids.
   - High renewables scenarios are more costly than other options, due to the factors outlined above.
6) Including dispatchable base resources (such as nuclear or carbon capture and storage) reduces the cost and technical challenge of achieving deep decarbonization.
7) A diversified mix of low-carbon resources offers the best chance of affordably achieving deep decarbonization of the power system.

Several recent studies have found that these tradeoffs to decarbonization pathways - i.e. through a diverse mix of resources or focused solely or entirely on renewable resources - result in potentially significant differences in total electric system production costs; specifically, costs appear higher under a renewables-only pathway. Thus at the national level, evaluating the potential for electrification of other energy uses as a means of reducing GHG emissions will require a careful evaluation of the price of electricity in incentivizing and enabling such a pathway to decarbonization. The same will be true for the WMLP.

The Importance of Electrification

While there is no agreement on the technological pathway towards decarbonizing the electricity sector, there is an emerging expectation that we will likely need *more* electricity as part of any economy-wide decarbonization effort. The EPA estimates that the generation of electricity from fossil fuels accounted for 28.4 percent of all U.S. GHG emissions in 2016.[9] Transportation accounted for the largest share of GHG emissions (28.5 percent), followed by industry (22 percent) and commercial/residential building use (11 percent). Given this, reducing GHG emissions associated with the use of electricity alone will not be close to sufficient to meet long-term GHG reduction goals out to 2050. This is one reason why the decarbonization of the transportation, building use and industrial sectors represents an important priority for local governments.[10] Electrification represents one pathway to achieve these savings.[11]

Figure 2:



U.S. Environmental Protection Agency (2018). Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016

Displacing other, higher-GHG intensity uses and fuels (see Table 1) through electrification will almost certainly require significant increases in the production and consumption of electricity. Based on the current mix of electricity generation, the GHG intensity (measured by lbs of CO_2 per MMBtu of energy) of the last (or "marginal") power plant dispatched in New England to meet demand is approximately 127 lbs CO_2/MMbtu. This is comparable to the CO_2 content of natural gas, which follows from the fact that the *marginal* unit in New England is typically a natural gas power plant in most hours. The *average* CO_2 content of all electricity production, after accounting for nuclear, hydro, renewable and biomass, is lower than this marginal rate, and lower than the CO_2 intensity of transportation and building uses.

---

[9] Original data available from the EPA, here: https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions.

[10] For example, on June 1 2018, the Bloomberg Philanthropies announced a new grant opportunity for the nation's top 100 cities, aimed specifically at reducing GHG emissions from transportation and building use, noting that local policy efforts aimed at these sectors often have greater authority. For additional information, see: https://www.bloomberg.org/program/environment/climatechallenge/#overview

[11] Nationally, several studies have assessed the GHG emission reduction potential of large-scale electrification. For example, the U.S. Deep Decarbonization Study (completed in 2015) reviewed four scenarios with varying levels of technology innovations and combinations, efficiency gains, and electrification that could be used to achieve an 80 percent reduction in GHG emissions relative to 1990 levels by 2050. Across all four scenarios, that study found that *total energy* (due to efficiency gains) use would decline by approximately 30 percent while *total electricity* generation would increase between 60 and 113 percent. See Williams, J.H., et al. "Pathways to deep decarbonization in the United States, US 2050 Volume 1 Technical Report." 2014, Revision with technical supplement, November 16, 2015, Table 7.

Table 1

Fuel	lbs of CO_2 per MMBtu
Coal (bituminous)	205.7
Diesel fuel and heating oil	161.3
Gasoline (without ethanol)	157.2
Propane	139
Natural Gas	117
ISO-NE electricity (marginal unit)	*127*
ISO-NE electricity (system average)	*107*

Notes and Sources: CO_2 content of fuels is provided by EIA. CO_2 content per MMBtu for ISO-NE electricity is estimated using 2016 reported emission rates (lbs CO_2/MWh) and marginal heat rates (MWh/MMBtu). Total system average would be lower with an average, rather than marginal, system heat rate. See ISO-NE 2016 Air Emissions Report. CO_2 rates do not include GHG emissions associated with upstream or downstream requirements (e.g., processing, transport, or transmission/distribution losses).

The total GHG emission savings from electrification is a function of the difference between the CO_2 content of the fuel underlying the specific use (e.g., gasoline for transportation, oil for building heat), and the efficiency of the process governing the movement and use of fuel from the point of production to end use. That is, one must compare the total GHG emissions to achieve the same end use (e.g., vehicle miles traveled, or monthly home heating) using electricity, to the total GHG emissions using an alternative fuel. For example, the total GHG emissions of a home currently using an oil furnace for heat would be the CO_2 emitted at the point of combustion, plus the GHG emissions associated with extraction, processing, and transport/distribution of the fuel. Using electricity would instead result in GHG emissions associated with burning the required fuel at a power plant that otherwise would not be needed (usually natural gas in New England) to meet the home's heating electricity demand plus electrical transmission and distribution losses, as well as the GHG associated with extraction, processing and transport of that fuel to the power plant (including methane losses at wells, processing plants, and in pipelines).

Historically, basic economics has deterred any meaningful electrification of transportation and building sectors. However, the economics of electrification has improved fairly rapidly in recent years, and projections going forward continue this trend. For example, a recent study by the DOE noted that it is currently more cost-effective to operate an electric vehicle than a gasoline vehicle in every U.S. State, based on average fuel and electricity prices.[12] And a recent study by RMI on building electrification found that in at least some locations it may be more cost effective to install new electric heat pumps in residential applications in areas that do not have access to natural gas, in new construction, or in instances when a homeowner needs to simultaneously retrofit both an air conditioner and furnace.[13] Whether or not this is the case in specific locations will depend on local climate, building envelopes, and local cost factors.

Electrification of Building Use

Several studies point to the potential for electrification of both hot water and space heating needs. In addition to GHG emission reductions, these resources offer an additional source of flexible demand services for the grid.

Electric water heaters are particularly well suited to serve as behind-the-meter storage or as a demand response resource, since water can be heated well in advance of customer need. However, according to the Rocky Mountain Institute (RMI), less than 1 percent of all hot water heaters are currently enrolled in demand response programs.

Electric resistance water heaters (as opposed to electric source hot water heaters) can also provide valuable ancillary services to the electric grid. RMI (2018) notes that aggregated water heaters provided more than 100 MW of capacity to PJM in 2017.

Combining the electrification of both space and water heaters may increase the economic benefits to consumers, through sharing of components or replacement of service lines.

WMLP and the Potential for Decarbonization Through Electrification

The Phase I Report focused on near-term measures to reduce GHG emissions associated with the current use of electricity provided by the WMLP. At present, the total GHG emissions (assuming the full retirement of RECs in the WMLP portfolio) is approximately 69 million short tons or 62.5 metric tonnes of CO_2. At the same time, the total technical potential for GHG emission reductions from the building and transportation sectors in the Town of Wellesley could be on the order of an additional 80,000 metric tonnes. Importantly, this estimate assumes that current transportation and building demand is met with electricity provided from the New England power grid at current levels of CO_2 emissions per MWh generated.[14] To the extent that the marginal CO_2 emission intensity of the

---

[12] Department of Energy, Office of Energy Efficiency and Renewable Energy. Fact of the Week #1033, June 11, 2018. Available: https://www.energy.gov/eere/vehicles/articles/fotw-1033-june-11-2018-washington-state-has-greatest-fuel-cost-savings

[13] That study included case studies using utility specific data in Oakland, Houston, Providence, and Chicago. RMI (2018), pp. 47-48.

[14] Total electrification potential and GHG emission reductions were calculated as follows:

For transportation, we estimated total vehicle miles traveled by Wellesley residents of 265 million miles per year, based on 2016 average vehicle miles traveled (VMT) per capita in Massachusetts of 9,170 (U.S. Department of Transportation) and Wellesley population of 28,909 (U.S. Census Bureau American Community Survey 5 year estimate). We assumed average miles per gallon of 21.6 mpg with average kg of CO_2 per gallon of 8.887 (U.S. EPA). We assumed average efficiency of electric vehicles of 33 kWh per 100 miles, with average emission intensity of electricity based on ISO-NE marginal emission rates of 842 lbs CO2/MWh. To estimate technical

New England power grid declines, estimated reductions in CO_2 from these sectors through electrification would be higher than 80,000 metric tonnes.[15]

Based on existing efficiencies of residential heating appliances and electric vehicles, electrification of these uses could increase total demand from the WMLP by approximately another 160,000 MWh – essentially doubling the current portion of WMLP demand not already met through GHG free sources. Table 2 calculates the potential additional CO_2 reduction from the electrification of residential transportation and heating.

Table 2

	Total MWh	Total Estimated CO_2 (Metric Tons)	Net Electric CO_2 (Metric Tons)	Percent Reduction
WMLP Electricity Demand, GHG Sources (2020)	***160,000***	***62,585***	***62,585***	
Technical Potential for Electrification (Indicative Estimate)				
Residential Transportation	87,000	109,068	33,405	69%
Residential Heat	72,000	34,382	27,684	19%
Total	***159,000***	***143,450***	***61,089***	***57%***

Notes and Sources: Analysis Group calculations. See text for additional detail.

While Table 2 illustrates the total technical potential, the actual market penetration and evolution of electrification will ultimately depend on customer attitudes and adoption rates, which will be driven in large part by economics and by the extent to which state and federal governments promote electrification through energy and environmental policy measures. The economic potential of

---

potential, we assume all fuel vehicles are replaced by electric vehicles, with no change in vehicle miles traveled.

For residential heating, we relied on the number of homes with natural gas and fuel oil/kerosene heaters in Wellesley; data provided by the 2015 EIA Residential Energy Consumption Survey for total energy demand (in Btu) per system type in Massachusetts; and conservative estimates for average fuel utilization efficiency (AFUE) based on current energy star appliances (95 percent for natural gas and 85 percent for fuel oil/kerosene). We assumed that this total thermal load was replaced by electric air source heat pumps with a heating seasonal performance factor of 8.2 btu per watt-hour. Total emission savings were calculated as the difference between relative CO_2 content of each fuel and the marginal emission rate of electricity provided by ISO-NE.

This estimate of technical potential is likely conservative and may underestimate total potential. In particular, our indicative estimate of building use only includes energy demand for air source heating and does not include energy demand for hot water heaters. According to the 2015 EIA Residential Energy Consumption Survey, 5.6 million homes in New England have a water heater, with an equal number served by electricity as natural gas.

[15] While significant change in the CO_2 emission intensity of the New England power grid may be unlikely prior to 2030, the current trend of state policy and technological change suggests that it is quite possible in the 2030 - 2050 period. How and to what extent this is true depends on evolution of a complex set of economic, market, reliability, and technical factors affecting the region's electricity demand and supply.

electrification will depend on the difference in operating costs (including, critically, the price of electricity), total capital costs to purchase and install new or retrofit equipment, the prevalence of subsidies and/or discounts through policy incentives, and individual preferences for payback periods based on individual discount rates.

Taken together, at both the National level and within the Town of Wellesley, the emergence and continued growth of new electricity supply and demand technologies - and the costs associated with using them – will be critical to determining the likely pace by which decarbonization goals will be met, in whole or in part, through electrification. And there is a high degree of uncertainty around this evolution. This level of uncertainty stands in stark contrast to the aggressive GHG reduction requirements and goals in place and advancing, at least in the Northeast states. These circumstances point to the importance for utilities to anticipate regulatory changes and emerging technology developments, and to actively prepare physical infrastructure and rate design for potentially significant decarbonization/electrification scenarios in the 2030 - 2050 timeframe.

III. Decarbonization and Electrification in the WMLP Context

WMLP and the Regional Context

To date, the broader decarbonization discussion has focused on the electric grid in its entirety, and/or on resource requirements and programs that are administered on a regional or state basis. Many of the technology options and grid management strategies - as well as coordination of distributed resource options - require a regional perspective to recognize the true potential value of various low-carbon electrification technology and strategy options. Examples included load aggregation and management of demand response; widespread integration of major grid-connected renewable resources through transmission grid investment; regional management of generation resource variability through dispatch and generation resource curtailment; and administration of markets to value low-carbon resource attributes such as with RGGI, RPS, and clean energy standards. Finally, a meaningful contribution to meeting decarbonization objectives through electrification will, in the end, require development of favorable economics and/or regulatory requirements for low-carbon electricity resources and strategies over the broadest possible market region.

On a regional basis, while there may be debate about whether or not all energy demand can be met through renewables in the future, it is important to acknowledge the starting point: in 2017, wind and solar combined accounted for only 4.1 percent of total energy generation in ISO-NE, while all renewables (and hydro) together generated 19.4 percent of all power.[16] To meet future GHG emission goals consistent with the New England states' laws and policies, the share of renewables will need to increase far beyond current levels, and relatively quickly. If one does not believe retrenchment in GHG goals and requirements is in our future, then the only questions revolve around *which* resources and strategies will get us there, and how will that pathway be shaped by the mandate of power system reliability and the goal of cost minimization? Will nuclear generation remain in the resource mix and for how long; is carbon capture and storage a plausible future technology (nationally or regionally); are major transmission infrastructure developments (for hydro, on shore wind, and/or off shore wind resources) necessary and politically feasible; and how quickly may distributed resources (solar, batteries) and distributed aggregation strategies (microgrids) evolve to the point of meaningful contributions?

Given the magnitude of the challenge and the need for wide-ranging actions, the role of individual utilities and municipalities can be subsumed by broader market changes, state policies, and technology trends. In turn, decarbonization and electrification concepts and strategies sensible in the regional or national context may not apply to the individual actions that can or should be taken by a single state or an individual utility in isolation.[17] Given this, it is useful to consider WMLP's possible long-term

[16] ISO-NE "Resource Mix", accessed June 2018. Available: https://www.iso-ne.com/about/key-stats/resource-mix/

[17] We note, for example, the evolution of ongoing legislation within Massachusetts. The Phase I Report outlined current regulations, including the establishment of a clean energy standard, which requires competitive suppliers of electricity to procure 80 percent of load with qualifying resources by 2050. And more recently, in

strategies not only in consideration of WMLP's customers, demand, and resource profile, but also against the backdrop of the regional GHG and electric system context.

Understanding the Relationship Between WMLP Demand and Low-Carbon Resources

In considering WMLP's options to control the GHGs associated with its operations, it is useful to review the matching of its load shape to the generation of acquired low-carbon resources, in order to understand potential benefits of using a mix of resources, or the use of market-based resources such as RECs.

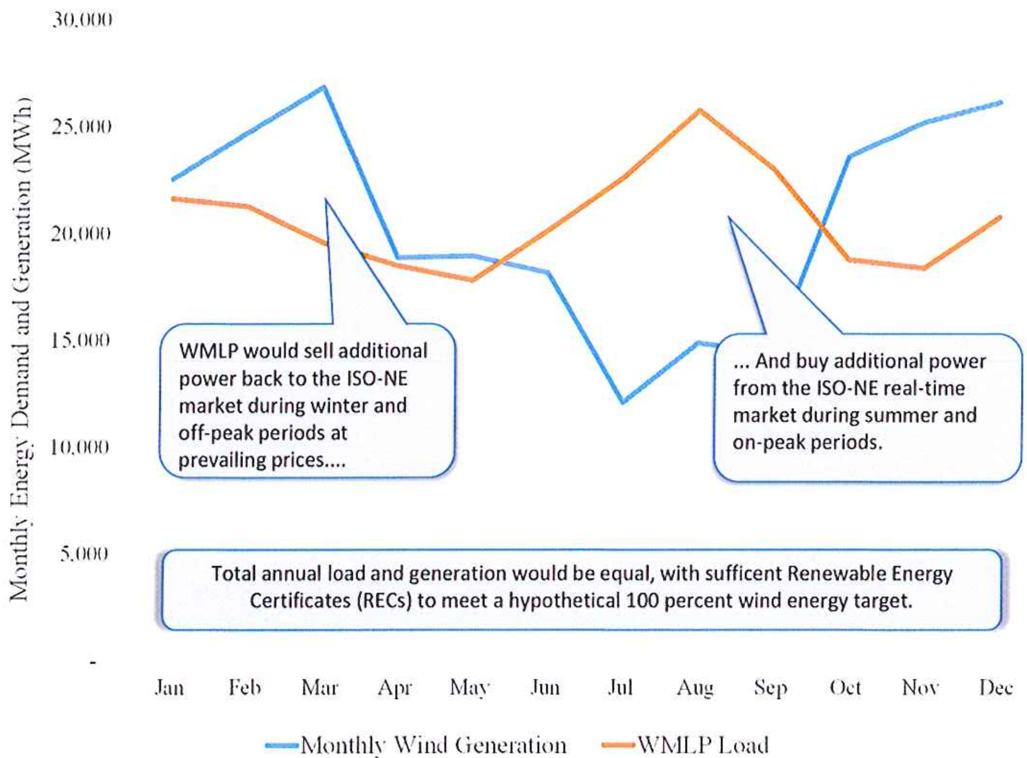
As the most simplified example, Figure 3 compares WMLP's total monthly energy demand with the average monthly generation profile of an 98 MW wind resource operating with an average annual capacity factor of 29 percent.[18] On an annual basis, a wind resource of this size produces enough RECs to fully offset WMLP consumption, enabling the WMLP to be GHG-emission free on an energy basis. However, Figure 3 highlights the physical, temporal differences between this renewable supply and WMLP demand. In the spring and winter months, when wind generation exceeds WMLP demand, excess wind power would either need to be curtailed (i.e., not used) or exported to the broader grid and other users. In contrast, from June through September, the WMLP would need to buy additional power from the ISO-NE grid. In effect a decarbonization pathway based on a single resource like this would mean the WMLP would be using the broader ISO-NE grid as a largescale battery, with sufficient storage capacity to operate on a monthly timescale.

August 2018, MA passed "An Act to Advance Clean Energy", H.4857, which increased the state RPS to 35% by 2030 (and 45% by 2040), requires 1000 MWh of storage by 2025 (up from 200 MWh by 2020), and creates a process for determining a new clean peak standard.

It is worth noting that earlier in the year, the MA Senate had considered additional legislation with respect to future clean energy pathways. Senate Bill 2302 was notable for its requirement to meet 100 percent of Massachusetts total energy needs by renewable energy by 2050 and to obtain 100 percent of all electricity consumed within the State by renewable resources by 2035. On June 14, 2018, SB2302 was amended for Senate Bill 2545, "An Act to Promote a Clean Energy Future," which was unanimously passed that same day. SB 2545 also would have established additional, more ambitious state procurement goals for energy storage (2 GW), expand offshore wind procurements to 5 GW of capacity by 2035, created market based compliance mechanisms for GHG emission reductions in the transportation and building sectors, and established new provisions for demand charges only in the event that they are based on pre-defined system peaks and applicable to customers with near real time access to electricity usage data.

[18] See Figure 3. The generation profile is based on 2017 hourly production, as reported by ISO-NE. Average annual and monthly capacity factors were estimated assuming total installed nameplate capacity of 1300 MW, based on the 2017 CELT generator report.

Figure 3: Comparison of Monthly Wind Generation and WMLP Demand

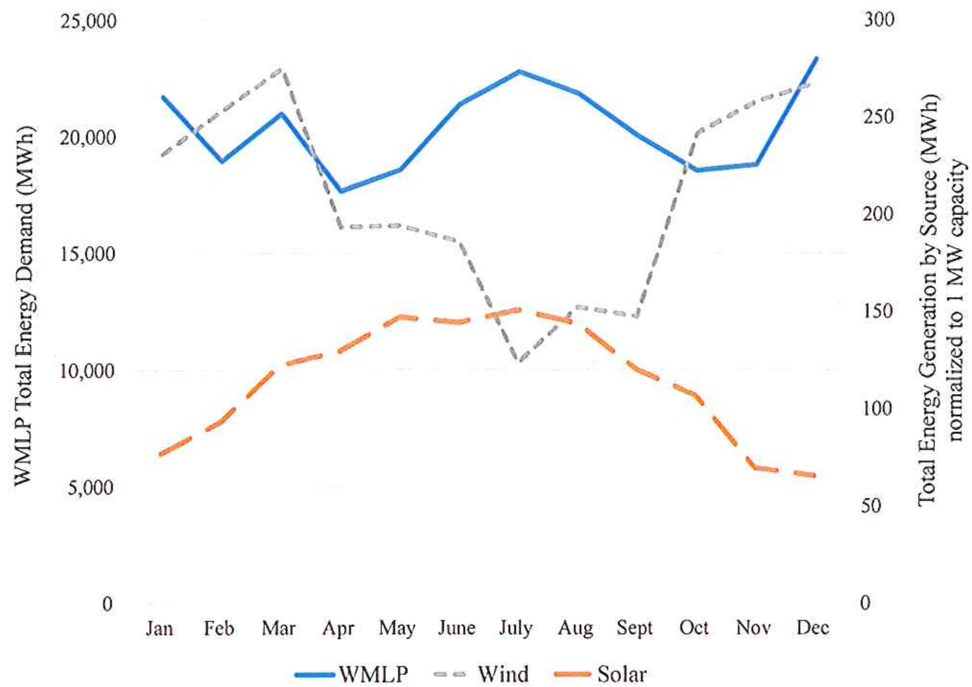


Notes and Sources: 2106 WMLP actual load. Monthly wind generation relies on reported 2017 ISO-NE hourly data, available at: https://www.iso-ne.com/isoexpress/web/reports/operations/-/tree/daily-gen-fuel-type. Average annual capacity factor was approximately 29%, based on 1300 MW of total nameplate installed capacity, per the 2017 ISO-NE CELT Report. At this capacity factor, WMLP would require 98 MW of wind capacity to produce 248.2 GWh.

Similarly, the 98 MW of wind capacity could theoretically meet the approximately 60 MW peak demand of the WMLP (or similar daily peak demand levels). Yet this would depend on the capacity factor of the wind resource during the peak periods, whether or not the WMLP had large-scale storage capability to shift wind generation to match the peak demand, or whether the WMLP could shift consumer demand during such a peak. Absent such measures attenuating generation or consumption on a daily and hourly basis, the WMLP would require other resources or regional capacity market purchases to meet its peak load obligations.

On a monthly basis, Figure 4 shows the potential benefits of an increase in portfolio diversity. Solar production tends to be higher during summer months and partially offsets the reduction in wind energy production. (In contrast to Figure 3, Figure 4 plots generation profiles for wind and solar on the right hand axis, with production normalized to 1 MW of capacity.) In this sense, a combination of solar plus wind would likely be more effective at directly meeting monthly energy loads than either solar or wind alone. This is not to suggest that wind and solar alone would be the most efficient or cost-effective solution – but rather, another simplified example of how a diversity of resources with differing attributes and generation profiles can complement one another from the perspective of matching generation with demand. While storage offers one solution to help match the output of renewable generation to system load, there remain important questions about the technical capabilities and economic value of storage, particularly at high penetration levels.[19]

Figure 4: Monthly WMLP Demand Relative to Monthly Wind and Solar Generation



[19] To this end, Denholm and Mai (2017) assessed the storage duration required to reduce renewable curtailment in the Electricity Reliability Council of Texas (ERCOT). The authors reviewed three scenarios in which wind and solar collectively provide 55 percent of all electricity demand by the year 2050, a substantial increase from the 15 percent generated by wind in 2016. Without storage, the authors found that anywhere from 11 to 16 percent of total renewable energy would be curtailed, and that curtailment was minimized with a mix of 37 percent wind and 18 percent solar. The authors reviewed varying combinations of battery storage (based on both power and energy capacities) to reduce curtailment. With just four hours of storage duration (for an 8..5 GW power battery), curtailment could be reduced by 40 percent. Illustrating the declining benefit of increased storage, the authors found that it would take 40 hours of duration to reduce curtailment by 85 percent and nearly 200 hours of duration to fully eliminate curtailment. Based on current cost curves for battery storage technology and a range of future energy costs, the study found that "all simulations reveal... a significant decline in value beyond four hours of capacity" and that the incremental value of storage is relatively low beyond the first few hours of duration.

The same considerations apply when viewed on a daily basis. Figures 5-8 plot the WMLP peak summer day of demand and peak winter day of demand, with hypothetical generation curves for wind and solar, which are normalized to 1 MW for illustration purposes. (The purpose of Figures 5 -8 is to compare the shapes of each generation and demand curve – by itself, these hypothetical 1 MW resources would obviously be insufficient to meet WMLP demand.)

During the peak summer day, total demand reached its annual peak of 61 MW, with demand greater than 60 MW for the hours ending 16 through 18 (see Figure 5). In contrast, solar generation was greatest during the day during the hours ending 12 and 13. Wind generation roughly matched the total WMLP demand on this particular summer day – but as Figure 6 shows, over the course of an average June month level, wind does not effectively serve as a summer peak resource. On the peak day, generation dipped unexpectedly around hour ending 8 am and then again for hours ending 14 to 17. This mismatch in generation and demand would require the WMLP to purchase (or sell) additional energy from the ISO-NE, likely produced from thermal resources that could be dispatched in real time to meet load obligations, or require the WMLP to match its own load profile through combination of demand response or storage. It similarly could affect WMLP's total payments for capacity, reserves and other ancillary services. To the extent economic storage is developed for this purpose, additional benefits could be realized under other system conditions, such as mitigation of dependence on natural gas during peak winter demand.

Figure 5: Load Profile – Peak Summer Day (June)

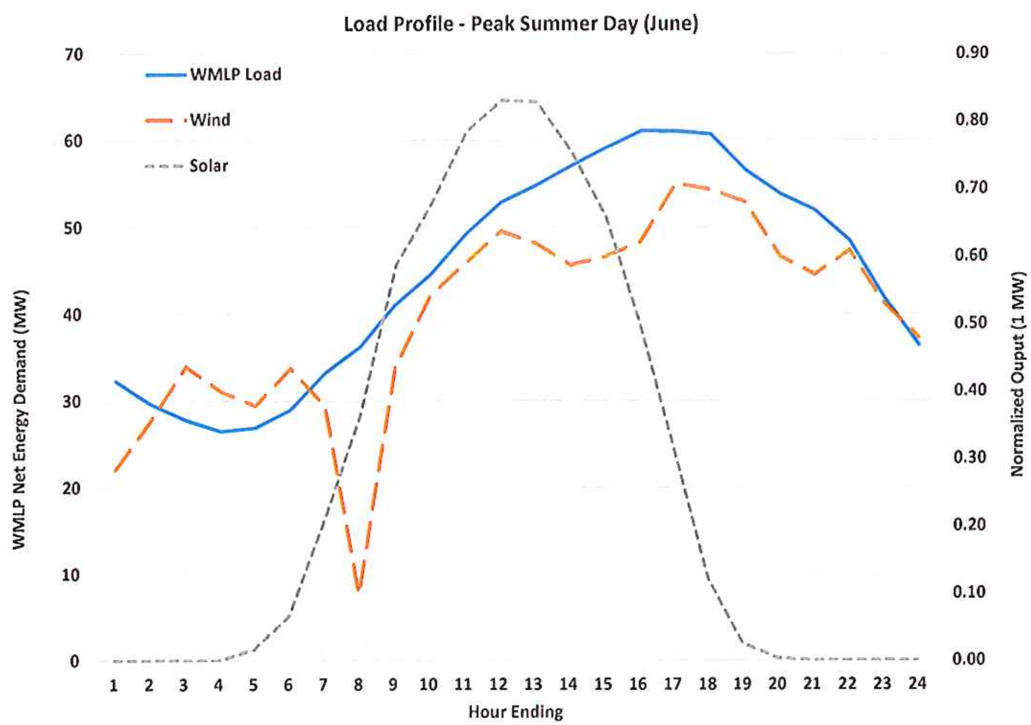
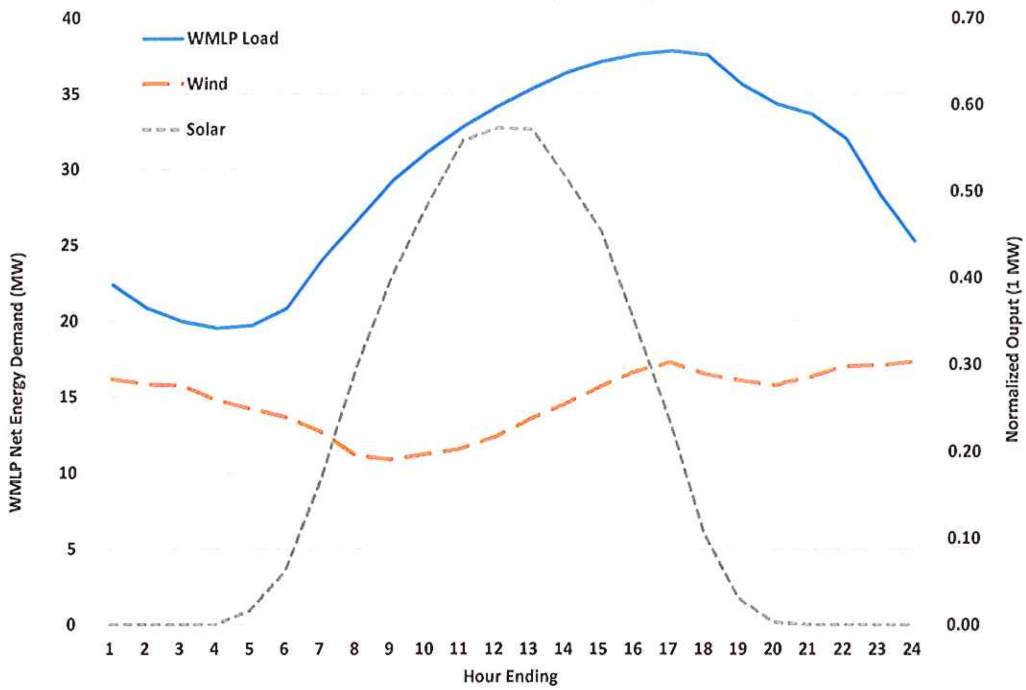


Figure 6: Load Profile -- Average June Day



This comparison of the actual peak day and monthly averages during the summer months illustrates some of the potential decisions and tradeoffs when sizing and operating a potential storage application across multiple value streams. On the one hand, storage could be used to reduce or "shave" the peak demand. A 2 MW battery with 4 MWh of energy capacity (that is, a battery that can discharge 2 MWh for 2 hours) could be used to reduce the peak demand from 61 MW to 59 MW over the peak hours, which could result in potential capacity market savings between $55,000 and $90,000 per year.[20] However, in this instance, the battery may not be fully available to provide energy during the reduction in wind generation during the morning or late evening hours.

Shown together, Figures 5-8 also illustrate the difference in system needs between summer and winter. In the summer, total capacity for an average day in June ranged from 20 MW to nearly 40 MW. (On the peak day, demand ramped from a low of 26 MW to a peak of 61 MW). In contrast, load was relatively

[20] Specifically, a 2 MW/4 MWh battery would be able to reduce the peak of 61.13 MW in hour ending 16 to a peak of 59.65 MW. Total energy in the battery would need to be discharged with perfect foresight in hours ending 16, 17, and 18 to reach this new equilibrium peak. This reduction from 61.13 MW to 59.65 MW would use 4 MWh of energy over three hours and reduce peak capacity by 1.48 MW. (Note that, in this example while the battery is rated at 2 MW, this does not necessarily lead to a reduction in peak demand of 2 MW. The actual peak reduction depends on the impact on demand and consumption over the full period of operation, with the new peak potentially shifting to a different hour.) At the 2016/2017 clearing price of $3.15/kW-mo, total savings would be approximately $55,000. At the max clearing price of $15/kW-mo from FCA 2017/2018 in NEMA, the total savings would be approximately $90,000.

constant throughout an average December day, with the majority of hours ranging from 30 to 40 MW (on the peak day, demand ranged from a low of 34 MW to a peak of 41 MW, with the majority of hours in a more narrow range around 40 MW of demand). In these winter months, there is likely less value from a reduction in peak energy use. There may be a lesser need for the energy provided during solar during the middle of the day, and instead, a greater need to provide additional energy during early morning hours.

Figure 7: Load Profile – Peak Winter Day (Dec)

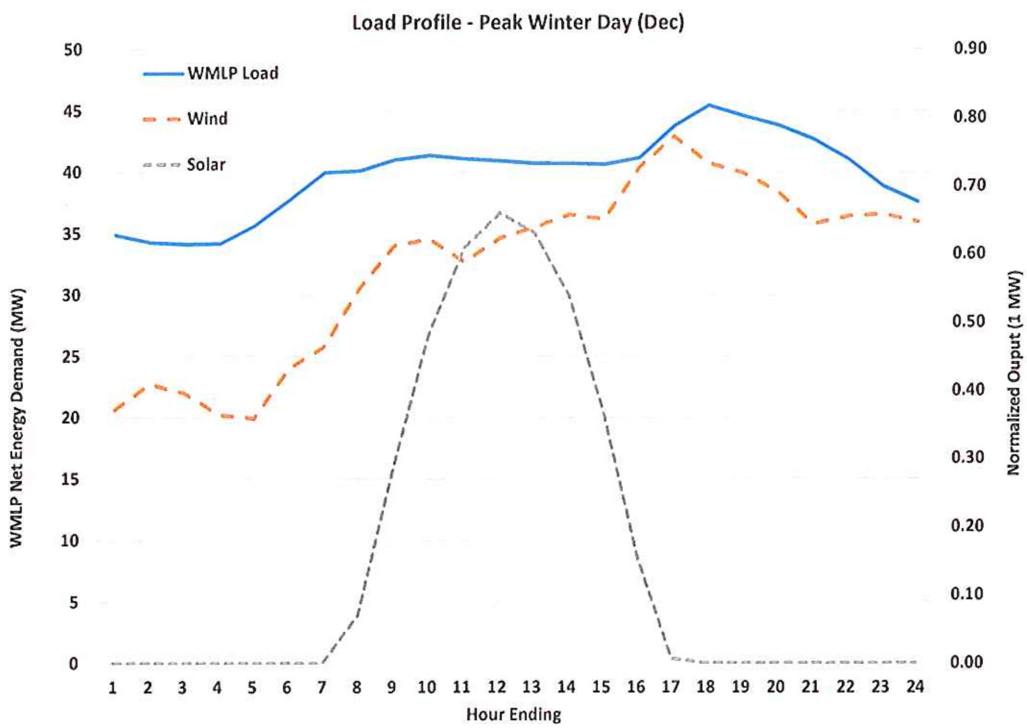
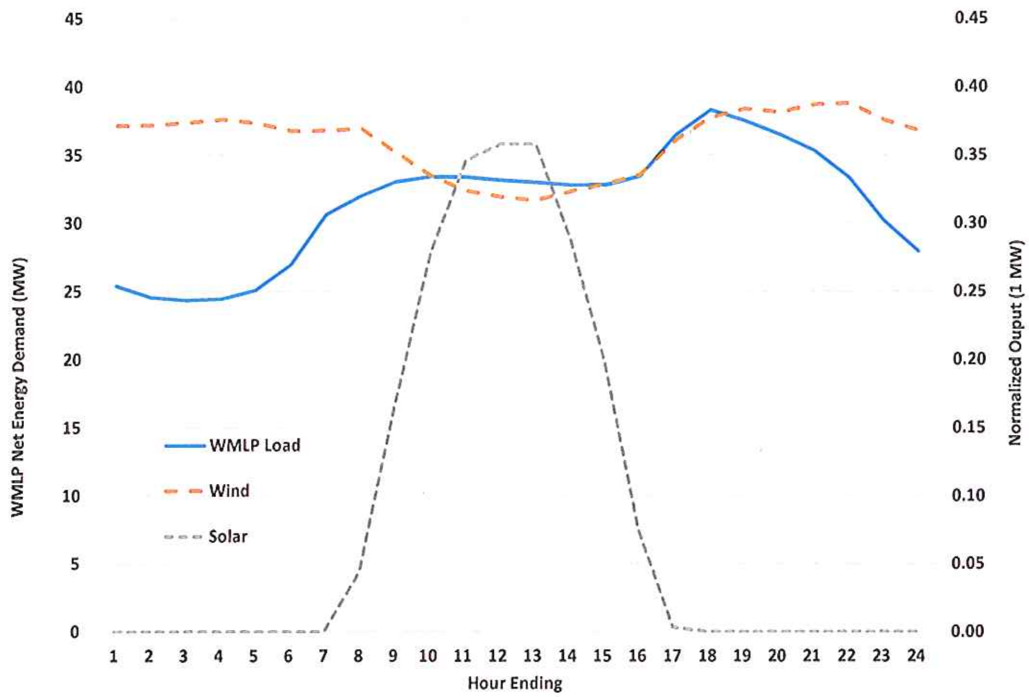


Figure 8: Load Profile – Average December Day



This review of monthly and daily energy demand helps illustrate the potential importance of WMLP's actions as part of a broader regional decarbonization pathway. That is, in the most narrow sense, the WMLP could meet its *annual* GHG emission reduction goals through REC purchases alone or through PPAs with REC eligible projects. On an hourly, daily, or monthly basis however, the WMLP will need to rely on wholesale markets to purchase (or sell) energy and capacity to match real-time energy needs against its supply portfolio. A practical implication of this circumstance, discussed in the Phase I Report, is that increased purchases in the wholesale market increase the uncertainty in and volatility of the WMLP annual budget. Net purchases (sales) could increase or decrease total costs, depending on the timing and quantity of transactions. Budget volatility carries its own financial cost, given the time and resources to manage the budget.

This degree of uncertainty is heighted by the continued evolution of wholesale markets in the context of changing resources and state policies. In particular, trends suggest that wholesale markets in the 2030 - 2050 period will tend increasingly towards higher penetrations of variable renewable resources.[21] At

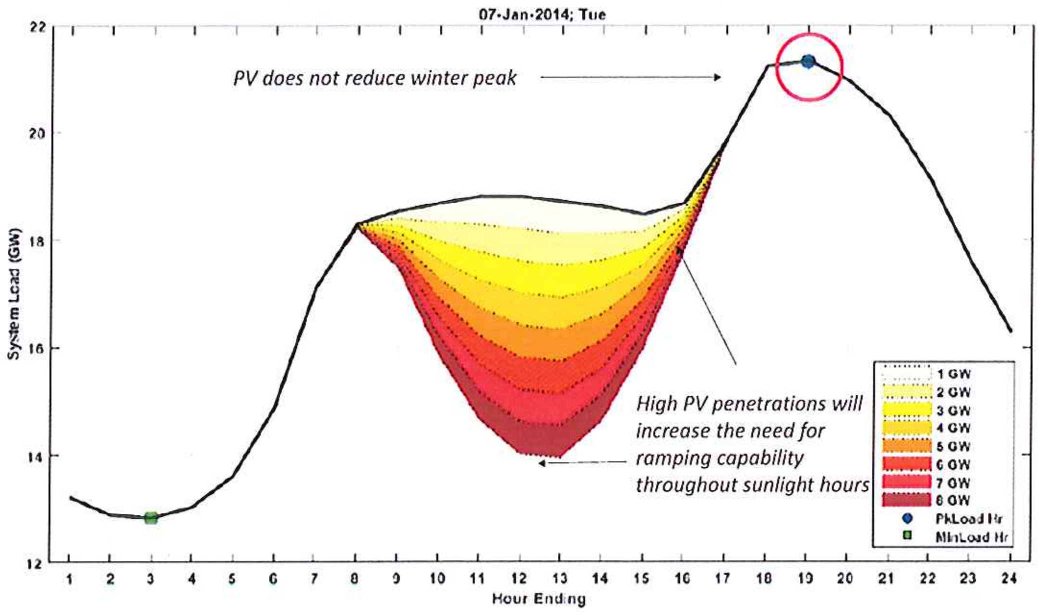
[21] Within MA, the state RPS will reach 35 percent by 2030 (see FN 27). And in 2018, the ISO-NE noted wind made up almost 60 percent of new resources in the current interconnection queue. (ISO-NE REO 2018, p. 10)

Similarly, Bloomberg New Energy Finance (2018) recently predicted that by 2050, falling battery prices will lead to the economic deployment of renewables sufficient to meet 50 percent of total global electricity demand.

higher levels of renewables, and as individual decarbonization pathways by individual entities evolve, the demand for the timing and types of services provided by the market will also change. With increasing quantities of zero marginal cost, variable renewable resources, energy prices will likely be lower on average – with greater variation between days depending on resource availability.[22]

Yet price impacts are not limited to the energy market. The price of energy, capacity, and ancillary services in the broader market will all adjust based on these changing system demands. In competitive markets, a decrease in energy prices with increased volatility will likely lead to an increase in the price of capacity and the price of ancillary services. Figure 9 also helps to highlight this point. Using a peak winter day with growing solar penetration, the ISO-NE points to an increased need (and hence value) of fast ramping resources that can provide power later in the day.

Figure 9: The New England "Duck" Curve – "Deep Load Reductions During Winter Daylight Hours Result in Steep Ramp Into the Evening Peak"



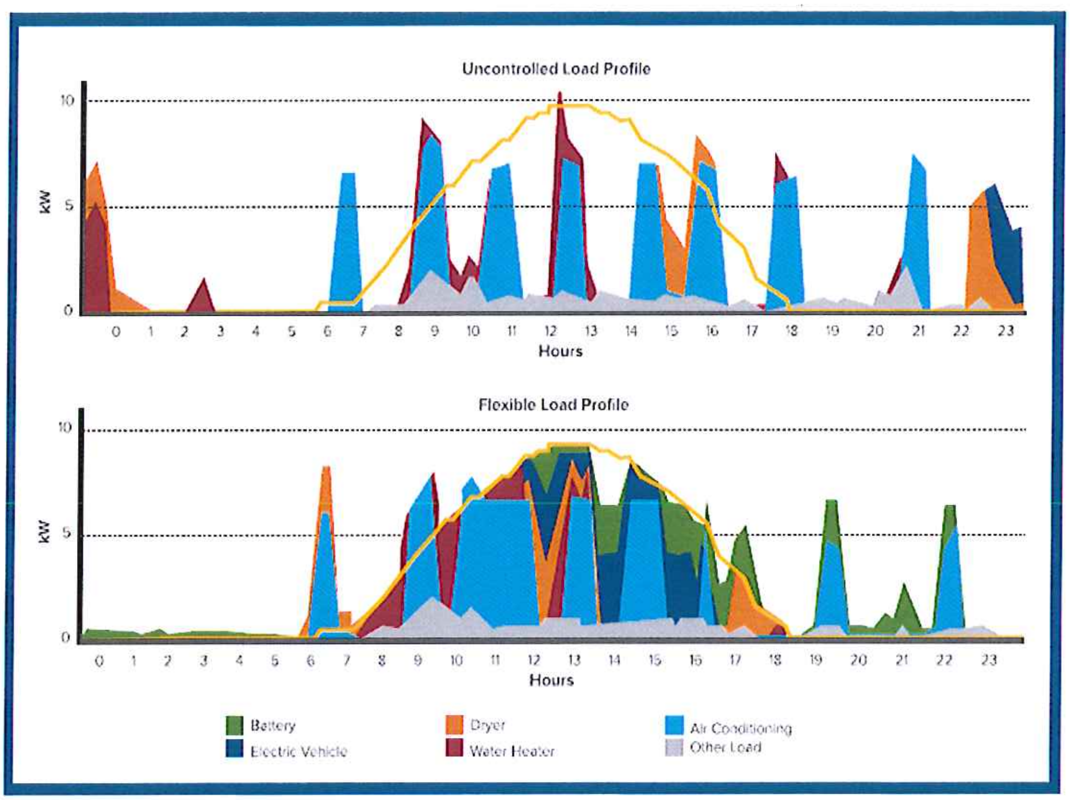
Notes and Sources: ISO-NE 2018 State of the Grid: ISO on Background. Presented by Gordon Van Welie, February 27 2018, slide 49.

Consistent with the outlook of greater electrification, the BNEF Report also finds that time of use tariffs and dynamic charging of electric vehicles further support the integration of renewables and add an additional 10 percent of new demand.

[22] Researchers at the Lawrence Berkeley National Laboratory recently evaluated the impact of three scenarios with wind and solar penetrations of 40 to 50 percent in 2030 on wholesale power prices in New York, California, Texas, and the Southwest Power Pool. Across all regions, they found that wholesale power prices would decrease between 15 and 39 percent, with a higher number of hours priced below $5/MWh (suggesting a greater need for capacity revenues). The increase in variable renewable energy generation would also make energy prices more volatile, push peak periods later into the evening hours, and lead to a diurnal price profile. See Seel, Mills, and Wiser (2018).

In addition to fast ramping capacity, system planners will also likely come to rely on flexible demand side solutions. To illustrate this point, see Figure 10, from a recent RMI Report on the electrification of buildings. Illustrative renewable solar generation is shown by the orange line; demand from various customer uses are shown in shaded areas throughout the day. Two concepts are explored - significant growth in electricity demand without economic or regulatory incentives to manage load shape ("Uncontrolled"), and one where rate design, economic incentives, or regulatory requirements are present to influence the use of technologies and actions to control the timing of expanded electricity demand ("Flexible"). In the Uncontrolled load profile, residential uses for heating and cooling and electric vehicle charging happen throughout the day, resulting in several different peak periods. In contrast, in the Flexible load profile, grid connected devices are used to intelligently schedule and control the use of electricity during periods of greatest value to the grid. An earlier RMI report estimated that grid flexibility of existing electric uses could save between 10 and 15 percent of potential grid costs;[23] the potential value may be even higher in future scenarios of electrification.

Figure 10: Flexible Demand to Match Variable Supply Resources



Notes and Sources: Rocky Mountain Institute, "The Economics of Electrifying Buildings: How Electric Space and Water Heating Supports Decarbonization of Residential Buildings", 2018, Figure 2.

---

[23] Rocky Mountain Institute, "The Economics of Demand Flexibility: how "flexiwatts" create quantifiable value for customers and the grid", August 2015.

These observations regarding the future evolution of the wholesale markets point to several conclusions for the WMLP.

- First, programs or policies that can reduce energy demand during future peaks will be increasingly more valuable. In 2017, the system peak occurred between 4 and 5 pm. As the system peak moves later into the day, energy efficiency programs that target indoor lighting or other uses may increase in value relative to programs that target current on-peak uses such as air conditioning (e.g., as residents return home and increase air conditioning load).
- Second, an increase in capacity prices will increase the value of WMLP policies or programs that can reduce WMLP peak demand. This suggests considering a suite of demand, supply and pricing programs that could help manage peak demand, including time-varying rate structures, targeted demand response, and battery storage.
- Third, an increase in energy price volatility and new diurnal price curves will increase the value of flexible demand, and the ability to help shift WMLP load throughout the day. This will increase the value of flexible demand response, flexible customer load, and rate structures that can better align demand with energy prices.
- Finally, a reduction in wholesale power prices, with increased price volatility, could lead to net losses (or profits) to the WMLP, depending critically on its portfolio of resources/contracts and how these affect the timing and frequency with which WMLP balances needs with real-time market purchases and sales. This points to heightened attention to the evolution of resource contracting and hedging strategies held over time by the WMLP relative to its changing demand shapes and changing regional market conditions.

These observations suggest that over the long-term, the WMLP will likely be able to minimize its own costs if it is able to more closely and more actively match its supply portfolio of low and no carbon energy with the changing nature of demand from WMLP customers. This focus holds true across a wide range of future supply pathways, by allowing the WMLP to minimize sales and purchases of energy in the real time market, thereby reducing its exposure to increasing capacity and ancillary service prices. Further, it is a useful focus regardless of the WMLP's future load shape – whether it stays constant based on current demand or if it evolves over time through the electrification of new uses. Given the importance of electrification to meeting broader economy-wide GHG emission reductions, the WMLP should continue to monitor and assess the potential implications of changes in demand in order to best understand the extent to which electrification will increase supply challenges and market risks, or can be used as a demand-side solution to these risks.

Nevertheless, trends in emerging technologies suggest that in the coming decades the WMLP could play an important role in the pace and ultimate scale and scope of electrification in the Town of Wellesley. Incentives and rebates for new electric appliances, such as electric water heaters or heat pumps, can reduce the total consumer costs to install new or retrofit units, potentially flipping the economics. The installation of electric vehicle charging stations tends to encourage electric transportation use. And favorable electricity rates, which for Wellesley are low compared to the surrounding region, will lead to greater annual savings and faster payback periods. Similarly, favorable *rate design* could have the same effect; that is, new rate structures can provide meaningful incentives for managing total energy costs, through the setting of variable time of use rates and/or new rate classes for new electricity uses.

If trends or policies increase the pace of electrification, it will be important to plan for it in advance; how and when new sources of electricity demand are added to the WMLP system will strongly influence the cost to meet that demand. The WMLP's role in how things evolve and/or are managed will determine whether new sources of electricity use emerge as supply side challenges that increase costs and operational risks, or as demand-side solutions, helping improve load factors, decrease variability, and lower costs.

The most significant - and potentially most disruptive - example of this would be ubiquitous availability of affordable electric vehicles, and the new electricity demand challenges that would arise with consumer electric vehicle charging patterns. On the one hand, electric vehicles could provide an important source of storage or new demand for low cost electricity, either by being charged in the middle of the day (particularly if paired with solar generation, and as a way to avoid curtailment) or by being charged during the night, using cheaper electricity produced off-peak. On the other hand, electric vehicle charging during the late afternoon/early evening peak – when individuals return home – could increase existing WMLP peak demand which occurs between 6 and 8 pm during both summer and winter months (see Figures 5-8). An increase in peak demand from electric vehicles during this time would likely increase WMLP charges for ISO-NE capacity and transmission service, thereby raising the cost of electricity for all WMLP customers.

IV. Observations and Recommendations: WMLP Planning and Operations in the 2030 - 2050 Period

Overview

In the Phase I study we evaluated the suite of GHG emission reduction measures that are likely to be available to the WMLP in the near-term (that is, prior to 2030). Our focus was on near-term actions, including measures that build from recent WMLP experience with demand side reductions in energy, supply side procurement of renewable energy, and the developing market for distributed energy resources. The Phase I Report also addressed the procurement of renewable energy credits (RECs) in proportion to GHG emission reduction goals. The Report outlined the market potential, costs and potential benefits from the purchase of RECs from existing projects in the secondary market, the direct purchase of energy, capacity, and/or RECs through long-term contracts with new or existing renewable resource projects, and reductions in total demand from energy efficiency or distributed energy resources. These strategies were not presented as an either/or choice, but rather, a potentially diverse portfolio of strategies that could lead to the lowest cost and greatest flexibility for the WMLP and its customers.

Notably, many of the GHG reduction pathways we discuss in the Phase I Report will likely remain as additional GHG reduction options beyond 2030; that is, while potential GHG reduction quantities and the technology costs may differ from our Phase I Report estimates, new or existing grid-connected renewables, nuclear generation, distributed resources and energy efficiency, and REC purchases will continue to offer the WMLP additional GHG reduction opportunities. While we do not discuss them explicitly in this report, we assume that to be the case.

In this Report we consider more qualitatively the period 2030 - 2050, and the challenges it may present the WMLP given current technology and policy trends. What is known with certainty is that things will continue to change. This is because the electric industry and potentially the provision of energy for transportation and building services will undergo significant and accelerated transformations over this time horizon - driven by a combination of both accelerating technological change and state and federal energy and environmental policy. But yet, the WMLP is a relatively small player in two much larger arenas - the electric, transportation and heating fuel industries that play out at regional, national and international scales; and an energy and environmental policy framework determined most significantly through regional power system and market changes and at state and federal levels. In this sense, the best path forward for the WMLP will depend in part on developments in these other arenas. Given this uncertainty, it is nearly impossible to chart a specific pathway for the WMLP as it relates to the specific mix of technologies and policies to further GHG reductions.

Thus with respect to the longer term, the WMLP's role will necessarily be *both* proactive and anticipatory/reactive. In this report, we review what we believe are the key considerations related to potential future changes over this time period that the WMLP may want to monitor, and how they may affect the WMLP's reliability, cost, and GHG reduction obligations.

Our review in the prior sections reflects an emerging perspective on industry and policy conditions governing the evolution of GHG controls and decarbonization of energy supply and use. Specifically, we observe or assume the following factors in considering the context for the WMLP over the next few decades:

- First, we assume for the purpose of our review that over the period 2030 - 2050 municipal, state, and potentially federal policy efforts affecting at least the Northeast U.S. to reduce the emissions of GHGs into the atmosphere will continue and, if anything, accelerate. While it is not possible to establish with certainty the form or scope of GHG controls, we consider it highly likely that efforts to reduce GHG emissions will continue to progress.
- Second, we recognize that the *electric sector* reductions we reviewed in the Phase I report will not on their own keep pace with the desired or required level of reductions in GHGs from *all sectors* of energy supply and use.
- Third, based on current assessments of technologies and the costs of achieving GHG reductions, electrification is emerging as a primary focus for meeting aggressive GHG reduction goals, particularly with respect to achieving reductions in current non-electric sectors (including transportation and building use).
- Finally, in order for electrification to be an effective strategy for overall GHG reductions, major changes in the supply, delivery, and use of electricity would be required. This would include some or all of the following, all of which would affect the WMLP in fundamental ways: (1) major shifts in the regional mix of grid-connected generating resources (and associated transmission infrastructure) resulting in dominance of renewable resources whose output varies with prevailing weather conditions; (2)substantial increases in distributed technologies (e.g., rooftop PV) and energy management technologies and approaches (e.g., controllable load, battery storage) in industrial, commercial and residential applications; and (3) transformational shifts in the level and shape of customer electricity demand resulting from advanced metering and/or time of use applications at regional, company, and distribution feeder levels.

These conditions, which we review in prior sections, set the context for our review of how GHG reduction efforts could affect WMLP over the 2030 - 2050 time period, and how WMLP should respond. We do not mean to assert or conclude that this is how the industry will evolve; rather, based on current information and the assumption that efforts to control GHG will continue to expand, this is currently a potential future scenario and the one of most significance for WMLP planning, investment, operations, and revenue recovery.

We thus focus on these conditions, and consider the implications for WMLP. The key features of electricity supply in such a transformation are (1) more variability in grid-connected generation and associated challenges in managing exposure to wholesale energy, capacity and ancillary services markets; and (2) *simultaneous* increases, decreases and/or changes in the variability of customer demand - in aggregate and on individual distribution feeders - with operational reliability and revenue recovery implications. It is easy to recognize that generation resources and customer demand have always changed; yet in a decarbonization and electrification scenario the pace and magnitude of such changes could accelerate well beyond historical experience. Distribution companies like WMLP would be significantly affected, would have to manage them from reliability and cost perspectives, and can - if they so choose - *proactively* prepare for, promote, and adapt to such a transformation.

Observations

A key observation is that in the context of decarbonization and electrification, maintaining the reliability of the electric grid – and managing the increasing variability of electric demand – will continue to be the vital task of the WMLP. And it will need to remain a core focus within any decarbonization effort. This is an obvious statement, but one that takes on additional weight and complexity as total demand for electricity grows, and the supply of that electricity is increasingly provided by (a) variable resources like wind and solar, and (b) more widespread adoption of distributed resource and load management technologies and approaches. These necessary decarbonization strategies require increasing visibility into, anticipation of, and response from power system planning, operational, and revenue recovery perspectives.

While electrification offers significant potential for future GHG emission reductions, it would also pose a new set of challenges and opportunities for both the WMLP and its customers. An increased use in electricity could benefit the WMLP in the form of additional revenues and revenue stability. An increase in revenues and sales could spread fixed charges over a wider base and offer additional funds for the WMLP to invest in programs to the benefit of its customers. Increased electrification could also open the door to increased innovation in energy use, through combined electricity-heating-transportation applications designed to create more flexibility for customers and enable more flexible responses to changing price signals. On the flip side, an increase in electricity use, particularly during periods of high demand, could lead to an increase in ISO-NE energy, capacity, ancillary services, or transmission charges, or all of the above.

Under these conditions, how much electricity customers use will continue to matter, but *when* and *how* future electricity is consumed will begin to matter more, with important implications for the magnitude of associated GHG emission reductions, the reliability of WMLP operations, and the total cost to WMLP customers. And because the decision to electrify building or transportation uses will depend, in part, on the cost of electricity relative to other fuels, a focus on costs is critically important to assessing these future GHG emission reductions.

Our review of these conditions leads to the following observations:

- ***Uncertainties in the path for decarbonization increase dramatically in outer years:*** The path for GHG emission reductions for WMLP and the Town beyond 2030 can not be established with any certainty at this time. The path will depend on state and federal energy and GHG emission policies and the pace of change affecting energy technology capabilities and costs over the next ten to twenty years.[24] Grid-connected and distributed low/zero-carbon resource costs and performance will continue to evolve rapidly; and pre-commercial distributed technologies - including battery storage, EVs, electric heat pumps, and microgrid technologies and configurations - could prompt discontinuous shifts in the industry. Evaluations of long-term (i.e., 2030 and beyond) GHG reduction technologies and approaches now are almost certain to be outdated by the time such investments would need to be made to achieve them.

- ***Nevertheless, it is useful to review the potential impact of current and emerging low-carbon technologies and strategies on key WMLP responsibilities:*** Given these uncertainties, in this Phase II Report we review the characteristics of technologies that could soon become more widespread and contribute to decarbonization, and consider how a transition to them would affect WMLP planning, operations and cost recovery. From this vantage point, the Report evaluates the impact of potential decarbonization actions and technologies on customers' demand for electricity, WMLP's supply portfolio, and the implications these have for WMLP procurement, distribution infrastructure, and rate design. In particular, it is difficult to imagine decarbonization without significant shifting of generation to variable low-carbon resources, and without major changes in customer load shapes through electrification (electric vehicles, electric heat pumps) and more active management of customer load. Our focus, then, is on how a transition to such technologies and strategies may affect, and be influenced by actions of, WMLP.
- ***Emerging technologies can exacerbate or help manage increasing load variability:*** On the supply side, challenges to power system operations can emerge with accelerated penetration of low/zero-carbon variable renewable technologies. Yet emerging and advancing technologies and strategies offer opportunities to more closely align low or no carbon generation with customer demand, including (for example) battery storage, new energy efficiency technologies, load management, and carbon capture. First, falling battery prices, changes in wholesale market rules, and state procurement targets could make battery storage increasingly economic for a wider range of uses and deployment scenarios. Battery storage currently can be used on short time scales to store excess renewable generation, but technological advances may improve opportunities for storage to help meet extended gaps in load and supply. Second, changing load shapes will likely change the relative costs and benefits of energy efficiency technologies, and could promote greater prioritization for programs that address future peak period needs. And future advances in carbon capture and storage, particularly when combined with increasingly more efficient natural gas fired generation, could support an important source of dispatchable low- or no-carbon generation used to meet peak demand or other gaps in supply and demand.
- ***Changes in supply and demand will be intrinsically linked over time:*** The likely pace of change affecting WMLP in the coming decades suggests that it will be important to recognize that these

[24] One need only look at the pace of change since 2007 in natural gas production capabilities and the price and performance of natural gas, wind, and solar technologies to understand how dramatically the industry may change - in ways not easy to anticipate - between now and 2050.

changes in supply and demand may be intrinsically linked. For example, a new TOU rate structure that increases the price of electricity during peak periods and decreases the price of electricity during off-peak periods will likely help shift system load from the late afternoon or evening into the night. This in turn might increase the value of wind resources that generate during off-peak periods or increase the need or magnitude of storage resources to be paired with solar generated during the day. Similarly, an increase in electricity prices during peak periods would raise questions about whether the retail rate remains the appropriate credit - if any - for distributed generation resources that provide net energy back to the grid.

- ***WMLP may wish to focus on strategies to harmonize customer demand with the shape of low- and zero-carbon supply resources:*** On the demand side, it is likely that the path to 2050 will require the WMLP and its customers to be focused more on the shape of customers' loads, and better matching of the aggregate demand for electricity with the generation characteristics/timing of variable renewable generation. The focus of this Phase II Report addresses this broader question of how to more closely match the generation of low and no carbon electricity supply with the energy demand by WMLP customers, and how to best meet this goal in an era of changing load shapes as new sources of electricity demand are brought online.
- ***A focus on the incentives built into rate design can help harness customer response and customer-sited technologies to help solve rather than worsen net load variability:*** For example, the WMLP can meet these "load matching" goals in part through tailored supply resource decision making; but it may also benefit from more active shaping of customer demand (or a combination of the two). Customer load can be affected by customer responses to changes in rates and rate structures that provide appropriate price signals, and incentives to shift demand to lower-cost periods or to periods of greatest renewable energy production. Customer demand can also be managed and optimized through "smart" devices and AMI that can support additional demand response programs controlled by the WMLP or the system operator. In this sense, future sources of customer load - such as EVs and appliances - could evolve to be more of a demand solution than a supply challenge. Yet rate design is by nature a slow-moving beast; in order to effectively harmonize supply and demand on the WMLP system under forward-looking decarbonization scenarios, it will make sense to identify and begin to evaluate rate design benefits sooner rather than later.

> **"An important question and consideration for the WMLP is how to let new sources of electricity use serve as *demand side solutions* rather than *supply side challenges*."**

The challenges and cost of WMLP distribution grid operations and investments will depend on the pace of changes in underlying supply and demand, and WMLP's ability to plan for and manage changes over time: The changes likely to be induced by rapid technological and cost changes in distributed supply resources, and/or by the shifting of load due to evolving rate structures and new distributed efficiency/load management technologies, will require careful and integrated assessment of distribution grid operations and investments. Grid facing investments will be needed to handle an increase in two way power flows from distributed resources. And customer facing investments in AMI could be helpful to provide greater insight and ability for customers and system operators to respond to changes in prices and intelligently control demand. More granular data on real-time loads at the customer level and on the distribution system will also allow for strategic planning and evaluation of potential benefits for the deployment of storage or other behind the meter resources.

While 2030 may seem a long way off, it is clear that the pace of technological change, the advancement of carbon policies, at least in the Northeast, and the impact on the nature and shape of electricity demand and consumption, are all increasing. Moreover, planning for distribution investments - whether to adapt to changing load shapes or to proactively promote electrification and demand management opportunities - require long lead times. Finally, out of concerns related to continuity, transition, and fairness, the process of instituting new rate classes, new rate designs, and new allocation of customer costs is one that must happen with careful thought and at a tempered pace.

The Town of Wellesley has demonstrated its commitment to reducing greenhouse gases and serving as a leader within Massachusetts on environmental issues. The WMLP has been an active and supportive partner in the Town's collective efforts. As the surrounding power system, the state, and the electric industry continue to look to electrification as a tool for decarbonization, and transition to a lower-carbon electric system, the WMLP should continue to proactively anticipate and address the reliability, cost, and energy management challenges these circumstances will raise. Doing so will give the Town of Wellesley the best chance possible to reach its broader goals.

Select References

Bloomberg New Energy Finance, "New Energy Outlook 2018", available: https://about.bnef.com/new-energy-outlook/#toc-download

Denholm, P. and T. Mai, "Timescales of Energy Storage Needed for Reducing Renewable Energy Curtailment", National Renewable Energy Laboratory, September 2017.

Frew, B.A., Becker, S., Dvorak, M.J., Andresen, G.B., Jacobson, M.Z. "Flexibility mechanisms and pathways to a highly renewable US electricity future", *Energy* (101), 2016, pp. 65-78.

Heard, B.P., B.W. Brook, T.M.L. Wigley, and C.J.A. Bradshaw, "Burden of proof: A comprehensive review of the feasibility of 100% renewable electricity systems," *Renewable and Sustainable Energy Reviews*, 2017, pp. 1122-1133.

ISO-NE, 2018 State of the Grid: ISO on Background. Presented by G. van Welie, February 27, 2018.

Jenkins, J. and Thernstrom, S. "Deep Decarbonization of the Electric Power Sector: Insights from Recent Literature", Energy Innovation Reform Project, March 2017.

MacDonald, A.E., Clack, C., Alexander, A., Dunbar, A., Wilczak, J. and Xie, Y. "Future cost-competitive electricity systems and their impact on US CO2 emissions", *Nature Climate Change*, Jan 2016, pp. 1-71.

National Renewable Energy Laboratory, "Renewable Electricity Futures Study", Hand, M.M.; Baldwin, S.; DeMeo, E.; Reilly, J.M.; Mai, T.; Arent, D.; Porro, G.; Meshek, M.; Sandor, D. eds. 4 vols. NREL/TP-6A20-52409. Golden, CO: National Renewable Energy Laboratory. 2016.

Rocky Mountain Institute, "The Economics of Demand Flexibility: how "flexiwatts" create quantifiable value for customers and the grid", August 2015.

Rocky Mountain Institute, "The Economics of Electrifying Buildings: How Electric Space and Water Heating Supports Decarbonization of Residential Buildings", 2018.

Seel, J., A. Mills, and R. Wiser. "Impacts of High Variable Renewable Energy Futures on Wholesale Electricity Prices, and on Electric Sector Decision Making," Lawrence Berkeley National Laboratory, May 2018.

Sepulveda, N.A. et al., "The Role of Firm Low-Carbon Electricity Resources in Deep Decarbonization," *Joule*, September 2018.

United States Mid-Century Strategy for Deep Decarbonization, November 2016.

Williams, J.H., et al. "Pathways to deep decarbonization in the United States, US 2050 Volume 1 Technical Report." 2014, Revision with technical supplement, November 16, 2015.