Fully Decarbonizing the New England Electric System: Implications for New Reservoir Hydro

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Summary

New England, New York and several eastern Canada provinces have all adopted ambitious goals to reduce greenhouse gases (GHG) and deploy clean energy with the ultimate objective of fully decarbonizing the regional energy system by roughly mid-century or shortly after.

This whitepaper addresses how best to achieve that goal in the electric sector and, more specifically, assess the viability of the 100% renewables pathway to full decarbonization without new reservoir hydro as suggested by some industry observers.

In brief, this whitepaper presents the view that fully decarbonizing the New England electric system by about mid-century will not be easy, free or without tradeoffs. The enormous buildout and rapid turnover required makes this a daunting challenge under most any conditions.

Solar and wind technologies can be an important part of this transition. But the seasonal mismatch between wind and solar generation and electric load – with long periods of surplus generation in the winter and deficits of generation in the summer – means that these intermittent sources of generation, even with battery storage, are not by themselves a practical path to full decarbonization.

Further, expanding this solar, wind and battery path to include a broader set of renewable technologies, but still excluding new reservoir hydro, exposes the approach to many technology development and deployment uncertainties. Because of this, a renewables-only path excluding new reservoir hydro is not likely to be a dependable approach to fully decarbonizing the New England electric sector.

There is, fortunately, a more promising approach. This rests on both long term planning and near term investment, and recognizing the importance of technology diversity and the flexibility to change course over time. The prospects for long term success would greatly benefit from a regional effort to map out a range of alternative technological pathways to full decarbonization by 2050. Given the limited time available to mid-century, the chances for success would also be materially improved by moving forward expeditiously with the deployment of proven and acceptably cost-effective low- and zero-carbon technologies. These could include solar and wind as well as other technologies that are firm, dispatchable and scalable to the challenge at hand. While the development of many such technologies in New England is currently constrained by technical and cost concerns, reservoir hydro is an exception. It is technically proven, cost-effective and can be deployed in the region today at scale to further the goal of decarbonization.

Fully Decarbonizing the New England Electric System: Implications for New Reservoir Hydro

Bruce Phillips[1]

I. Introduction

Over the last 10 to 15 years, all New England states, New York State and several provinces in eastern Canada have adopted greenhouse gas (GHG) and/or clean energy goals. Over time, as regional GHG emissions have started to decline, many of these states have made their policy goals increasingly ambitious. At this point in time, late in 2018, most of the region's GHG goals call for emission reductions of roughly 80% by 2050. [2]

As ambitious as these goals are, it is important to understand that they are interim rather than final goals. The ultimate objective is to fully decarbonize the New England energy system by roughly mid-century or shortly after, not just reducing but fully eliminating GHG emissions and doing that across all sectors of the regional economy. At the same time, the reliability, safety and affordability of electric service will need to be maintained. This challenge is daunting. We should not pretend it will be easy, free or without tradeoffs.

For that reason, it is important to think hard about the best way to achieve the goal of full decarbonization by mid-century. And, since it is difficult to precisely map out the entire path to mid-century given the numerous technological, economic and social uncertainties, it is also important that near term policy and investment decisions are flexible so that they increase the chances of eventual success.

This whitepaper addresses the challenge of decarbonization, focusing primarily on what has become known as the 100% renewables pathway, but also considering the need for other types of zero carbon electric generating technologies. The 100% renewables pathway – or more precisely "100% renewables without new reservoir hydro" – is the main focus because it is a well-recognized and popular approach to decarbonizing the electric system. The popular interest in solar, wind and battery technologies should not be surprising given their impressive cost reductions and performance improvements in recent years as well as their increasingly

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[2] For example, the New England states and New York have goals to reduce 2050 GHG emissions by 75% to 95%, and to achieve 10% to 75% renewable energy mixes by 2030 or 2040.

rapid deployment. But does this mean these technologies are also well suited to fully decarbonize the electric system?

This whitepaper, more specifically, examines two versions of the 100% renewables without hydro approach to full decarbonization:

1. Wind/solar/batteries – this version calls for full decarbonization to be achieved solely with wind, solar and battery technologies.
2. Broader Renewables without Reservoir Hydro – this version calls for wind, solar and battery technologies along with a broader set of renewable technologies (such as concentrated solar power, off-shore wind, pumped hydro storage, thermal energy storage, interregional high voltage transmission and customer demand response), but still excluding new reservoir hydro.

In brief, there are four main points to be taken from this paper.

1. Fully decarbonizing the New England electric system by about mid-century will not be easy, free or without tradeoffs. In fact, it is a daunting challenge.
2. The seasonal mismatch between wind and solar generation and electric load means these intermittent sources of generation, even with battery storage, are not by themselves a practical path to full decarbonization.
3. The many uncertainties associated with technical development and large-scale deployment of a broader set of renewable technologies, again excluding new reservoir hydro, make this an undependable approach to full decarbonization.
4. A more promising approach rests on long term planning to map out a full range of alternative technological pathways to full decarbonization and, at the same time, near term investment in diverse zero-carbon technologies including solar, wind and other technologies that are firm, dispatchable and scalable. In New England today, most firm, dispatchable and scalable technologies are constrained by technical and/or cost concerns, but reservoir hydro is an exception. It can be deployed in the region today at scale to further the goal of decarbonization.

The remainder of this paper is organized in four main sections. First, it briefly covers several important policy considerations that shape the subsequent material. The second and third sections present assessments of the two versions of the 100% renewables without new hydro approach to full decarbonization. The fourth and final section addresses the need for complementary firm, dispatchable and scalable zero-carbon generating technologies and the role that new reservoir hydro could play in a fully decarbonized New England electric system.

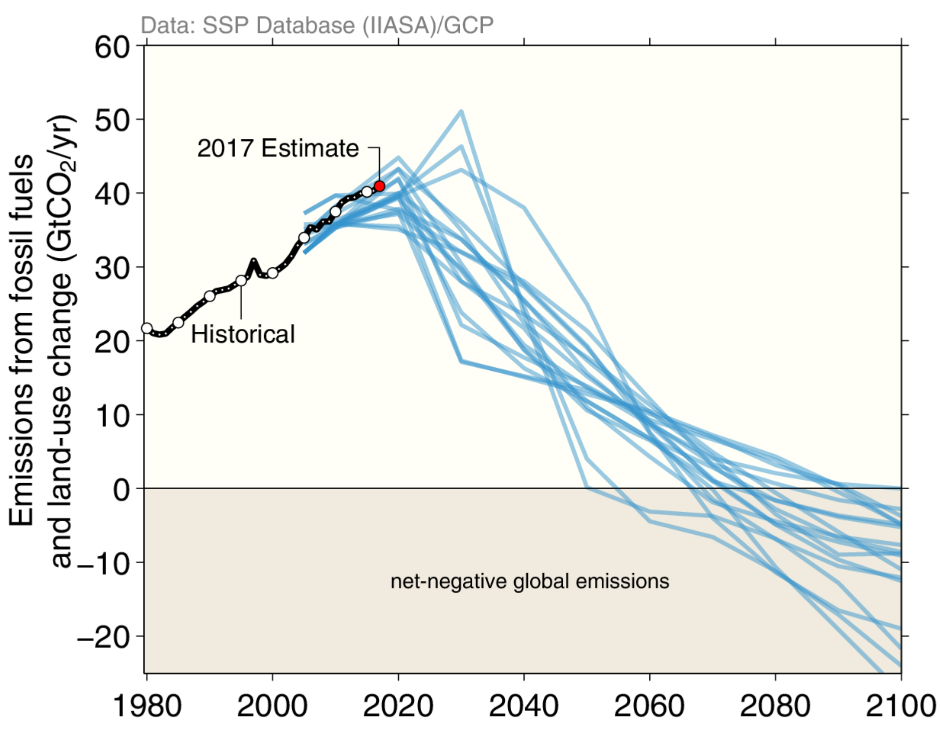
II. The Challenge of Climate Change Mitigation in New England

Before turning to the two assessments of the 100% renewables approach, it is important to appreciate the scale and speed of the transformation that climate change mitigation will require.

The Emissions Goal: Get to Zero by Roughly Mid-Century

The policy context for climate change mitigation efforts in New England involves the much larger effort to fully eliminate global GHG emissions over the next several decades.

Major global studies of climate stabilization conclude that in order to avoid the adverse impacts of 2°C warming, global GHG emissions need to decline rapidly, reach the zero level shortly after 2050, and then become net-negative (meaning that, on a net basis across all sectors of the economy, land uses and other natural environments able to absorb carbon, GHG are removed from the atmosphere rather than emitted into it.) This steeply declining time pattern of global emissions is illustrated in the following chart which compares the growth in historic emissions since 1980 to a range of emission reduction scenarios over the coming decades.



Source: Global Carbon Project, Global Carbon Budget 2017, Published 13 November 2017

While total global emissions across all sectors will need to reach zero sometime shortly after mid-century, major studies also conclude that the electric system should be decarbonized first, or roughly by mid-century.[3] This is because many of the technologies required to decarbonize the electric sector are relatively well known and a number of these have become increasingly cost-effective in recent years. Focusing on early decarbonization of the electric sector allows other sectors of the economy such as transportation and industry to be partially decarbonized through electrification. This "electricity first" approach implies a goal of decarbonizing the electric sector in about 30 years and somewhat longer for other sectors of the economy.

For the New England region as elsewhere, fully decarbonizing the electric sector by roughly mid-century will be an immense challenge. There are at least two reasons for this.

<u>Enormous Buildout</u>

The scale of the buildout required to fully decarbonize the regional electric system is enormous. Several metrics will help put this in context:

- *Replacement of Fossil Only* – At a minimum, full decarbonization of the New England electric sector requires replacing the portion of total electric generation currently supplied by fossil fuels, which is mostly natural gas-fired generation. In New England during the year 2017, this amounted to 52 TWh, or 42% of total regional electric consumption.
- *Replacement of Fossil and Nuclear* – Alternately, if the buildout entails replacing fossil generation and also the region's nuclear generation, a total of 84 TWh of generation will need to be replaced. This represents 68% of total regional electric consumption in 2017.
- *Replacement of all Except Wind and Solar* – If, instead, the buildout is intended to replace all generating resources other than wind and solar (that is, fossil, nuclear, hydro and electricity imported from adjoining regions) then 119 TWh of generation will be needed. This is 97% of regional electric consumption.
- *Current Generation plus Electrification* – Since decarbonization studies generally conclude that the most practical and cost-effective way to eliminate GHG emissions from the transport and industrial sectors of the economy involves partial electrification of these sectors, overall demand for electricity is expected to grow under decarbonization. This additional generation will also need to be carbon-free and, depending on the mix of zero-carbon liquid fuels and electrification required to decarbonize other sectors, it could well result in a doubling of the demand for generation.

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[3] For instance see United States Mid-Century Strategy for Deep Decarbonization, the White House, November 2016.

Regardless of the exact way this is carried out, decarbonization will require an enormous buildout of the New England's electric system. This is true when evaluated on the basis of energy generation, as presented above, but it is particularly striking when looked at on the basis of generating capacity. This is because the capacity factors (or utilization) of solar and wind facilities in the region are generally lower than conventional sources of generation. As a consequence, replacing current generation with an equal amount of solar and wind generation would require a disproportionately large amount of solar and wind capacity. Even without the increased overall demand that would come from electrification of the transportation and industrial sectors, this shift from higher capacity factor to lower capacity factor sources of generation could double the amount of generating capacity in the region.

Rapid Turnover

Further, this ambitious buildout will need to occur at very rapid pace, without much time for trial and error.

As explained earlier, most multi-sector decarbonization studies conclude that the electric sector will need to be decarbonized first, or roughly by mid-century.

To put this 30 year period in context, historians studying the energy sector and global energy transitions conclude that humankind has experienced just two grand energy transitions in its history, one from biomass to coal and a second from coal to oil and gas. While the duration of these global transitions can be measured in various ways, it is fair to say each has taken at least 50 years.

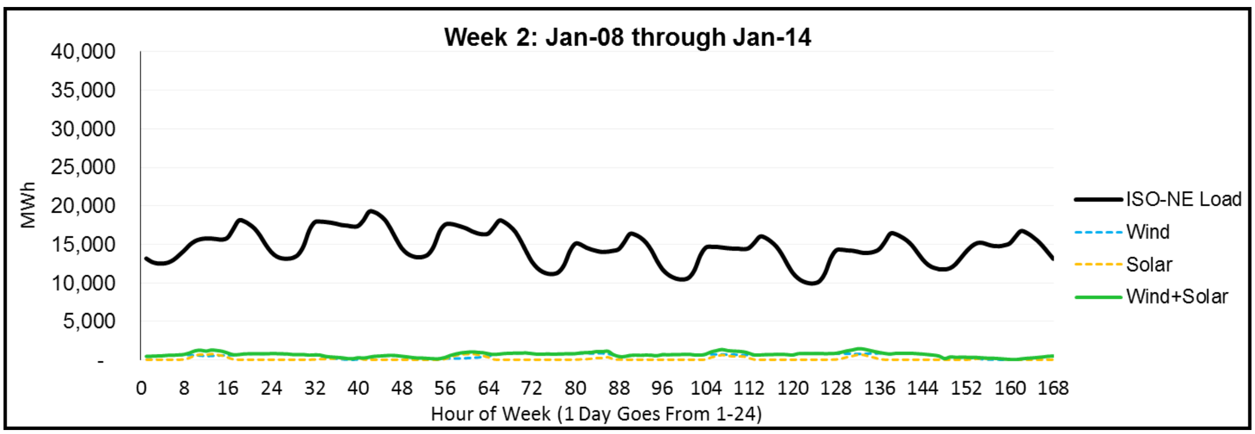
These two time periods are relevant to the challenge of decarbonizing the New England electric system: they suggest that, if the 2°C warming goal is to be achieved, there is only one chance to successfully manage the transition. If instead of 30 years, the 2°C warming goal could be achieved by decarbonizing the global energy system in 200 years, then a strategy of trial and error could be workable. A first solution could be pursued, tested, and a second one adopted if the first one failed. But that is not the current situation. If the 2°C warming goal is to be met, there are only several decades available to manage a transition, and history suggests that the transition is likely to take at least several decades to complete. The likely consequences of not meeting this goal would be to rely more heavily on net-negative carbon technologies which are not well developed and/or to live with the adverse impacts of a warmer climate.

The scale of the buildout and the rapid turnover required to fully decarbonize the regional electric system make this a daunting challenge. Adding to this, for the public to continue to support efforts to achieve ambitious climate goals, this buildout and turnover will need to be done in a manner that preserves the reliability, safety and affordability of electric service to customers.

III. Wind, Solar and Batteries, by Themselves

This next section of the paper examines the first of the two versions of the "100% renewables without new hydro" approach to full decarbonization. It asks whether the New England electric system can be fully decarbonized by relying solely on wind, solar and battery systems, and addresses that question by looking at generation and load data in New England during the year 2017.[4]

The following chart shows hourly electric loads along with wind and solar generation during the second week of 2017, January 8 through January 14, which was reasonably representative of conditions during the winter of 2018. The solid black line at the top of the chart represents hourly electric load in New England, generally ranging between 15,000 MWhs at night and close to 20,000 MWhs during highest demand days. Wind and solar generation, and the sum of the two, are represented by the blue, yellow and green lines, respectively.[5] As shown in the chart, wind and solar generation are a small fraction of total electric load. On an annual basis during 2017, New England wind and solar generation represented only about 3.4% of total electric load.



Source: NorthBridge analysis based on 2017 NE-ISO data.

The next chart shows the same data for a representative summer week in the middle of July. It shows a very similar pattern, with wind and solar generation a very small fraction of electric loads.

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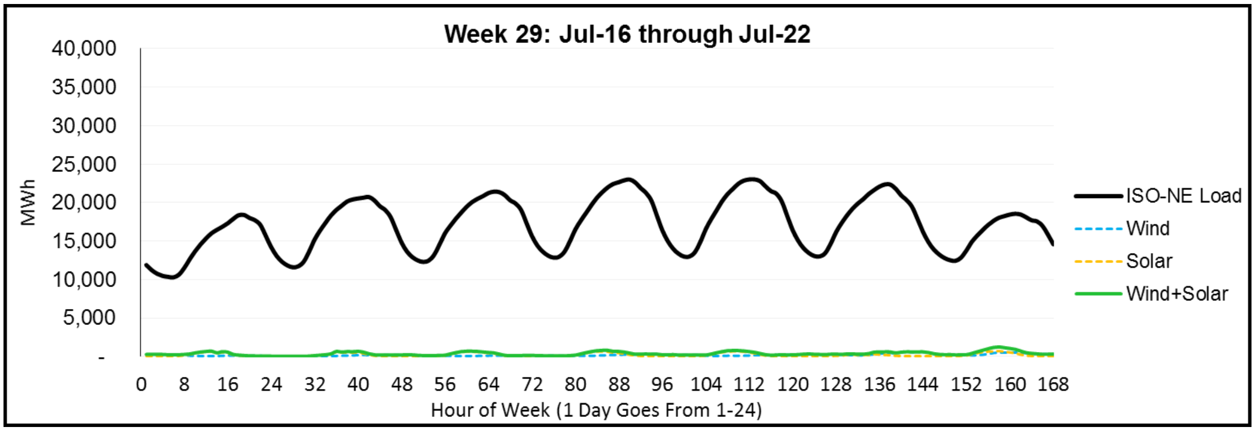
[4] This assessment is based on an analysis of onshore wind and solar generation along with electric loads in New England during the year 2017 drawing on chronological hourly data from the NE-ISO among other sources.

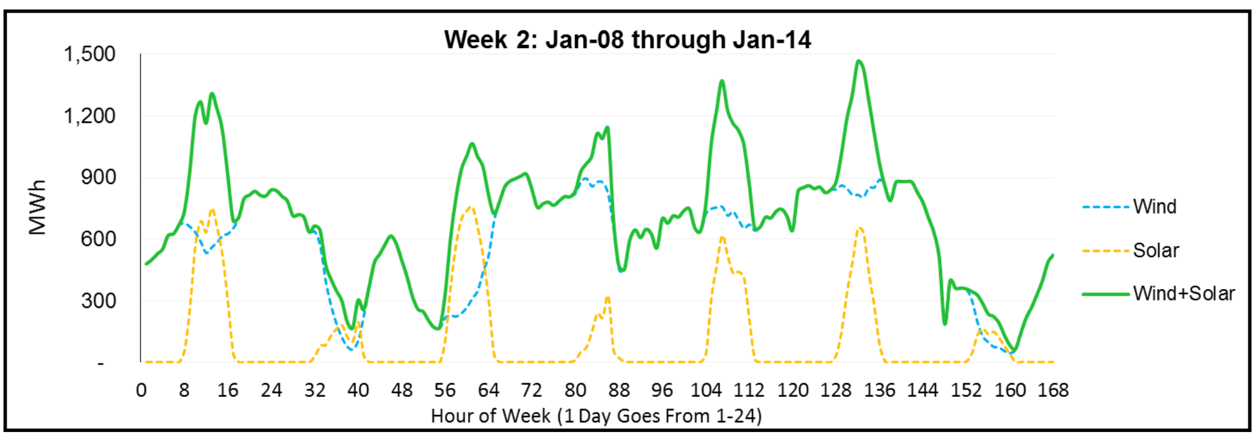
[5] Because data for generation from operating off-shore wind projects in New England during 2017 was lacking, this analysis is limited to on-shore wind. In New England, off-shore wind is generally expected to have higher capacity factors than on-shore wind but could experience somewhat similar variability issues.



Source: NorthBridge analysis based on 2017 NE-ISO data.

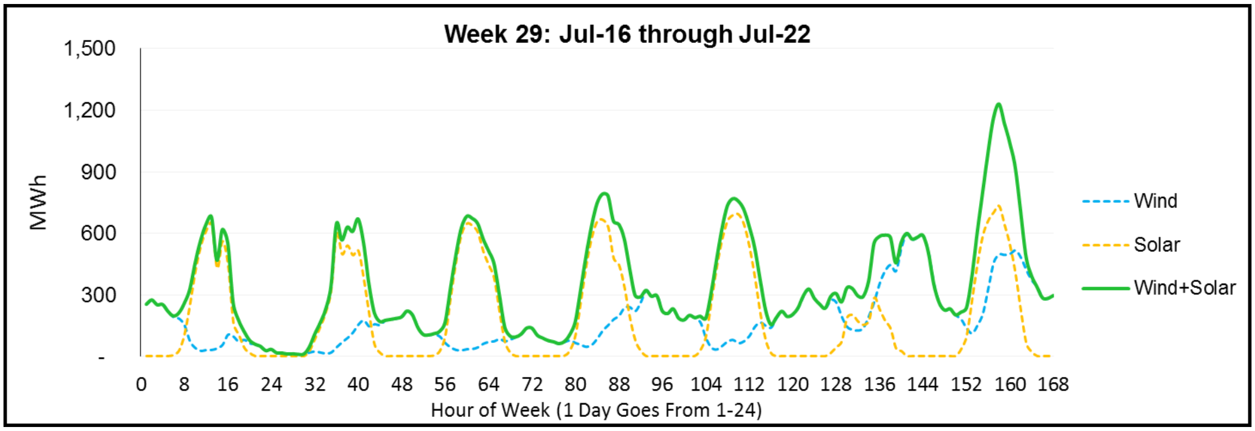
The next two charts look more closely at the patterns of wind and solar output during these two weeks, revealing an important observation about the seasonal pattern of wind and solar generation.

The following chart presents data for the same winter week shown earlier. In the chart below, the pattern of solar output (shown in yellow) can be clearly seen for each day of the week although output is higher in some days than others. Wind output, which also varies on a day-to-day and hour-by-hour basis, is shown in blue and the sum of solar and wind generation is shown in green. While total solar and wind generation varies substantially on an hourly basis, it tends to range between 600 MWhs and 900 MWhs per hour.



Source: NorthBridge analysis based on 2017 NE-ISO data.

The corresponding chart for the summer week, shown next, reveals a generally similar hourly pattern. Solar generation peaks each day and wind generation fluctuates during the week. What is quite different from the winter week, however, is the total average amount of solar and wind generation. In contrast to the winter week which roughly ranged between 600 MWhs and 900 MWhs per hour, total average solar and wind generation during this summer week ranged between 300 MWhs and 600 MWhs, quite substantially less than in the winter. This large difference in generation is driven primarily by the wind rather than solar output and, as will be seen shortly, is a seasonal rather than weekly phenomenon.

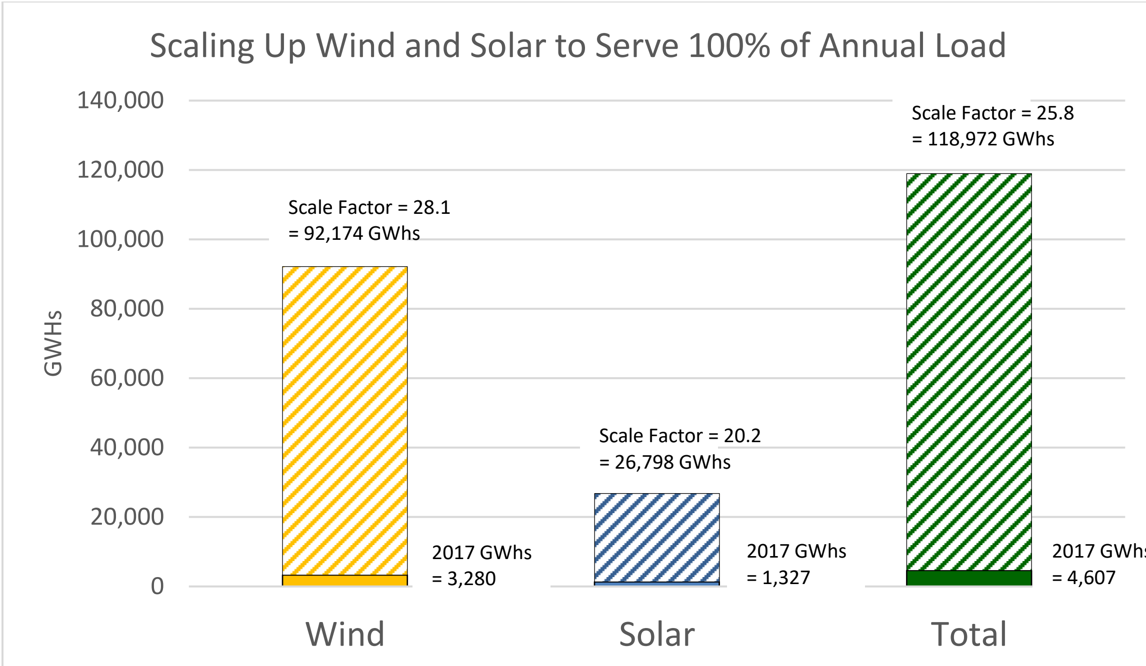


Source: NorthBridge analysis based on 2017 NE-ISO data.

In order for wind, solar and batteries to supply all of New England's generation, the total amount of wind and solar generation seen during 2017 would need to be scaled up and the hourly output of that generation would need to closely match the hourly pattern of electric loads.

For total annual wind and solar generation to equal total annual electric load, this would require scaling 2017 wind generation by a factor of 28, 2017 solar generation by a factor of 20, and the two sources of generation by a factor of 26. These scaling factors are shown in the figure below. [6]

[6] The scaling factors for wind and solar used in this analysis were chosen to minimize the difference between hourly solar and wind generation and hourly electric loads over the course of the year, that is to minimize the sum of surplus and deficit generation across the year.



Source: NorthBridge analysis based on 2017 NE-ISO data.

In addition to this scaling of solar and wind generation, this analysis assumed a 12 GW battery system was built to address short term hourly imbalances of generation and load. This amount of battery capacity is equal to 50% of the regional peak load in 2017.

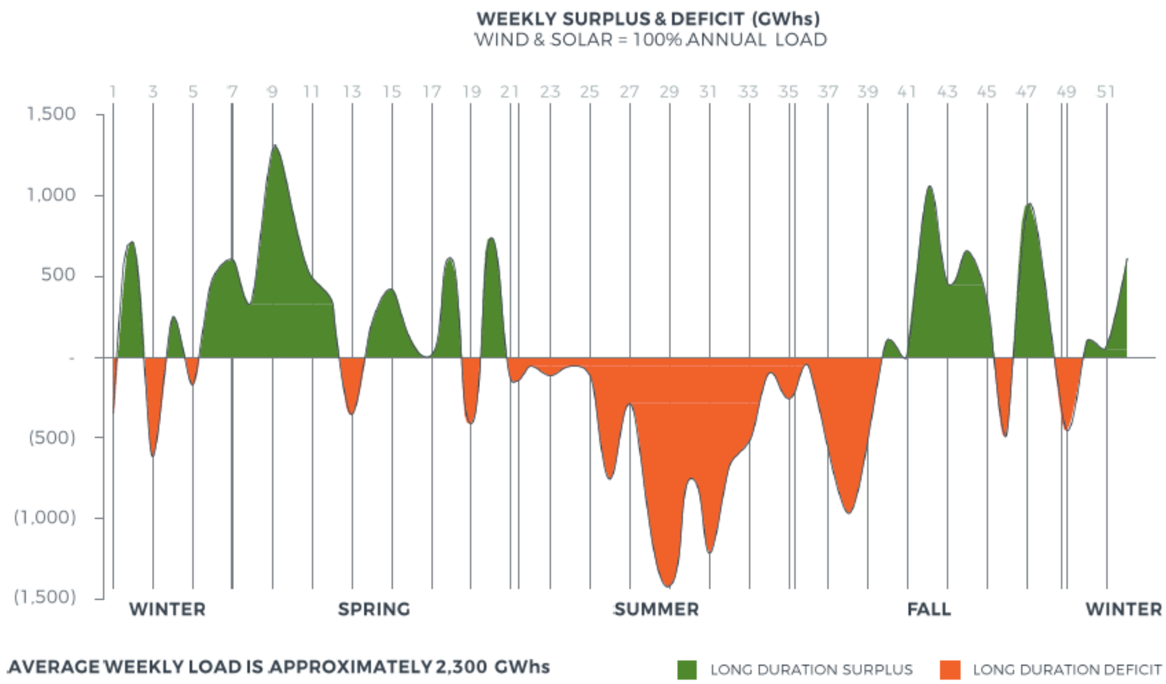
Assuming this scaling of wind and solar generation and the development of a large scale battery system, how would the time pattern of wind and solar output compare to the time pattern of electric load?

The answer is shown in the following chart, with the results presented on a weekly basis for all 52 weeks of the year, left to right across the chart.

The areas shown in green above the horizontal line are weeks when total solar and wind output (adjusted through time with the battery system) exceeds electric load. These are weeks when solar and wind are, in total for the week, sufficient to serve load and, in fact, produce surplus generation.

The areas in orange below the horizontal line are weeks when solar and wind output (again, adjusted with the battery system) are less than electric load. In these weeks, there is a deficit of generation, and customer loads would need to be curtailed due to insufficient generation.

ANNUAL PATTERN: WINTER SURPLUS & SUMMER DEFICIT AFTER WIND, SOLAR & BATTERY SCALE UP



Source: NorthBridge analysis based on 2017 NE-ISO data.

The most important point to take from this chart is the seasonal pattern. Long-duration periods of surplus generation in the winter and spring seasons are followed by long-duration periods of deficits during the summer season before the surpluses return again in the fall. This pattern is consistent with the relative amounts of solar and wind output seen previously in the two weekly charts where winter wind generation far surpassed summer wind generation. This seasonal pattern of relatively strong winter wind output and relatively weak summer wind output is not unique to New England, it is observed across most of the continental United States.

Note also in this chart that the largest weekly deficit during the summer months is about 1,400 GWhs. By way of comparison, the average weekly load in New England during 2017 was about 2,300 GWhs. This suggests the magnitude of summer load curtailment (and winter surplus generation) can be quite substantial, perhaps over 50% of average weekly load.[7]

This long-duration mismatch between electric loads and wind and solar generation is exceedingly difficult to address with wind, solar and battery technologies alone.

[7] This deterministic looks at the patterns of intermittent renewable generation does not account for hourly, daily and even week-long solar and wind "droughts" which occur periodically.

While the summer deficit issue could be addressed at least in part by building yet more solar and wind capacity, this additional capacity would compound the frequent periods of surplus energy produced in the winter and spring seasons.

It also cannot be overcome with today's battery technologies because they have been designed to discharge stored energy over a period of four to eight hours, not the multi-day, week or month-long periods needed to address the seasonal mismatch problem. In concept this could be overcome by building more battery capacity but the amount of battery capacity required to overcome several weeks of large energy deficits would quickly dwarf the electric system. Further, when today's batteries are used just once-a-month or once-a-season rather than a daily basis, their cost per use rises dramatically.

All of this highlights a fundamental problem with relying exclusively on wind, solar and battery systems to decarbonize the New England electric system – the large seasonal mismatch between solar and wind generation on the one hand, and electric loads on the other.

As a consequence, relying on solar, wind and batteries alone is almost certainly an impractical way to fully decarbonize the regional electric system. Customers are very unlikely to accept having a large portion of their load curtailed for extended periods in the summer while paying for an electric system that produces large quantities of unused generation during the winter.

IV. Broader Mix of Renewables, but without New Reservoir Hydro

Most energy and climate policy analysts studying the challenges of deep decarbonization are aware of the practical limitations of systems relying solely on wind, solar and batteries. To address these concerns, analysts have looked at the second version of the "100% renewables without new reservoir hydro" approach to decarbonization identified earlier in this paper. This second version calls for wind, solar and battery technologies along with a broader set of renewable and supporting technologies but still excluding new reservoir hydro.

As with the first version:

1) On-shore wind
2) Solar PV
3) Battery Storage

In addition, this second version calls for:

4) Off-shore wind

5) Concentrated solar power (which uses a mirror system to concentrate solar energy and produce heat to power a conventional electric generating plant)
6) Pumped hydro storage (which stores energy in the form of water pumped into an elevated reservoir before the water is released to generate electricity)
7) Thermal energy storage (which involves the storage of thermal energy and its transfer between objects or energy systems to produce electricity)
8) High voltage transmission (to tie together distant sources of renewable generation and electric load)
9) Customer demand response, curtailment and energy efficiency (to better match load with generation during periods of limited renewable output)

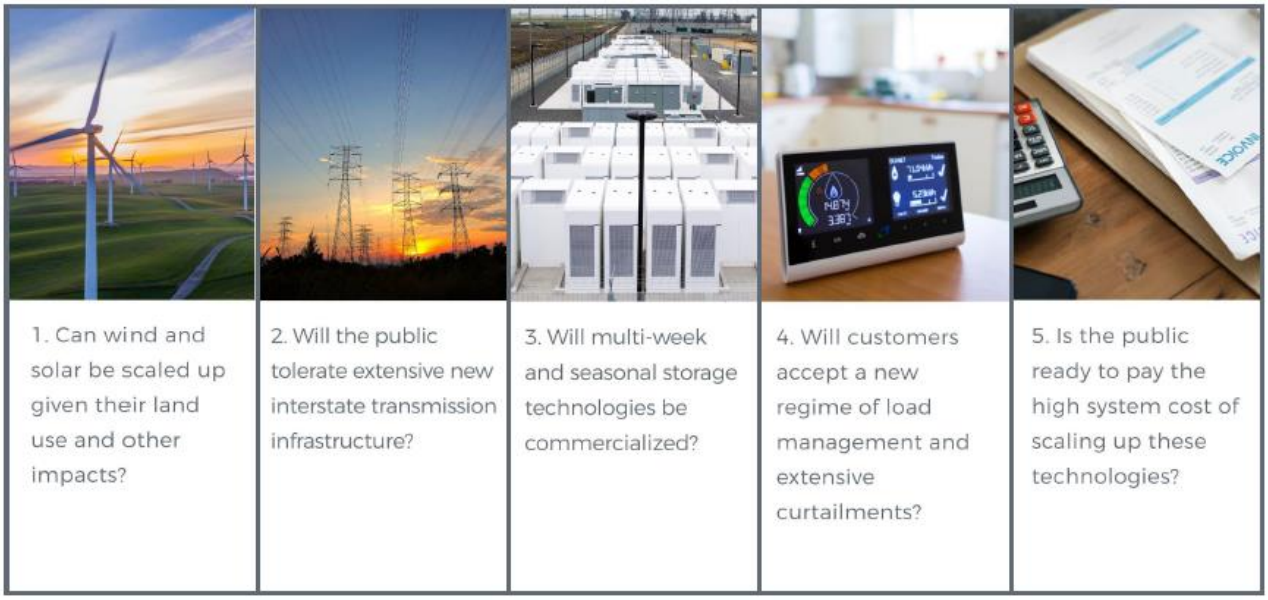
Could this expanded renewables approach without new reservoir hydro approach be successful? On paper or in a technical sense, the answer is yes: it should be possible for these technologies to closely match generation and load.

The more important question though, is whether this is a dependable or likely path to full decarbonization.[8] This is important to ask since, as discussed before, many studies point to the need to fully decarbonize by about mid-century, which does not leave time for a trial and error approach. Having a technological pathway that might work is helpful, but not as helpful as one that is dependable and likely to work given all the uncertainties involved. Getting it right the first time around is important.

To simplify this discussion of how dependable the second "broader mix" path might be, consider five elements of uncertainty underlying this approach:

A. <u>Scale Up</u> - Can both wind and solar be sufficiently scaled given their land use requirements and other impacts?
B. <u>Transmission</u> - Will the public tolerate extensive new interstate transmission infrastructure?
C. <u>Seasonal Storage</u> - Will multi-week and seasonal storage technologies, such as thermal energy storage, be proven and commercialized?
D. <u>Load Management</u> - Will residential, commercial and industrial customers accept a new expanded regime of load management and curtailment?
E. <u>Electric Costs</u> - Is the public ready to pay the cost of fully decarbonizing the electric system with these technologies alone?

[8] While this paper does not address the question of whether this approach could be a cost-effective path to full decarbonization, a number of other studies have concluded that this is likely to be materially more expensive than other approaches relying on a more diverse mix of zero-carbon technologies.

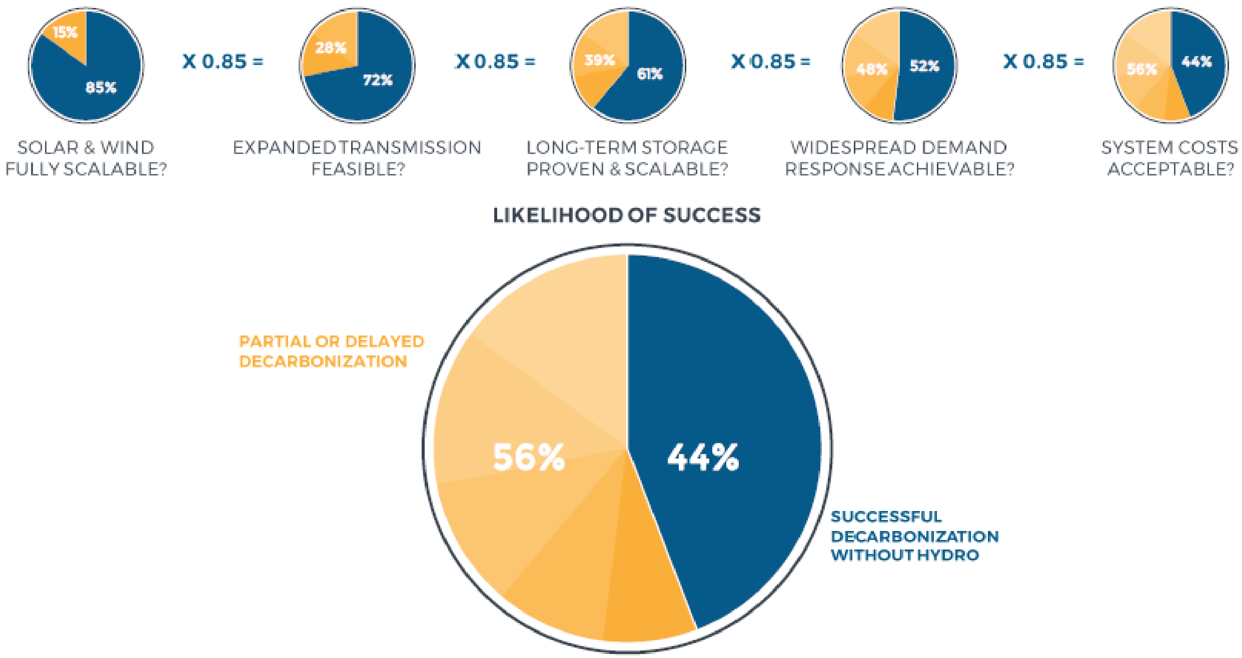


Certainly, it is possible that each of these questions might be answered affirmatively. And, if so, then these five hurdles might be overcome and this approach could be successful. But the more important issue here is dependability. The question is not if a particular technology pathway might decarbonize the electric sector by mid-century, but instead how likely it is to achieve that goal. To understand that, the individual and collective likelihood of each of these five questions needs to be considered.

To examine this, consider a simple mental math exercise. Assume for the moment that each of these five uncertainties has an 85% chance of success, in other words that the likelihood of overcoming each hurdle is 85%. If the only uncertainty was whether wind and solar could be scaled up, the overall chance of success would be 85%. But if there are two uncertainties – wind and solar scale up and also the transmission build out – then the chances are lower. Instead of 85%, they drop to 72% (which is 85% times 85%). As each additional uncertainty is added with an 85% chance of success, the cumulative chance of overall success continues to drop. With five uncertain events, each with an 85% chance, the cumulative chance is only 44%, which is close to a 50/50 coin flip. [9]

The results of this simple exercise are shown in the figure at the top of the following page.

[9] Mathematically, 85% times 85% times 85% times 85% times 85% equals 44%.



The point of this example is not to say the likelihood of this particular approach to full decarbonization has exactly a 44% chance of success. The point instead is that any inflexible strategy that has a number of uncertain elements with individual independent probabilities less than 100% will have an overall chance of success well below 100%. In this case, five uncertain elements, each with an 85% chance of success, translates to an overall probability of 44%. Other representations of this type of approach with a realistic number of uncertainties and probabilities will have generally similar overall chances of success.

This is to say, the approach is not dependable.

A more practical and dependable approach would rest on a diversified strategy with multiple technology options and greater flexibility over time. For example, consider another approach that relies on two independent paths to full decarbonization, the first one identical to what was just described and a second involving a different set of zero carbon technologies. Realistically, these paths need not be fully independent from one another, but for the purpose of this example assume they are. If each of these has a 44% likelihood, they collectively have an overall chance of success of 69%, quite a substantial improvement over the single path approach with its 44% change. If a third independent path was created, also with a 44% likelihood, the overall chance of success for the three paths increases to 83%. Multiple options and flexibility materially increase the overall chance of success.

This observation, that inflexible strategies in the face of uncertainty have lower probabilities of success than more flexible strategies with multiple options, is really just common sense. It has many parallels in everyday life.

Consider, for example, the process of getting to the airport in time to catch an important flight. Someone could choose to leave home at the last moment, without thinking about whether there might be a traffic jam on the way, whether parking spaces are available and whether extra time might be needed for airport security. Even so, if everything went right, the person might catch the flight. But each one of these uncertainties adds to the risk of missing the flight, and the chances of catching it would be increased with better planning, more options and greater flexibility (mapping out alternative routes to the airport, finding a backup parking lot, choosing the shortest airport security line, etc.).

For another example, consider how the manager of a baseball team manages his or her lineup throughout the course of a game. The manager could choose a starting lineup and then make no substitutions throughout the entire game. This could be a winning strategy, but the inflexibility of this approach makes it risky. For the team to win, the starting pitcher would have to pitch well through all nine innings, the hitters would have to hit and score runs, and the fielders would have to play good defense. The odds of winning would be much higher with the flexibility to use relief pitchers, pinch hitters and defensive replacements in the late innings.

Fortunately, just the way the chances of catching a flight or winning a baseball game could be improved through planning, options and flexibility, the odds of mitigating the threat of climate change can also be improved.

V. A More Practical and Dependable Path: Resource Diversity

A more promising path to full decarbonization would involve pursuing all available low- and zero-carbon generating technologies. This includes, especially, low- and zero-carbon technologies that produce output at the scale needed to rapidly decarbonize the entire regional electric system and also provide firm and dispatchable energy (that is, technologies that are available on-demand whenever needed and that can be turned up or turned down in response to fluctuating load levels and generating output at other power plants.)

This does not mean turning away from wind and solar technologies, particularly when they can provide cost-effective energy. It does mean considering a broader and more diversified mix of technology options and deploying the most practical and cost effective ones over time to achieve the mid-century decarbonization goal.

Fortunately, there are a number of such firm, dispatchable and scalable technologies that may become technically proven and reasonably cost effective in New England over the coming decades.[10]

- *Carbon Capture*. Carbon capture and sequestration technologies have been proven at commercial scale in the electric sectors of the United States and Canada, and at least one promising next generation technology is currently being tested at demonstration scale level in Texas.[11] These technologies, however, are most cost effective in regions of North America where the captured carbon dioxide can be used for enhanced oil production. Given the distances required to transport carbon dioxide captured in New England to other regions with more suitable sequestration opportunities, these technologies do not appear cost competitive in this region today.
- *Nuclear*. Today's nuclear generating technology is also technically proven and new plants are being actively developed overseas. But the technology faces public opposition in New England and also economic challenges as new plants using today's technology are substantially more expensive than other sources of new generation in this region. Next generation nuclear technologies are under development in the U.S. and abroad, some in the R&D stage and others at more advanced stages, but none are as yet proven at commercial scale.[12]
- *New Renewables*. A number of next generation renewable technologies, including for instance advanced deep geothermal, are under development and hold promise but none are proven, cost competitive and fully scalable in the New England region at this time.
- *Reservoir Hydro*. In contrast to these other technologies, reservoir hydro is both technically proven and also cost-competitive in the New England region today.

These technology families are compared in the following figure.

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[10] Cost effective is used here to refer to situations where the total cost of a new generating source is less than the prevailing price of wholesale electricity or, if greater, where the cost premium expressed in terms of dollars per ton of carbon abatement is relatively low when compared to other technologies.

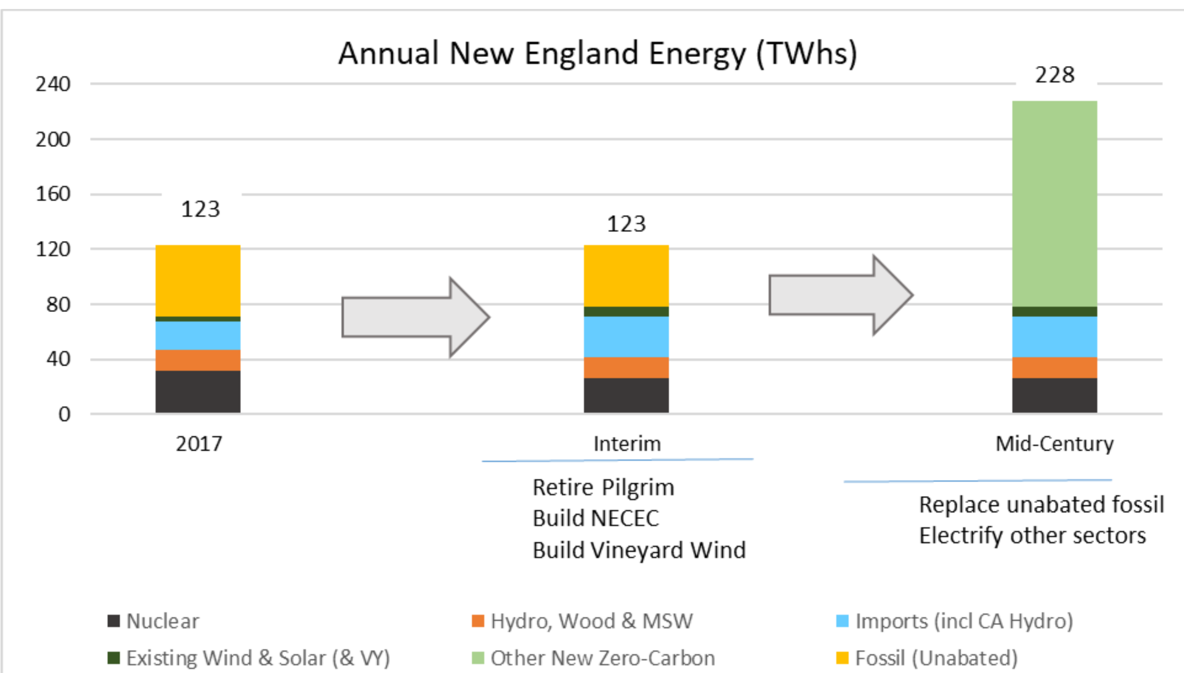
[11] See: 1) https://www.catf.us/2017/07/two-carbon-capture-projects/ and 2) https://8rivers.com/portfolio/allam-cycle/

[12] See: 1) The Future of Nuclear in a Carbon Constrained World: An Interdisciplinary MIT Study. MIT, September 2018. 2) Advanced Nuclear Energy: Need, Characteristics, Projected Costs, and Opportunities. Clean Air Task Force, April 2018.

FIRM, DISPATCHABLE & SCALABLE LOW-CARBON TECHNOLOGIES	CURRENT STATUS	
	TECHNICALLY PROVEN?	COST COMPETITIVE IN NEW ENGLAND?
Fossil Carbon Capture & Sequestration	✓	✗ NOT TODAY
New Nuclear - Current Technology	✓	✗ NOT TODAY
New Nuclear - Next Generation	✗ UNDER DEVELOPMENT	?
Advanced (Non-Hydro) Renewables	SOME YES OTHERS NO	✗ NOT TODAY
Reservoir Hydro	✓	✓

The status of these technologies will inevitably change and likely improve over time. However, as of this point in time, new reservoir hydro is the only firm, dispatchable, scalable zero-carbon carbon technology that is both technically proven and cost effective in New England. Adding this to the New England mix can improve the outlook for successfully achieving the region's climate change goals.

Finally, even with the near-term planned additions of new reservoir hydro and off-shore wind, the need to replace unabated fossil generation and electrify other sectors of the regional economy will create tremendous growth opportunities for many zero carbon technologies including wind and solar. The planned additions of reservoir hydro and off-shore wind are important, but still only initial steps toward full decarbonization of the regional economy.



VI. Implications

Fully decarbonizing the New England electric system by about mid-century will not be easy, free or without tradeoffs. The enormous buildout and rapid turnover that will be required make this a daunting challenge.

Solar and wind technologies can be important parts of this transition, but intermittent renewables alone without firm dispatchable zero-carbon sources of energy are not a practical or dependable path to full decarbonization. The seasonal mismatch between wind and solar generation and electric load – with long periods of surplus generation in the winter and deficit generation in the summer – means that these intermittent sources of generation, even with battery storage, are not by themselves a practical path. Further, the many uncertainties associated with the technical development and deployment of a much broader set of renewable technologies, but again excluding new reservoir hydro, make this an undependable approach to decarbonizing the New England electric sector.

There is, fortunately, a more promising approach. This rests on both long term planning and near term investment, and recognition of the importance of low-carbon technology diversity and the flexibility to change course over time as technical, economic and social preferences evolve.

The prospects for long term success would greatly benefit from a regional effort to map out alternative technological pathways to full decarbonization by 2050. Recognizing the inherent difficulty of predicting the future, rather than focus on any single pathway, the effort should identify a range of potential paths that collectively increase the odds of success. Assessing the technical and economic viability of these pathways would inform near term decisions about the best policies to turn possible futures into practical real-world options, and long term investment decisions determining the mix and pattern of deployment.

Meanwhile, the region also needs to move forward over the next five to ten years deploying a full complement of proven and acceptably cost-effective low-carbon technologies. These can include solar and wind, as well as other technologies that are firm, dispatchable and scalable. While the development of many firm, dispatchable and scalable technologies in New England is currently constrained by technical and cost concerns, reservoir hydro is an exception. It is technically proven, cost-effective and can be deployed in the region today at the scale needed to further the goal of decarbonization.