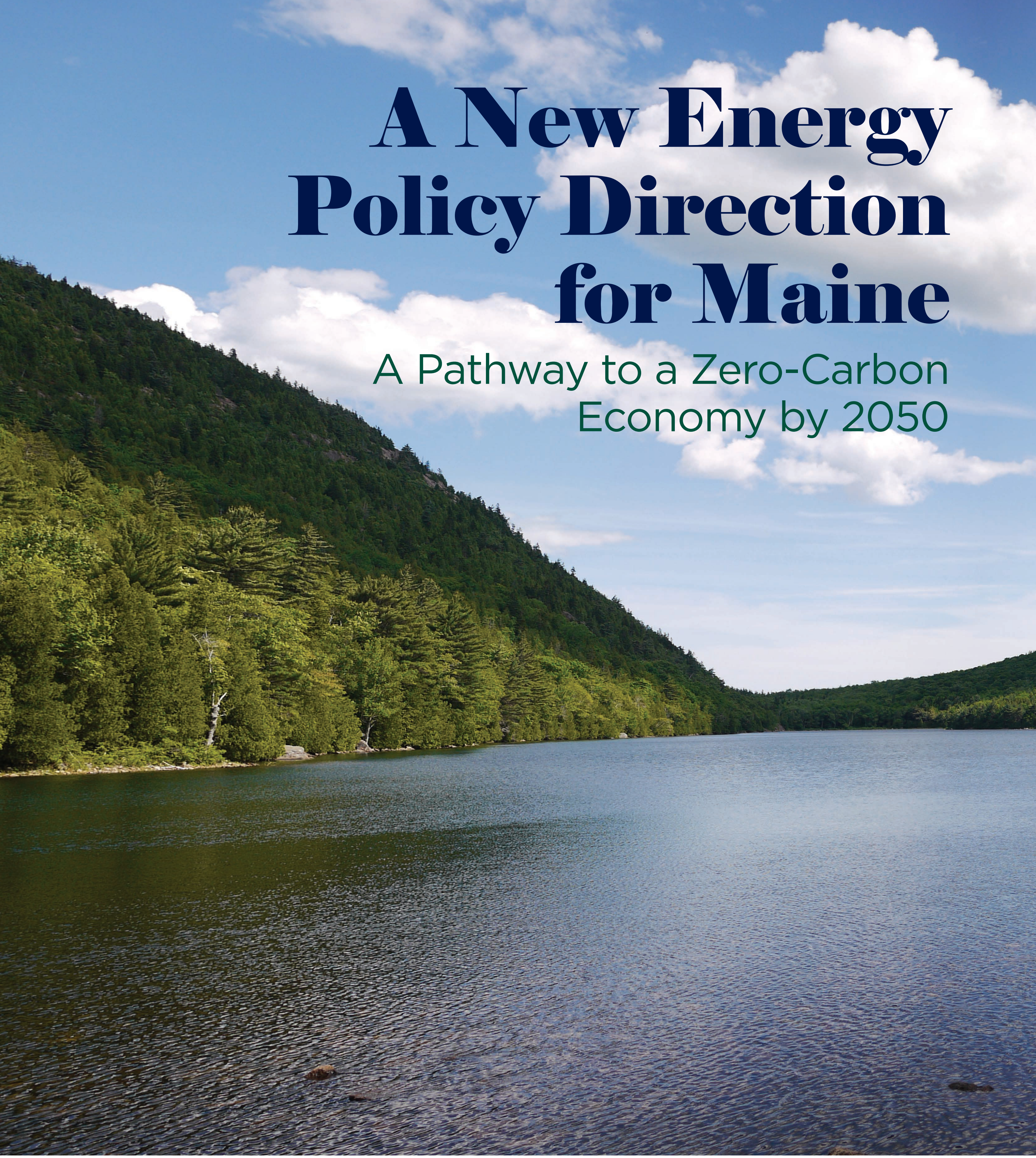

A New Energy Policy Direction for Maine

A Pathway to a Zero-Carbon Economy by 2050

Richard Silkman, Ph.D.

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Abstract

Over the past fifty years, energy policy in Maine has been driven alternatively by competitive pressures to keep energy prices low and environmental imperatives to reduce CO_2 and other greenhouse gas ("GHG") emissions. The net result of these efforts is that today energy prices in Maine are higher than the national average, while emissions are somewhat lower. Maine has paid a high price to achieve marginal reductions in GHG emissions.

In this report, I look to the next thirty years and specifically whether there is a feasible pathway for Maine to achieve a zero-carbon economy at a reasonable cost. I conclude that there is. This pathway is based on two pillars – the conversion of transportation, heating and processes to electricity (so-called "beneficial electrification") and the decarbonizing of the electricity sector through the development of renewable generation and battery storage (so-called "deep decarbonization"). Assuming reasonable rates of conversion of all sectors to electricity over the next thirty years and continuing declines in the real prices of solar photovoltaic systems and on-shore and off-shore wind generation and, importantly, declines in the costs of battery storage capacity, I show how Maine can accomplish a thirty-year transition to a zero-carbon economy without increasing the total amount it spends on energy each year, relative to the average it has spent each year over the past twenty years.

A key factor in this thirty-year transition is a shift in the energy sector from fuel and operating costs to capital investments. Essentially, deep decarbonization represents a substitution of capital for operating costs across the entire energy sector, thereby placing a premium on the ability to raise enormous amounts of capital as efficiently as possible. I estimate that this transition will require investments of close to $60 billion in new generation and storage technologies and in building out the electric grid to accommodate a nearly five-fold increase in peak demands that will result from beneficial electrification. I propose a new state structure – the Maine Energy Generation Authority – to accomplish this.

A second key factor is the development of off-shore wind. I show that off-shore wind generation tends to be countercyclical to solar PV generation in Maine and to offer a better match to electric loads after beneficial electrification. This allows Maine to reduce the amount of more expensive battery storage capacity to balance the mismatch between hourly, daily and seasonal electric generation and electric loads.

The transition that Maine and the world needs to accomplish over the next thirty years if we are to have any chance of mitigating the most adverse consequences of climate change and global warming is most daunting. I have laid out a pathway and a variety of policy prescriptions that address risks in a reasonable fashion by accelerating those actions and technologies that present lower degrees of uncertainty, while deferring those where the uncertainty is greatest. I focus initially on market mechanisms and voluntary activities. These, however, will not be sufficient to move us along the pathway. Accordingly, I identify mandates and requirements that are designed to make sure we track the complete pathway over the next thirty years.

I believe that this is the first attempt to set out such a pathway. As I note, it is only one such route to a zero-carbon economy in 2050. I trust that others will review my work, will identify its strengths and weaknesses and will offer improvements to it.

Acknowledgments

The genesis of this report lies in the Governor's Energy Office's ("GEO") proposal to develop a state energy planning roadmap. These efforts were funded by the U.S. Department of Energy. The intent was to engage private, public and non-profit stakeholders to develop an "Energy Planning Roadmap" to advance the state of Maine's energy, economic development and environmental goals. The objectives of the Roadmap, as set forth in the proposal to the U.S. Department of Energy are to:

1. Achieve energy and cost savings in the residential, commercial, industrial and transportation sectors.
2. Reduce pollution and greenhouse gas emissions.
3. Support the growth of a robust state and regional energy market and workforce, including products, services, infrastructure and manufacturing processes related to electricity reliability, energy efficiency, renewable energy, distributed generation, natural gas and transport, and other technologies.
4. Facilitate stakeholder and interagency discussions and activities that achieve Objectives 1 through 3 with emphasis on the electric power sector, natural gas supply, and transport; and integration of more renewable energy and energy efficiency into the state's portfolio.

More specific goals were the reduction of electricity sales and natural gas usage by 30% and peak electricity demand by 100 MW by 2020; reduction of oil use in home heating by 30% by 2030; the weatherization 100% of homes and 50% of businesses by 2030.[1]

[1] Attachment 1 of EERE 303: Statement of Project Objectives (SOPO), DE-EE0007222/000, Governor's Energy Office, Project Objectives, page 1.

The project team, led by very capable staff at the GEO and at E2Tech (the GEO's project's facilitator), assembled voluminous data sets regarding energy usage in Maine that provided a detailed picture of how Maine uses energy (demand for energy), where that energy comes from (supply of energy), how much the energy costs and the greenhouse gas ("GHG") emissions the production and use of such energy creates.

At the same time that this project was getting underway, cities and towns in Maine were becoming more active around the broader issue of climate change and global warming. Climate Action Teams ("CAT") were being formed in many communities, and their activities were leading to the adoption of forward looking and far-reaching policy statements regarding achieving major reductions in and even elimination of CO_2 and other GHG emissions by dates certain – e.g., 2030, 2040 and 2050. These initiatives represent clear expressions of serious public concern about a wide variety of public policy issues, the central overarching one being how Mainers use energy and where such energy comes from.

What has been striking about these two sets of activities – the GEO efforts to develop an energy roadmap, on the one hand, and citizen actions to achieve a carbon-free economy, on the other – is their lack of interaction. From the perspective of concerned citizens, the goals and objectives of the energy roadmap are too short-term, remain anchored in an essentially fossil-based energy sector and will not achieve the fundamental objective of mitigating climate change. Perhaps equally frustratingly, since they are not rooted in an understanding of how energy is used and produced, the activities of the CATs are too easily dismissed as naïve aspirational goals that simply fail to recognize the full extent of societal changes and their consequences that will be necessary to eliminate carbon across all sectors of the economy.

This report is in many respects an attempt to bridge these two perspectives. I take as given the increasingly accepted position that Maine and the rest of the world must become essentially carbon free by 2050 if we are to mitigate the worst impacts of climate change and global warming. This is the end mile-post of my roadmap. My starting line is where Maine is today – the detailed and nuanced picture of energy use and supply that the GEO has laid out. I rely on what I believe to be reasonable assumptions about the trajectories of performance, cost, efficiency, dissemination and development over the next thirty years (from 2020 to 2050) to fashion a pathway to a zero-carbon future.

While this report is written in the first-person singular, I make no claim that the ideas, assumptions, methodologies and analytical frameworks contained herein are entirely my own. I have benefitted over the last thirty-years from many remarkable relationships with people whose life work has been energy. At the top of this list are my partners, Mark Isaacson and Tony Buxton. We have spent countless hours in freewheeling discussions about energy – from the regulation of electric utilities to electric restructuring to the operation of competitive energy markets to gas pipeline development to renewable energy to distributed generation and grid reliability – discussions that have molded my thinking about all aspects of the energy sector. While we have not always agreed, it has been precisely those areas of disagreement that have been most beneficial.

I have also benefitted from my other partners, Steve Hinchman and Andy Price. Each brings a unique sophisticated perspective to energy discussions that is well informed by years of experience in a wide variety of projects and issues. When discussing energy, I have found that it really makes a difference to know something about physics, chemistry and engineering; it also helps immensely to be well-versed in environmental law, rules, regulations and procedures.

It also helps to have a very capable research assistant on projects like this. I was lucky to have Alice Dillon, a Maine resident who had just completed her junior year at Boston College in economics. Ms. Dillon was instrumental in tracking down wind speed information in the Gulf of Maine and in helping design and run the models that converted files of raw data into usable energy use and generation information.

I am also very much indebted to hundreds of clients that have come to Competitive Energy Services ("CES") with specific questions or concerns about energy related projects. There is no better way to learn about energy than by trying to understand and evaluate specific technologies, projects or developments that are being proposed when someone's money (including, occasionally, one's own money) is on the line. In this respect, I have been fortunate to have seen virtually every type of energy project – many "good" projects, a much larger number of "bad" projects, and I am sorry to say, too many projects that violated one or more fundamental laws of science.

I have benefitted from comments and suggestions made by David Flanagan and Tom Welch, both of whom graciously reviewed earlier drafts of this report. I emphasize "graciously", because they resisted the temptation to focus on the "elephant in the room" – that being the obvious fact that nothing Maine does on its own will impact climate change – and instead reviewed and evaluated the modeling, the assumptions, the results and the policy prescriptions in a broader context of collective actions.

Finally, I want to thank my wife, Lynne for her patience reviewing and proofreading various drafts, and Allie Ulrich for her many hours of assembling the report and transforming it into a visually pleasing and much more readable document.

At the end of the day, of course, I am the author of this report and take full responsibility for its content.

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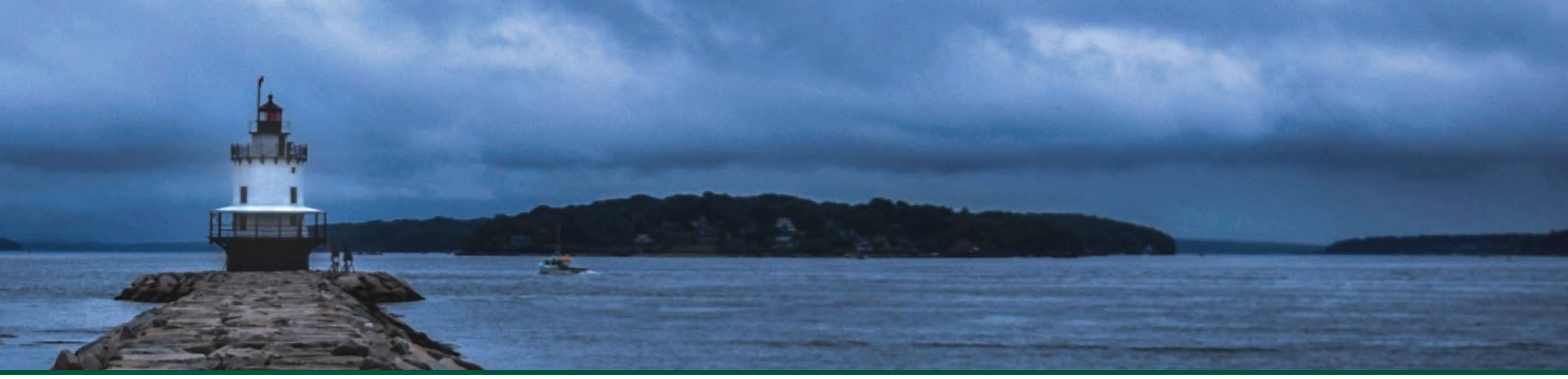

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Foreword

Richard Silkman's contributions to the common good are many, but his advances in energy policy and analysis have been particularly important to Maine and the rest of New England. This report builds on those contributions and offers a giant leap forward on the path to climate crisis solutions.

When electricity markets were deregulated, Dr. Silkman influenced the structure of the resulting competitive wholesale and retail markets. This included showing energy marketers first how to deal effectively with large electricity consumers, then reforming regulation so smaller commercial customers also could access competitive providers. He co-founded Competitive Energy Services, LLC, to facilitate commercial competitive access and through affiliates tested provision of retail competitive supply in Maine, Massachusetts and Texas. Dr. Silkman was the first residential customer to become a member of the End User sector of the reformed New England Power Pool, and, through Competitive Energy Services was the first to offer, with Interfaith Power and Light, renewable or "green" electricity for sale at retail in Maine. He testified on behalf of larger consumers in a score of federal and state proceedings, usually against electric utilities, including demonstrating conclusively that ISO-New England was not designed or managed to adequately benefit Maine electricity consumers. Seeking to reduce both energy costs to Maine manufacturers and New England CO^2 emissions, Dr. Silkman proved the investment viability of new and expanded natural gas pipelines into New England and within Maine.

Through his analyses and advocacy, Dr. Silkman has consistently challenged the New England energy status quo of heavy reliance on heating oil and motor fuels, unnecessarily expensive electricity and unwarranted electric utility dominance of critical decisions at consumer expense. Not surprisingly, the status quo often has taken offense.

To Dr. Silkman's great credit, he has persevered in his advocacy of consumer interests. With this publication, Dr. Silkman has gifted us with perhaps his most important work to date, a fact-based energy and technology analysis demonstrating how Maine, the most fossil-fuel reliant of the United States (other than remote Alaska and Hawaii), can practicably reach zero carbon in energy use by 2050 without any increase in societal energy costs. The product of two years of modeling and technology assessment, Dr. Silkman's study shows possibility where many had assumed political and economic impossibility and therefore had not acted. This is an enormous contribution to the conversion of modern economies to carbon neutrality. Yes, leadership and disciplined decision-making will be essential, but the common presumption of futility and then hopelessness when confronting the vast challenge of the climate crisis are demonstrably no longer justified, if they ever were. No, it won't be easy, but the anticipated climate-driven war between rich and poor, believers and non-believers in climate risk need not prevent consumers and governments from acting. Dr. Silkman's analysis is an historic contribution to the climate policy effort, and to the common good.

Tony Buxton
Co-Chair, Climate Strategy Group
Preti, Flaherty, Beliveau and Pachios. LLP

Chapter 1

Introduction & Overview

1.0 | Introduction

I begin with two questions. The first is why does Maine need an energy policy? The second is why does it need a new one now? With respect to the “why”, there are few things that are so fundamental to modern societies and their economies as energy. While not the most important factor of production – I believe that title goes to human capital - it certainly ranks very high on the list. Energy powers our factories, supports the flow of information, heats and lights our homes and enables the movement of goods and people. If you peel away the outer layers of virtually every aspect of society, what you find is energy. It is nothing less than the “heart-beat” of our modern world. This fact becomes crystal clear when we lose access to energy – during an electric power outage, when gasoline stations run dry during a major storm, when our oil tank in the basement runs out in the winter. Without energy, our society stops working.

This raises the second question - Why focus on energy policy now? The reason is that for the first time since the dawn of the Industrial Revolution, we have within our power the ability to harness unlimited energy resources to meet our ever-growing appetite for energy use and at the same time to reduce CO_2 emissions. Further, as I demonstrate in Chapters Two and Three, there is a plausible pathway that can achieve a transition to an economy in 2050 in which total energy use is at today’s levels, but total CO_2 emissions are reduced to zero and total annual energy costs (expressed in real dollars) are no higher during the thirty-year transition period than total annual energy costs have been on average since 2000. While this outcome may happen through the benign neglect of governments and reliance on competitive market forces, I do not believe it will do so in the time necessary to prevent some of the direst consequences of global warming. Instead, I believe its timely accomplishment will require a steady and concerted effort by all countries, states and communities, relying on government to create the necessary financial incentives and organizational structures to accomplish this objective.

Study after study has demonstrated the warming impact that decades of CO_2 emissions are having on the climate of our planet. Global warming has been called nothing short of an “existential crisis,” a condition that threatens the continued existence of our civilization. Ironically, the very scope of the crisis means that whether Maine acts to reduce its CO_2 emissions is essentially irrelevant. Maine’s annual CO_2 emissions of roughly 20 million tons represents about 0.05% of the 40 billion tons of CO_2 emitted annually world-wide. Nevertheless, for Maine to do nothing is unacceptable. As I discuss in the concluding chapter, where collective action is necessary to solve a problem, actions must be undertaken collectively, whether voluntarily or through coercion and/or compulsion.

My purpose here is to identify and evaluate in detail what actions Maine might take to eliminate CO_2 emissions, and what consequences these actions would be expected to have within Maine. While my focus is on Maine (and occasionally where useful on the United States), my analyses are done within the context of similar types of actions taken individually as part of the broader collective actions required by the other New England states, by the United States and, indeed, by the rest of the world.

Most of the energy used today in the U.S. and across the world to power economies is created by burning fossil fuels, primarily coal, oil distillates and natural gas. This, in turn, is impacting our planet's climate and polluting the air we breathe. With every dollar of Gross Domestic Product produced, our environment suffers further degradation, and our long-term outlook is more at risk. We dare not slow economic growth rates for fear of impacting the health of our economies and prosperity of our nations; yet, current conditions are not sustainable.

Maine is not immune to these conditions. Indeed, it could be argued that to understand Maine, we must understand energy. From the wind captured by the sails of merchant vessels, to the harnessing of our rivers to power our factories, to the burning of our immense forests to heat our homes, the story of Maine is very much the story of our ability to use energy. Maine's development patterns reflect the ability to capture and use energy, as settlements sprang up first along our coast and then at major falls on our great rivers. These settlements, in turn, spawned their own suburbs in the 20th century, supported in large part through plentiful and inexpensive oil. During this entire time, Maine's unstated energy policy was quite simple - use as much energy as it could afford to promote the economic well-being of its residents and businesses.

Two events brought home the central role of energy in the economy and the need to pay more attention to Maine's energy sector. The first was the rapid rise in oil prices that triggered the economic crises in the 1970s. In less than a decade, Maine's economy and, indeed, the U.S. economy and economies around the world, lost their footings, as they were battered by inflation, unemployment and stagnation. Energy could no longer be ignored. In what may best be described as the largest peace-time energy policy and planning effort in our history, our focus at all levels of government turned to energy, resulting in the establishment by President Carter of the cabinet level Department of Energy, followed by similar efforts in many of the states, including Maine.

The second event was the environmental movement. By the early 1970s, the consequences of unchecked energy use focused attention on the harms created to our country's rivers, groundwater and air quality from the production and use of energy. This led to the passage of clean air and clean water acts at the national level and improved environmental monitoring and more stringent permitting standards in many states, including Maine. One approach to reducing pollution was simply to use less energy through energy conservation. This objective was realized through legislation and regulations focused on improving efficiencies, such as automobile mileage standards, more energy efficient building codes and appliance efficiency standards.

Interestingly, by the time these policy efforts got into full swing, energy conditions had reversed. The rapid rise in energy prices in the 1970s was followed by an equally rapid fall in real energy prices through the 1980s. At the same time, expansionary efforts to correct the effects of stagnation in the world's developed countries were beginning to bear fruit, leading to increases in energy consumption to support expanding economic activity. A full-scale push was on to find new sources of oil and natural gas to support not just the economic expansion of western economies but also the rapid industrialization of China, the so-called Asian Tigers, India and other less developed countries across the globe. The use of energy was once again encouraged, albeit within the confines of tightened regulations to protect critical natural resources and the environment.

This pedal-to-the-metal approach to energy use began to be challenged, as the threat of global warming due to increased concentrations of CO_2 in the atmosphere became more widely accepted. Initially, the threat of climate change was addressed through efforts to protect forest lands to absorb CO_2 from the atmosphere and through conversions from coal and oil to natural gas – the so-called "clean energy alternative". The latter was facilitated by the revolutionary drilling technology called "fracking" that unleashed huge quantities of natural gas at very low prices and by efforts to develop liquefaction facilities to move large-scale geographically trapped natural gas resources to countries in need of energy.

Today, the threat to our environment is being addressed through the development of renewable generation technologies, specifically wind and solar. These have been fueled by astonishing advancements in technology and manufacturing processes that have reduced the cost of generating electricity to the point where these alternatives are now cost competitive with fossil fuel generation in much of the world.

The central feature of my proposed new energy policy is the proposition that Maine can achieve a transition to an essentially carbon-free economy by 2050 without increasing the annual amount it spends on energy or reducing the total amount of energy it consumes. To accomplish this, Maine must transform its use and production of energy. This requires that Maine convert its heating, industrial and commercial process and transportation sectors from using fossil fuels to using electricity. This conversion is sometimes referred to as beneficial electrification.[2] I show how reasonable adoption rates of electric vehicles, heat pumps and industrial and commercial processes can achieve the first part of this transformation over the next thirty years.

Second, producing the electricity to support beneficial electrification requires the development of zero-carbon, renewable energy generation on an unprecedented scale. For Maine, I estimate that this requires investing an average of $2 billion a year for the next thirty years in new solar PV, on-shore and off-shore wind and battery storage systems and in expansions to the electric grid to accommodate the increased use of electricity and the interconnection of thousands of new distributed and utility-scale generating plants within the state. Together, beneficial electrification and renewable generation will result in the deep decarbonization of Maine's economy – achieving essentially zero-carbon emissions by 2050.[3] This need not and cannot be just an aspirational goal. Instead, I identify a pathway for achieving this result without increasing total annual spending on energy and propose a series of policies that facilitate its achievement. I put forward this conclusion as the foundation of a new energy policy for Maine.

1.1 Fifty Years of Maine's Energy Policies

Energy is what economists call an "intermediate good". It is not generally consumed as an end product; rather, it is used in the production of goods and services that are consumed by residences and businesses in the economy. The gasoline in our tank enables us to move from one place to another; the wood we burn in our stoves heats our homes; the natural gas that is used by a generator produces electricity which is then used to power our society; the electricity that is used in our factories and offices results

[2] A good working definition is Beneficial Electrification (or strategic electrification) is replacing direct fossil fuel use (e.g., propane, heating oil, gasoline) with electricity in a way that reduces overall emissions and energy costs. This can include, for example, switching to an electric vehicle or an electric heating system – as long as both the end-user and the environment benefit. (http://www.eesi.org/projects/electrification)

[3] I have chosen the year 2050 to be consistent with most U.N. IPCC studies that identify this year as the year the world needs to eliminate CO_2 emissions to prevent the more severe consequences of global warming from occurring. See Global Warming of 1.5°C: An IPCC Special Report on the Impacts of Global Warming of 1.5wC Above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development and Efforts to Eradicate Poverty, United Nations Intergovernmental Panel on climate Change, October 2018. https://www.ipcc.ch/sr15/

in the production of valued goods and services. Because energy is an intermediate good, its value is determined by the results of its use. This means that all policies that are designed to impact energy use must be evaluated on both the direct impact they have on energy production and consumption and on the indirect impacts they have on the consequences of the production and use of that energy.

I believe that there are three aspects of the use of energy that are overarching and therefore should be the ultimate targets of energy policies. First, energy is used to produce goods and services that we value and that we consume. The higher the value of the goods and services that are produced from each unit of energy used in their production, the better off we are. Second, while energy is an intermediate good, in order to use energy, we must first purchase it. We must spend money to obtain energy. The more energy we obtain for a given amount of money spent, the better off we are. Finally, when we use energy we often create emissions that may be harmful to our health or to the environment. These are called environmental externalities, and include CO_2 emitted during production (and the climate impacts of atmospheric CO_2) as well as such things as incidences of asthma, waste water discharges into rivers, methane leaks into the atmosphere and particulates that are emitted into the air. The more energy we are able to use for each externality we produce through its use, the better off we are.

I refer to these three measures - (a) the amount of useful economic output per btu of energy input, (b) the amount of btus of energy that can be obtained per dollar spent on energy and (c) the amount of btus of energy that can be used per pound of CO_2 emitted, as "Conversion Efficiency", "Production Efficiency" and "Externality Efficiency", respectively, and define each more precisely as follows:

- Conversion Efficiency is the rate at which the overall economy converts energy into useful finished goods and services. I measure the numerator as real Gross Domestic Product ("GDP") and the denominator as millions of btu ("mmbtu"). The higher the ratio, the better is the Conversion Efficiency.
- Production Efficiency is the rate at which dollars spent on energy are converted into energy btus. The more btus per dollar spent on energy, the higher the Production Efficiency. The numerator in this measure is the number of btus of energy used; the denominator is the total amount spent on energy.[4]
- Externality Efficiency is the number of btus of energy that are produced per pound of CO_2 emitted into the atmosphere. The fewer pounds produced per btu of energy consumed the better. The numerator is the number of btus of energy used; the denominator is the total CO_2 emissions from this energy used.[5]

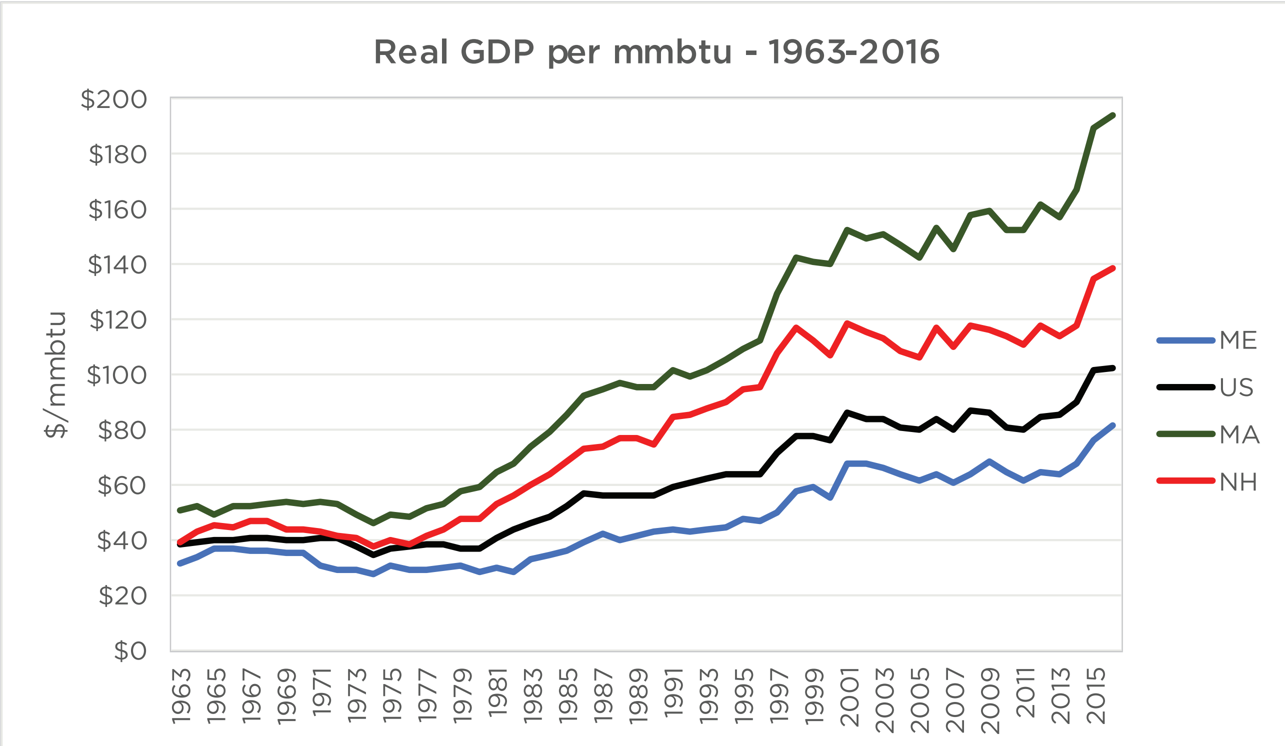
I am able to create these three efficiency measures from U.S. Department of Energy's Energy Information Agency (EIA) state-level energy data extracted from its State Energy Data System or SEDS datafiles. This data provides a consistent historical record of energy use for each of the fifty states and for the District of Colombia. I have focused on Maine, Massachusetts, New Hampshire and the U.S. for comparison purposes.

There are certainly other factors that impact policies related to energy. For example, for the past forty years our national policy has emphasized energy independence – the concept that energy produced in the United States is preferred to energy that is produced overseas and imported into our country. A second example is resiliency. The U.S. Strategic Petroleum Reserve is a government funded stockpile of oil that can be called upon in emergencies to provide energy to critical sectors of our economy. Yet another example is equity – the need to ensure that the basic needs

[4] This is the inverse of the price of energy. I use the inverse so that a higher value of this measure is better than a lower value.

[5] Because the overwhelming factor impacting the earth's climate is CO_2 in the atmosphere, I have limited my focus to CO_2 and not addressed other environmental externalities.

FIGURE 1-1 | Conversion Efficiency – Real GDP per mmbtu of Energy Used



of our citizens are met through programs like the Low-Income Heating and Energy Assistance Program. While these are important issues, I believe they are less fundamental to the role played by energy use in our economy than are the three measures noted above. If Maine is successful in achieving better performances in the three measures noted, the result will be higher income and wealth levels and lower environmental pollution levels and therefore more resources to devote to accomplishing these other objectives. Accordingly, I focus here on these three measures in evaluating how Maine has performed over the past half century.

To gauge Maine's performance, I examine how these three measures discussed above change over time and change in comparison to other states and the U.S. as a whole. The results for each of these performance measures are shown in **Figures 1-1** through **1-3**.

Figure 1-1 shows Conversion Efficiencies. Maine is clearly lagging the rest of the country and is well behind both New Hampshire and Massachusetts on this measure. In part, this reflects the fact that Maine's underlying economy is more energy intensive than its two New England counterparts. Beginning in the late 1970s at the height of the energy crisis, the economies of these states and especially Massachusetts began the process of moving from more energy intensive activities to higher value service sectors. Maine's economy lagged in this transition. Maine is achieving less than half the economic value as Massachusetts for each mmbtu of energy consumed and lags well behind New Hampshire and the rest of the country. This would be less of a concern if energy were very cheap in Maine compared to elsewhere, but as shown in the next exhibit, this is not the case.

Figure 1-2 provides a comparison of Production Efficiency across the same jurisdictions. Since this measure is in effect the inverse of the price per mmbtu and since all three New England states are in essentially the same energy markets, we would expect their performances on this measure to be very similar. While New Hampshire and Massachusetts are in fact virtually identical on this measure over the entire period, Maine's experience is quite different. From 1970 through the early-1990s, Maine looks very much like the country as a whole and much less like its New England neighbors. However, beginning in the mid-1990s this situation changed, as Maine's Production Efficiency fell more rapidly than the nation's fell. Today, Maine looks the same as Massachusetts and New Hampshire, and all three states lag the U.S. on this measure of performance. Whatever energy price advantages Maine had through the 1980s have disappeared. The consequences of this have been seen in the fates of Maine's most energy intensive industries.

Maine's performance vis a vis the country with respect to Production Efficiency suggests that its policy of encouraging more widespread use of native renewable energy resources did not have an appreciable impact on energy costs. Throughout the 1980s and into the mid-1990s, the rate at which Maine was able to convert expenditures on energy into usable energy btus mirrored the nation and was well above that of other states in New England.

Beginning in the mid-1990s Maine began to diverge from the nation on this measure and move toward Massachusetts and New Hampshire. There were three policy changes that caused this shift. First, new federal policies were implemented that required electric utilities to provide open access to their transmission grids to non-utility generators, thus facilitating open and competitive wholesale markets for electricity. Second, the New England states responded to this shift in federal policy by establishing a region-wide organization, ISO-NE, and new market rules governing the operations of electricity transmission and the wholesale sale of electricity. Finally, Maine restructured its electric utilities by requiring them to divest their electric generating assets. The intended effect of these changes was, in the words of Tom Welch, former chair of the Maine Public Utilities Commission, to ensure that electricity prices in Maine converge to national prices, so that Maine will never be an outlier when it comes to energy prices.

Figure 1-2 shows that this intent has been only partially realized. Maine energy prices have converged to those in New England. There is now no longer any significant difference

FIGURE 1-2 | Production Efficiency – mmbtu of Energy per Real Dollar Spent

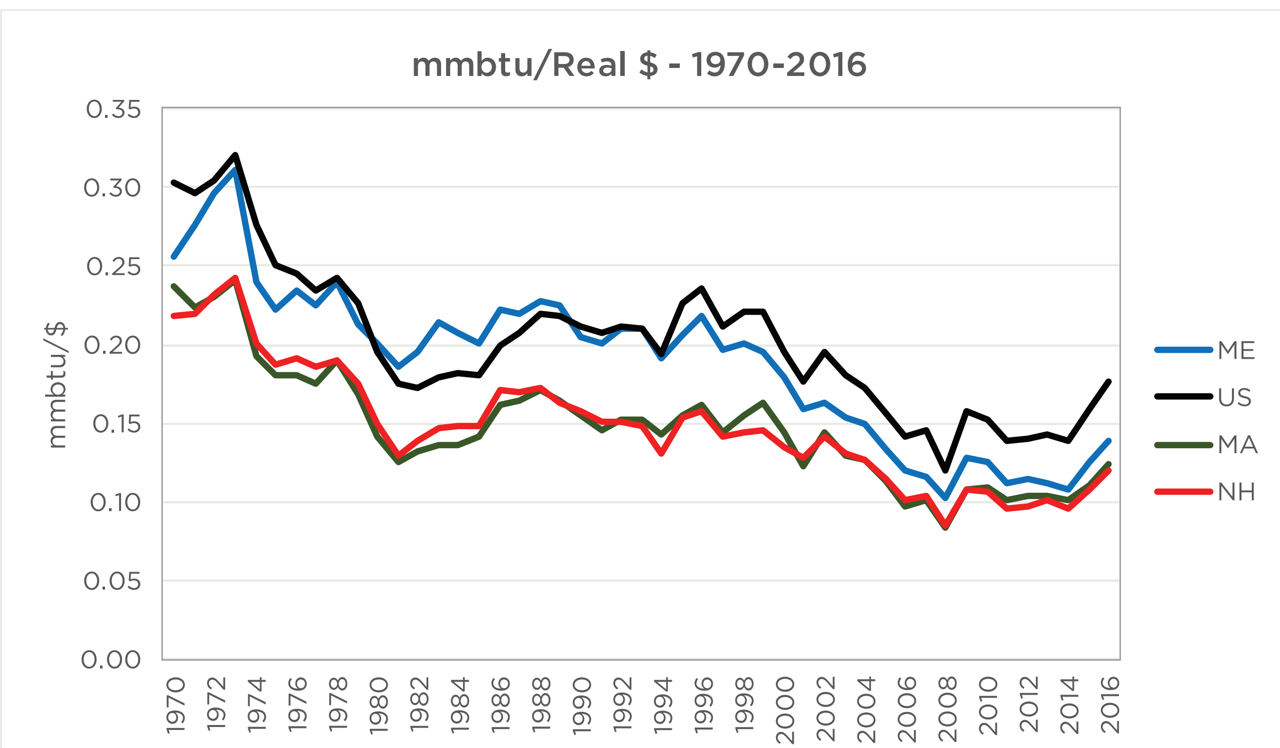
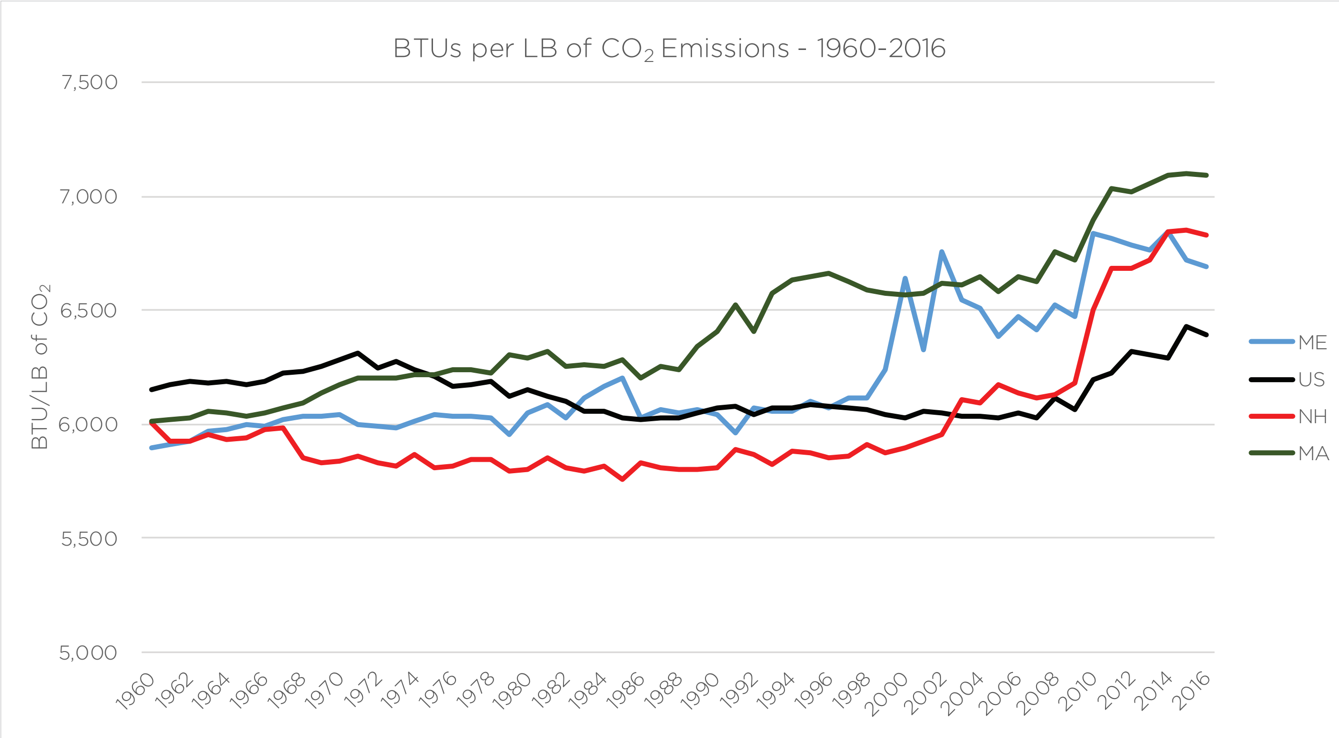


FIGURE 1-3 | Externality Efficiency - Energy btus Used per Ton of CO_2 Created



between how many btus can be obtained per dollar spent in Maine vs. Massachusetts vs. New Hampshire. However, while energy prices have converged across New England, the gap between Production Efficiency in New England compared to the rest of the country has remained, and the graph suggests that it may widen in the future. The primary reason for this is natural gas. The divergence between continental prices for natural gas on the one hand and worldwide prices for oil and LNG on the other, combined with the lack of adequate natural gas pipeline infrastructure to deliver U.S. natural gas supplies into New England are keeping Production Efficiency in New England low relative the nation as a whole.

The third measure – Externality Efficiency – is shown in **Figure 1-3**. This graph shows that Maine and the other two New England states have performed far better than the U.S. as a whole. The early portion of this separation occurred during the 1970s and 1980s when the oil embargoes and rapid price increases led to a shift to coal across most of the country. The more recent portion of the separation of New England reflects the shift to natural gas, especially in the electric generation sector and to increases in renewable energy. Relative to the rest of the country, New England produces about 6% more energy btus for the same amount of CO_2 emissions.[6]

The changes noted above in each of these three efficiency measures reflect to some degree the influences of Maine energy policy. Maine's first major energy policy initiative during this period followed the energy crisis in the 1970s that was triggered by oil embargoes that led to rapid price increases. To respond, Congress adopted the Public Utilities Regulatory Policy Act or "PURPA".

[6] Energy btus in Figures 1-1 through 1-3 are accounted for in the state in which primary energy sources are consumed. This can create anomalies when, for example, an electric generation plant that produces electricity using coal is located in one state, but the electricity is delivered into other states for final consumption. That state may perform relatively poorly on this Externality Efficiency measure by being an exporter of coal-fired electricity generation. The increasingly regional nature of the U.S. and New England electric grids and the movement to competitive wholesale markets supported by open access to transmission grids has tended to exacerbate the locational mismatch between the use of use of primary energy to generate electricity and the actual consumption of that energy.

This far reaching legislation paved the way for many changes in the nation's energy policy, but none were as significant as the opening of the electric generation market to independent power producers through the requirement that utilities purchase energy generated by non-utility generators at a price equal to the utility's avoided cost of generation – that is, at the costs the utility would have incurred to generate electricity but for the independent power producers.

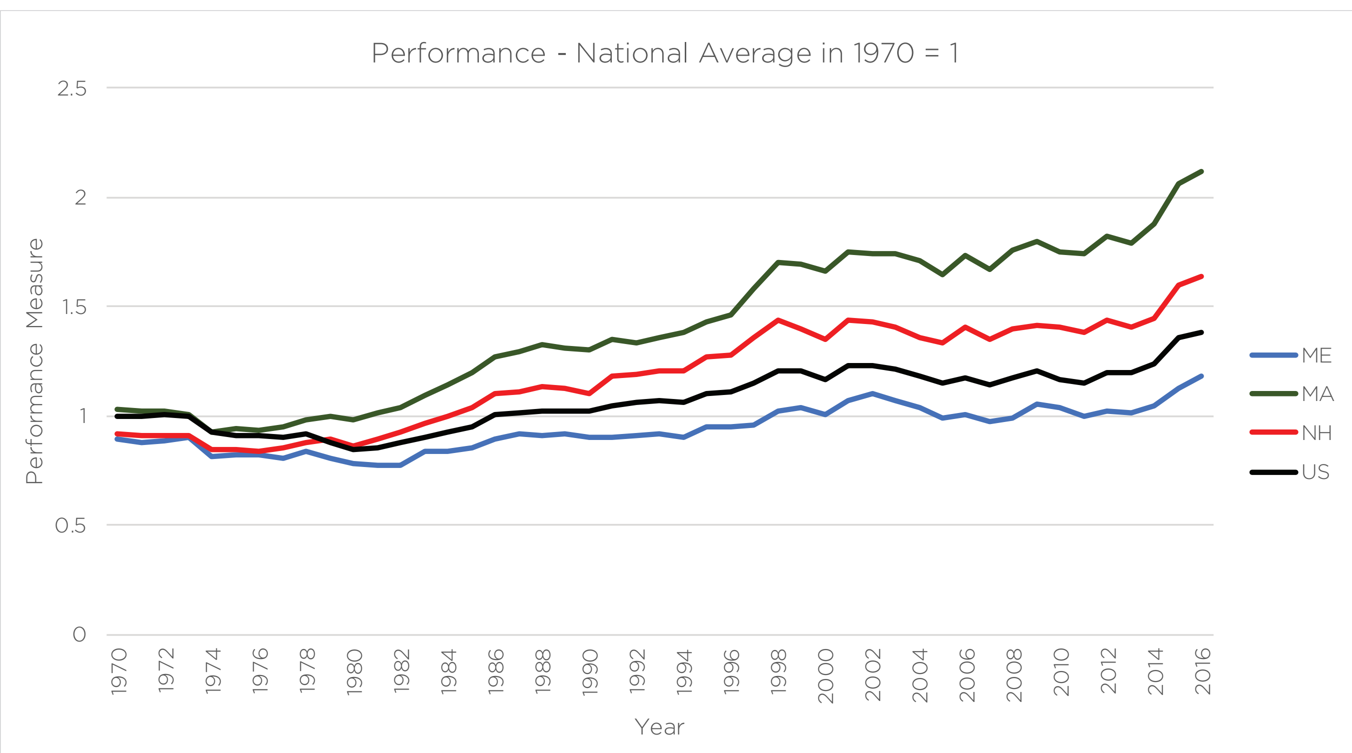
In the early 1980s, Maine enacted its version of PURPA. Because Maine had hydroelectric opportunities that could be developed and biomass resources that could be harvested to generate electricity, Maine was able to expand the share of renewable energy sources in its energy sector. This improved its Externality Efficiency measure as shown in **Figure 1-3**.[7]

The improvement in Externality Efficiency, however, had secondary consequences to Maine's economy. One important consequence that emerged from Maine's adoption of PURPA was the development of large-scale cogeneration at many of Maine's major paper mills. Because the value of the electricity generated in these cogeneration plants was higher than the cost to generate the electricity, the result was a reduction in the effective price of energy for these mills. This new cost reduction extended the operations of some of these mills longer than would otherwise have occurred. This was a contributing factor to Maine's relatively poor performance with respect to Conversion Efficiency, as Maine retained many of its most energy intensive industries longer than other states in the region. Maine's energy policy of requiring electric utilities to purchase electricity generated by independent power producers at the utility's avoided costs altered the underlying cost relationships for these companies, thus impacting their management and operational decisions.

Figure 1-4 provides a chart showing how Maine has performed across all three measures compared to Massachusetts, New Hampshire and the U.S. since 1970. This chart uses the

[7] The increase in the proposed number of plants to use Maine's forest and biomass resources to generate electricity led the then chair of Maine's Public Utilities Commission to characterize Maine's energy policy as "Burn Maine first."

FIGURE 1-4 | Overall Comparison of Energy Performance Since 1970



simple average of the relative performances on the three measures – Conversion Efficiency, Production Efficiency and Externality Efficiency – as the overall measure of performance. Using the simple average gives each measure equal importance. This is a simplifying assumption, but absent any compelling argument to more heavily weight one or two of the measures, I believe it is reasonable. The base for this comparison is the value of this measure in 1970 for the U.S. I set this value equal to 1.00 as a benchmark.

The results show that national performance on this aggregated measure has been varied. Relative to the value of this measure in 1970, national performance fell during the energy crisis in the 1970s, rose consistently from 1981 through 1999, fell again during the first part of this decade to a low during the great recession in 2008 but has since ridden the fracking wave to return to its starting point.

Throughout this entire 45-year period, Maine's performance has been below that of the nation and somewhat less volatile. Maine was not as impacted as the country by the energy crisis during the 1970s and did not rebound from that crisis as robustly as the country over the two-decade period that followed. Since 2000 Maine's performance has generally tracked that of the country, although it may be important that the gap has widened over the last four years shown. Like the nation, Maine ended 2016 up slightly from where it began in 1970.

The experience of our neighboring states has been very different from Maine's. New Hampshire began at the same level as Maine in 1970 at about 90% of the value of the U.S. Since then, however, New Hampshire has outperformed Maine, tracking much closer to the performance of the country. By 2016, New Hampshire's performance is almost 25% higher than the country and about 35% higher than Maine.

The Massachusetts experience is even more profound. Beginning at the same level as the U.S., its relative performance had almost doubled by the late 1990s before declining precipitously during the early 2000s. Even with this decline, however, by the end of this period, its performance was 50% higher than the U.S. and 67% higher than that of Maine. The principal driving factors for this inter-state differential is the more pronounced conversion of first the Massachusetts and then the New Hampshire economies away from energy-intensive manufacturing and toward the high-end service sectors – finance, insurance and real estate.

Over the past 45 years, during periods of high and low energy prices, economic expansion and contraction and tightening and relaxing of environmental regulations, the net result of the sum of all Maine's various energy policies and initiatives has been to leave Maine no better or worse off relative to the nation as a whole with respect to the average of three key indicators of energy sector performance. Put differently, to the extent that the objectives of Maine's energy policies have been to increase - relative to the nation and peer states - the amount of economic value obtained for each btu of energy used in the economy, to increase the number of btus of energy available for each dollar spent on energy and to increase the amount of energy btus that can be produced for each pound of CO_2 emissions created, the results of these policies are indistinguishable from the results of the policies adopted by the country.

Over more than four decades spanning seven gubernatorial administrations, three of which were Democrats, two of which were Independents and two of which were Republican, Maine has been less adept at using its energy btus to produce high-value goods and services and has lost its relative energy price advantage compared to its neighboring states. It is only in the area of reduced air emissions that it has achieved success. This track record raises the question of whether beneficial environmental outcomes can only be achieved at the expense of higher energy costs that have damaging effects on Maine's economy.

1.2 | Overview of Chapters Two - Six

The remainder of this report examines this question. I do this by focusing on what it would take to achieve deep decarbonization of Maine's economy and near zero carbon emissions in Maine by 2050. The next chapter defines what such an end state might look like in 2050, and how much energy would cost, assuming deep decarbonization is achieved through a combination of beneficial electrification of virtually all Maine's economic sectors and the development of renewable energy resources to meet the much higher electric energy demands. I conclude that a plausible end state exists in 2050, in which total CO_2 emissions are reduced to zero, but total annual energy costs (expressed in real dollars) are no higher than total annual energy costs have been on average since 2000.

Having defined such a plausible end state in 2050 in Chapter Two, Chapter Three focuses on the transition from the state of Maine's energy sector today to that end state in 2050. I show that under reasonable assumptions regarding (a) the rate at which various economic sectors transition from the use of fossil fuels to becoming 100% electric, (b) the rates at which renewable energy resources are developed and (c) the price curves for all forms of energy over the period 2020 – 2050, the transition can be accomplished. Further, I show that it can be accomplished at essentially the same annual energy costs each year over the thirty-year period as the annual energy costs Maine has incurred to meets its energy requirements since 2000. These results demonstrate that there is a plausible pathway to achieve the transition of Maine's economy to an essentially carbon-free economy by 2050 that will not impose financial burdens on Maine's residents and businesses.

The pathway defined in Chapter Three illustrates that a fundamental aspect of deep decarbonization that is achieved through beneficial electrification and renewable energy resources development is the substitution of capital in the form of significant investments in electricity generation, transmission and distribution plant and equipment for operating costs in the form of fossil fuel and maintenance costs. This conversion can only occur if vast amounts of capital can be drawn to the energy sector. This, in turn, can only occur and impose no financial burdens on energy consumers if the price of that capital is low. Chapter Four focuses on the magnitude of these capital flows and defines a new organizational structure – the Maine Electricity Generation Authority – that can achieve both requirements. I show that the Maine Electricity Generation Authority has the ability to raise the capital necessary to finance the development of renewable generation resources that are required to support beneficial electrification and do so at costs that maintain total energy costs at their current levels.

Chapter Five sets out a policy framework for accomplishing the deep decarbonization of Maine's economy. In this chapter, I offer a mixture of general policy prescriptions and specific legislation, recognizing that the transition to such an end state is a thirty-year process, during which the pathway laid out will need to be adapted to changes in the underlying assumptions I have made and to energy conditions more broadly.

The final chapter offers a few concluding thoughts.

There is no question that from our vantage point today, the realization of a carbon free economy by 2050 appears an impossible task. However, this is always the case with transformational events. Only the most visionary people in 1850 could have imagined the network of railroads in the country by 1880 and how these would reshape the American economy. Very few people in 1910 thought that by 1950 most of America would be electrified. Perhaps even fewer people could have imagined that from its initial deployment in the late 1970s, fiber optic cable would become, as the Royal Swedish Academy of Sciences declared thirty years later in 2009, "the circulatory system that nourishes our communications society" and be deployed in an amount that "If we were to unravel all of the glass fibers that wind around the globe, we would get a single thread over one billion kilometers long — which is enough to encircle the globe more than 25,000 times — and is increasing by thousands of kilometers every hour."[8]

In each of these cases, the transformations were made possible by three primary factors –(i) technologies that were scalable and that provided marked improvements over then-existing technologies, (ii) new organizational structures that made possible the raising of vast amounts of investment capital and (iii) government policies that supported and, in some cases, enabled the transformations to occur. In combination, these factors transformed our society from one economy to a very different economy thirty years later. These same three factors – technologies, capital and policies – will be needed to transform our carbon-intensive economy today to a carbon-free economy in 2050. This is the purpose of my effort – to determine whether such a plausible pathway can be constructed and to identify what it will take to accomplish just such a transformation.

Before turning to this effort at hand, I believe that it is important to discuss some of the more critical assumptions I am making that enable me to look thirty years into the future to an economy whose energy underpinnings bear very little resemblance to our economy today. The first item to emphasize is that I do not address inflation. All of the cost, price and expenditure figures are expressed in terms of today's dollars. This means that where these values do change, the changes are being driven by technology or by fundamental sectoral changes that impact real prices. These cases are limited, and where I have assumed them, I bring each such case to the attention of the reader. Given the volatility of energy prices over the past fifty years, it may appear that this assumption is inappropriate. I note, however, that while energy prices have been volatile, the real price of energy has been remarkably constant over most thirty-year windows over the last 50 years.

A second point I believe important to emphasize is that my goal is not to be precise about Maine's energy future. This would certainly be a fool's errand. Rather, my objective is to determine whether the aspirational goal of a carbon-free Maine by 2050 can be achieved in a manner that is technically feasible, internally consistent and reasonably plausible. This should not be interpreted to mean that the outcomes I identify are in any way predictive of the future. In fact, as I note in my concluding thoughts, I am far from confident that the scenarios I present in the following chapters are probable, and indeed, in my more pessimistic moments I believe them highly unlikely.

The third point is that I have modeled a very dynamic energy sector in an essentially static Maine economy. For all my analyses, I assume that the amount of energy Maine residents and businesses use in each of the next 30 years remains fixed at essentially current levels.[9] I do not consider changes in demographics, changes in housing stock, changes in industrial mix, changes in energy intensity or changes in government policies that could have an impact on energy use. What I do impose is the requirement that Maine's economy transition to a zero-carbon emission state over the thirty-year period from 2020 to 2050. As I discuss, this requires a restructuring of Maine's energy sector. Converting the entire transportation sector to electric vehicles, eliminating natural gas and distillate fuels as a source for heating and electrifying industrial and commercial processes are certain to have secondary impacts that effect energy usage and that extend deep into Maine's economy. For example, people may use more energy and use it in different forms when the environmental externalities from energy use are eliminated. Consideration of these secondary and tertiary impacts is well beyond the scope

8 Taken from the obituary of Charles Kuen Kao, the father of fiber optics. https://www.washingtonpost.com/local/obituaries/charles-kuen-kao-nobel-laureate-celebrated-as-father-of-fiber-optics-dies-at-84/2018/09/25/639fe01e-c008-11e8-be77-516336a26305_story.html?noredirect=on&utm_term=.7a7194f529c5

9 As discussed in Chapter Two, I do allow for increased use of electricity associated with increased penetration of air conditioning in Maine residences over the next thirty years.

of my effort. That said, the energy generation technologies that are identified as meeting the demands of beneficial electrification and deep decarbonization can be scaled both in scope and breadth and in cost in a near-linear fashion up or down to meet decreased or increased energy use by 2050. Accordingly, the absolute level of energy consumption in Maine will not alter the fundamental conclusions of this study.

Finally, I ask the reader to evaluate my analyses and conclusions in terms of technical feasibility, internal consistency and reasonable plausibility and not against the standards of probability (the likelihood of their occurrence) or optimality (whether they are the best of all possible outcomes). At each step, I ask that the reader only judge the reasonableness of each assumption, factor or other predicate that I use to achieve a zero-carbon Maine economy in 2050 and a 30-year pathway to achieve that outcome.

Unlike a magician who asks the same of an audience but then adds a "trick" intended to deceive the audience into believing the unbelievable, I have introduced no sleight-of-hand in the models. My results flow from my assumptions and parameters. If my assumptions and parameters meet the test of reasonableness, then my results will confirm the achievability of the aspirational goals being adopted by cities and states across the country. They say nothing, however, about whether those goals will actually be achieved and if so, in what timeframe.

Chapter 2

Achieving Zero Carbon by 2050

2.0 | Introduction

The best science today tells us that the next 30 years will be critical if humanity is to avoid what will likely be catastrophic consequences of climate change and global warming. To keep global temperatures from increasing 2°C, the world needs, at a minimum, to reduce annual CO_2 emissions to zero by 2050. This means weaning society off coal, oil, natural gas and the other forms of fossil fuel that are deeply interwoven into our economic and social fabrics and doing so in a timeframe that is unprecedented. There is a growing consensus that even this will not be enough to stop climate change, and that reversing global warming will require more than the elimination of carbon-based fuels. It will also require removal and sequestration of a significant amount of CO_2 already in the earth's atmosphere.[10]

Through a combination of fuel switching, technology enhancements, financial incentives, rules and regulations, the United States is achieving incremental reductions in CO_2 emissions, despite a growing economy. Energy-related CO_2 emissions fell to 5,134 million metric tons in 2017, down from a peak annual level of 6,021 million metric tons in 2007.[11] This is an important accomplishment; however, it is woefully inadequate relative to what is required to slow and ultimately stop global warming. Further, preliminary estimates show a 3.4% increase in U.S. CO_2 emissions for 2018, effectively undoing the total emission reduction gains in the prior three years.[12]

Achieving a zero-carbon economy by 2050 will require the elimination of carbon-based fuels across the entire world economy – a process often referred to as "deep decarbonization". A simple stroll along the streets of Portland, Maine provides insight into just how daunting a task this is. Every smoke stack, every chimney, every gas meter, every tailpipe, every locomotive, every boat, ship and marine vessel represents a point source of CO_2 emissions that must be either eliminated or converted to a non-carbon-based fuel to achieve deep decarbonization. As the scope of the stroll is extended to other parts of Maine, additional point sources of CO_2 emerge, including large factories, farm and other off-road equipment and airplanes, all of which add to the enormity of the task.

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[10] See for example, Elizabeth Kolbert, "Can Carbon-Dioxide Removal Save the World?" https://www.newyorker.com/magazine/2017/11/20/can-carbon-dioxide-removal-save-the-world and also, The Emissions Gap Report 2017, A UN Environment Synthesis Report, https://wedocs.unep.org/bitstream/handle/20.500.11822/22070/EGR_2017.pdf

[11] https://www.reuters.com/article/usa-natgas-eia-steo/update-1-u-s-carbon-emissions-seen-at-25-year-low-in-2017-idUSL1N1J311B

[12] See report issued by the Rhodium Group - https://rhg.com/research/preliminary-us-emissions-estimates-for-2018/

Given the current state of technology and energy options, deep decarbonization requires the electrification of most, if not all, of our energy use. This is because electricity can be produced using zero-carbon technologies such as wind and solar generation.[13] This zero-carbon electricity can be substituted for gasoline and diesel fuels across the transportation sector, for coal, home heating oil, natural gas and propane to meet the space and domestic hot water needs of all sectors of the economy and eventually for other carbon-based fuels used in industrial and commercial processes. This wholesale substitution of electricity for carbon-based fuels has come to be known as beneficial electrification and is receiving increased attention in the energy literature. Much of this attention is focused on the demand-side of the equation - the process of converting end-use consumption of energy to electricity, e.g., electric vehicles (EVs), air source and ground source heat pumps. Increasingly, the policy community has also begun to focus on the supply-side – the sources of zero carbon electricity generation that can be developed to meet the increased electricity demand in a manner that preserves grid reliability.[14] This work has highlighted the central role that storage must play to enable generation to match electricity loads, and in particular daily cycling storage to address the hourly generation profile of solar photovoltaic systems and seasonal storage to meet heating requirements in the northern latitudes.

This chapter examines how beneficial electrification will reshape electricity usage across all sectors of the Maine economy, and what it will require in the form of renewable generation, storage and grid expansions and upgrades to meet this usage with zero carbon emissions. To the best of my knowledge, it represents the first attempt in Maine to translate the aspirational goal of zero carbon by 2050 being advocated through local political processes into the real-world investments necessary for its achievement.

Section 2 describes the sources of primary energy and electricity used in Maine today by end-use. I define this as Maine's energy baseline and assume that total energy use remains flat through 2050. In effect, I am assuming that any increases in total energy use are offset by increased conservation and efficiency. Section 3 calculates how the use of electricity will increase significantly by 2050 as different end-uses are converted from a carbon-based fuel to electricity. Section 4 examines a variety of different electricity generation configurations for meeting 2050 electricity requirements, using combinations of zero emission wind and solar generation technologies. The total amount of storage under each configuration that is necessary to balance electricity demand and generation each hour over the course of the year is calculated, assuming there are no imports or exports of electricity from or to states or provinces that border Maine. Section 5 estimates the capital and operating costs of these configurations based on projections of unit costs for different electrical generation technologies and for the required amount of battery storage. These costs are converted to annual costs and compared to the total annual cost (inclusive of fuel) of Maine's current energy usage. Finally, Section 6 provides a set of concluding observations.

2.1 | Where Does Maine Get Its Energy Today?

Energy is used to support virtually all productive activity in Maine. Maine communities, residents and businesses use energy to produce goods and services, heat industrial, commercial and institutional facilities and residential dwellings, power

[13] Additional generation options include hydroelectric power, geothermal generation, traditional nuclear generation and nuclear fusion.

[14] See, for example, Mark Z. Jacobson, et.al., "A Low-Cost Solution to the Grid Reliability Problem with 100% Penetration of Intermittent Wind, Water and Solar for all Purposes (Supporting Information)," Proceedings of the National Academy of Sciences, 112, doi:10.1073/pnas.1510028112, 2015, for an analysis of U.S. electrification, and Ram M., Bogdanov D., Aghahosseini A., Oyewo A.S., Gulagi A., Child M., Fell H.-J., Breyer C., Global Energy System based on 100% Renewable Energy – Power Sector, Study by Lappeenranta University of Technology and Energy Watch Group, Lappeenranta, Berlin, November 2017, for a similar approach focusing on world-wide energy requirements.

trucks, buses and passenger cars as well as airplanes, railroads, marine shipping and pleasure boats and to provide traffic, street and area lighting. In identifying the sources of energy used in Maine, it is important to distinguish between what are called "primary" energy sources and what are called "secondary" energy sources. Primary energy sources provide energy directly. These include fossil fuels (oil, coal, natural gas, propane), biomass (solid, liquid), hydro, nuclear, geothermal, wind, tidal and solar. Secondary energy is produced using a primary energy source. The most significant secondary energy source is electricity. For my purposes, I focus on primary energy sources net of the amounts of these energy sources used in the production of electricity plus electricity itself. By removing those primary energy sources that are used to produce electricity such as oil, natural gas, and coal, I avoid double counting energy used in Maine.

It should also be noted that there is often a difference between where energy is delivered to consumers and where it is actually used. A good example of this is air travel. When a jet fuels in Portland at the Jetport, it typically burns very little of that fuel in Maine, yet all of that fuel is attributed to Maine. Conversely, when a tractor-trailer fuels in New Brunswick, Canada and delivers wood products to a factory in Massachusetts, most of the fuel is burned traveling through Maine, but none of the fuel is accounted for in Maine energy use.

Similarly, there is always some ambiguity about who constitutes Maine consumers of energy. Energy used by tourists visiting Maine and by seasonal home owners is accounted for in energy data as Maine energy use even though it is not used by residents of Maine. Since a significant part of Maine's economy is related to tourism, this can distort measures of per capita energy use.

On a larger scale, Maine's electricity grid is interconnected with the electric grids of New England and New Brunswick. This allows power to flow relatively seamlessly throughout the broader region, such that at any given time, consumers in Massachusetts may be using electricity generated in Maine, while at a different time, Maine consumers may be using electricity generated in New Brunswick or elsewhere within New England. This is reflected in often very large differences between the amount of electricity generated in Maine compared to the amount of electricity consumed by Maine consumers. For my purposes, since I am focusing on energy use, I use the amount of electricity consumed in Maine rather than what is generated within the state.

Finally, some energy is not reflected in energy statistics. Much of the wood used to heat Maine homes is home grown and home supplied. Since it is not sold through retail markets or reported to government sources, it is missed in the tabulation of energy use. The same is true for much of the energy that is generated and consumed behind the customer's meter. This includes a few large cogeneration operations, but also an increasing number of residential roof-top solar PV generating facilities.

Table 2-1 shows the amount of energy used in Maine by energy source and by end use sector, as reported by the U.S. Department of Energy's Energy Information Agency ("EIA") for 2016, the most recent year for which final data is available. I show usage measured in billion btus rather than the usual measures of usage such as barrels of oil, gallons of gasoline and kWh of electricity. I do this to enable easy comparisons across fuels. Total energy use is 384 trillion btus, 54 trillion (14%) of which represents fuels used in the production of electricity.[15]

This table shows that transportation is the largest consumer of energy, followed by the industrial sector and then the residential

[15] I have also included energy sourced from geothermal, hydroelectric and nuclear power as these are also primary energy sources. Only a small portion of this energy is not classified as being electricity that is sold to electric customers. EIA reports that in 2016 Maine got a very small amount of energy from geothermal (72 billion btus) and somewhat more from hydropower generated for use behind-the-meter (3,727 billion btus).

TABLE 2-1 | Maine Energy Consumption by Energy Source and Sector (2016)

	ECONOMIC SECTORS					TOTALS	
	Resid.	Comm.	Ind.	Transport	Elec.		
Energy Source			**(Billion btu)**			**(Billion btu)**	**Pct.**
Aviation Gasoline				128		128	0.00%
Asphalt & Road Oil			3,704			3,704	1.00%
Coal			421		1,773	2,194	0.60%
Distillate Fuel Oil	30,664	8,201	3,412	28,366	28	70,671	18.40%
Electricity	15,647	13,602	9,815			39,064	10.20%
Jet Fuel				6,524		6,524	1.70%
Kerosene	1,899	183	13			2,095	0.50%
Propane	6,540	6,522	320	66		13,448	3.50%
Lubricants			225	778		1,003	0.30%
Motor Gasoline		1,576	1,152	93,514		96,242	25.10%
Natural Gas	2,642	8,814	19,548	681	22,833	54,518	14.20%
Residual Fuel Oil		271	848	1,251	1,427	3,797	1.00%
Wood/Wood Waste	9,904	3,889	48,763		28,013	90,569	23.60%
	67,296	**43,058**	**88,221**	**131,308**	**54,074**	**383,957**	
	17.50%	**11.20%**	**23.00%**	**34.20%**	**14.10%**		
Geothermal Energy	72					72	
Hydropower		0	2,972		24,722	27,694	
Nuclear Energy						0	
	72	**0**	**2,972**	**0**	**24,722**	**27,766**	

sector.[16] Electricity consumption represents a small share of energy use – only about 10% of the total. The largest source of energy is wood and wood waste (which I will refer to as biomass) at just over a quarter of all energy used in Maine. About 30% of the biomass is used to produce electricity that is sold to consumers. A little over half of the biomass is used by the industrial sector, primarily to provide heat and electricity to the sector. About 10% of the biomass consumed in Maine is used by the residential sector to provide heat in one form or another.

The second largest energy source is gasoline followed by distillate fuel oil. These are used primarily to provide transportation and heat. Natural gas use follows closely behind, although much of the use of this fuel is for the generation of electricity for delivery to the electric grid. The use of natural gas has grown significantly over the past ten years as a result of the development of the Portland Natural Gas Transmission System and Maritimes & Northeast pipelines, combined with the price advantage natural gas has held relative to distillate oil. Rounding out the fuels used to provide heat across all sectors are propane and kerosene. Together they account for about 4.0% of total energy use.

The table shows that very little coal is used in Maine, and much of that is used to generate electricity. The remaining fuels are aviation gasoline and jet fuel, asphalt & road oil, coal

[16] I am not completely confident that all fuels used to generate electricity in the industrial sector are being accounted for correctly in the EIA data. While I expect that most of the electricity generated is by cogeneration and used behind-the-meter, it is possible that some is exported and sold as electricity in the market. This could introduce a double counting problem. In any case, I expect it to be small.

and lubricants. Together, these fuels make up about 3% of all energy sources used in Maine.

Table 2-2 shows only those fuels that I include in the analysis. I do not include any fuels used in Maine for the generation of electricity to avoid the problem of double counting certain fuels used in the generation of electricity.

Instead, the category "Electricity" is the amount of electricity that is consumed by Mainers regardless of where that electricity is generated. The table also does not include jet fuel and other oil-based energy sources such as asphalt and road oil and lubricants. These are relatively small amounts of energy for which there are no electric-based alternatives at this time. In addition, the conversion of transportation and industrial processes to electricity is likely to reduce significantly the quantity of lubricant fuel used.

The table also does not include energy from geothermal or hydro facilities located in the state. Since these are renewable energy sources, I assume that these are not displaced through decarbonization, but rather continue into the future at their current levels.

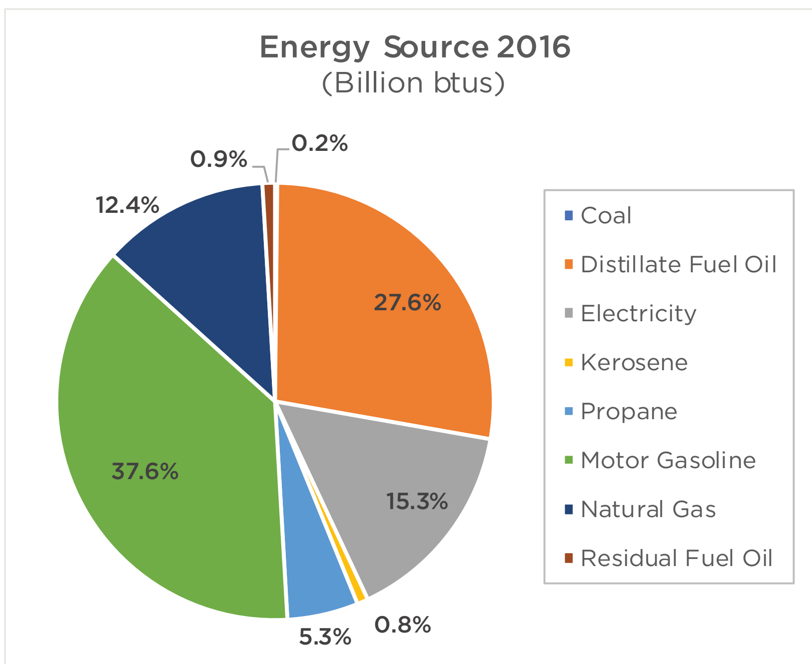
Finally, I have not included biomass in my analysis. I assume that whatever biomass that is currently consumed for heating and process purposes will continue to be consumed over the next 30 years, and therefore will not impact the analysis of beneficial electrification. I further assume that biomass that is currently being used to generate electricity in stand-alone facilities will not be used for this purpose in the future, as the biomass plants will not be able to produce electricity on a competitive basis when all electricity is being supplied by renewable energy resources with no fuel costs.

With these adjustments, Table 2-2 shows total Maine energy consumption of about 256 trillion btus of energy a year, only 15% of which is electricity.[17] Based on data collected and reported by the Independent System Operator of New England ("ISO-NE") less than half of this electricity consumption derives from zero carbon emission generation, including nuclear generation. The remaining energy consumed is from energy sources that emit CO_2 and must be converted to electricity for purposes of achieving deep decarbonization, as discussed below.

17 https://www.eia.gov/state/seds/seds-data-complete.php?sid=ME#CompleteDataFile

TABLE 2-2 | Maine Non-Renewable Energy Consumption plus Electricity Use - 2016

ENERGY SOURCE	CONSUMPTION (Billion btus)
Coal	421
Distillate Fuel Oil	70,643
Electricity	39,064
Kerosene	2,095
Propane	13,448
Motor Gasoline	96,242
Natural Gas	31,685
Residual Fuel Oil	2,370
TOTAL	**255,968**



The consequence of using the energy sources shown in **Table 2-1** is that Maine's total CO_2 emissions from energy use is around 20 million tons per year. This is calculated using standard EPA emission factors for the fuels shown in **Table 2-2**, and a value of 500 lbs of CO_2/MWh as the average emissions factor for the ISO-NE electricity grid. It is clear that Maine has a long way to go to eliminate carbon from its energy mix.

These energy usage levels are aggregate usages drawn from state-level data. As one thinks about conversion of various end-uses of energy from their existing fuels to electricity and then to develop generation configurations to provide the electricity required to meet total energy use using renewable energy, it is necessary to break down the above values into their end-use components and then further allocate these to consumption each hour over the course of the year. I describe how I do this for each of the energy sources in the following subsections.

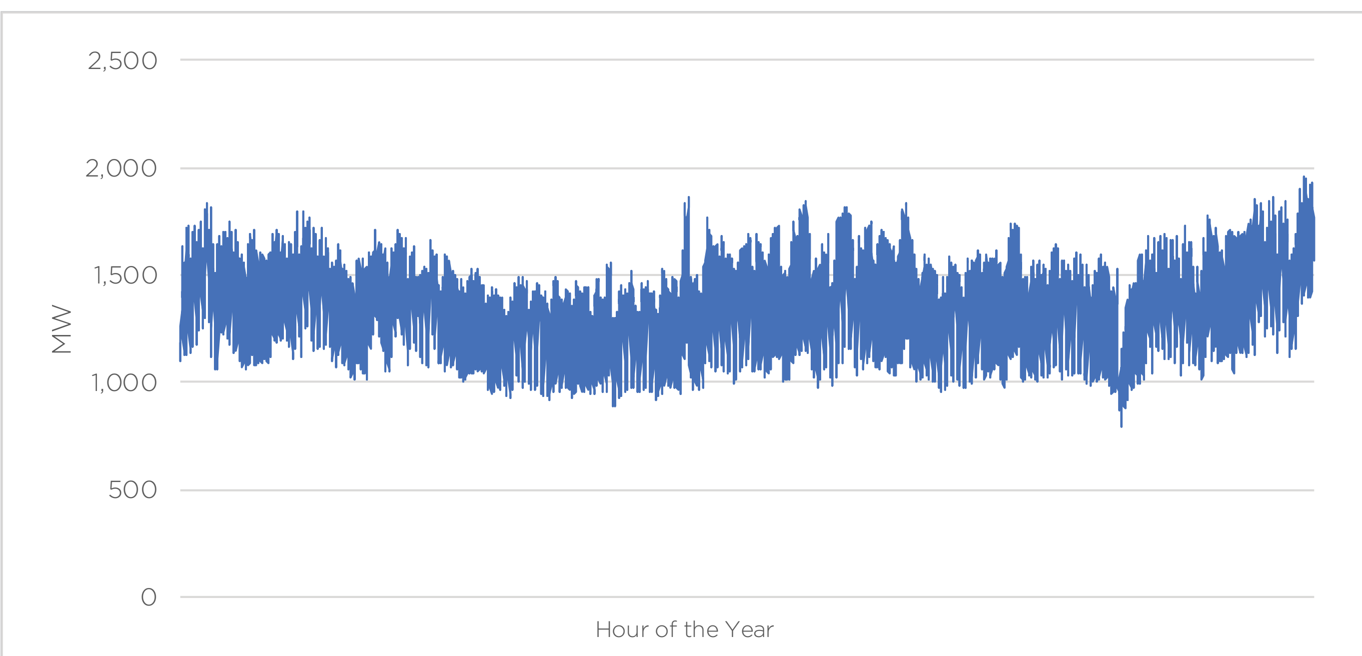
2.1.1 | Electricity

The Independent System Operator for New England or ISO-NE tracks electricity usage on an hourly basis across the New England region by load zone and by state. Maine electricity usage with the ISO-NE Control Area includes all customers of Central Maine Power Company and Emera Maine, except those that are in Aroostook County and served by what used to be Maine Public Service. The load data for these customers is available from the Northern Maine Independent System Administrator or NMISA. In both cases, usage is measured at the generator bus and the transmission interfaces into and out of each geographic region. The usage includes transmission and distribution losses on the grid, and is, therefore, the amount of electricity that must be generated to meet the load requirements of all customers in Maine at their respective points of consumption.

Figure 2-1 shows these hourly load levels over the course of 8,760 hours in the year (2017), beginning on January 1st and ending on December 31st. The graph is scaled to the range of usage and shown in MW/hour. (I adopt this same convention for all energy usages in the following sections.)

Current electricity usage shows some seasonality, with winter and summer loads higher than spring and fall loads. It also shows significant diurnal variation. Loads during the overnight periods are typically about half what they are during the peak periods

FIGURE 2-1 | Maine Hourly Electricity Loads - 2017



in the early evening. Overall, the maximum coincidental peak hourly load is 1,961 MW, resulting in a system annual load factor of 70%. This is a very high load factor – well above the national average. This high annual load factor is attributable to Maine's manufacturing base in conjunction with low air-conditioning penetration in the residential sector and higher winter heating requirements, relative to the rest of New England and the U.S. as a whole.

2.1.2 | Natural Gas

The development of the Maritimes & Northeast (M&N) and the Portland Natural Gas Transmission System (PNGTS) pipelines in the late 1990s led to the subsequent creations of local gas distribution utilities - Bangor Gas, Maine Natural Gas and Summit Natural Gas and expansion of Northern Utilities (Unitil). These, in turn, enabled expanded natural gas usage in Maine. EIA reports natural gas use in Maine by month for five sectoral end uses – residential, commercial, industrial, transportation and electric utilities. For my purposes, I have used the average monthly natural gas usage reported by EIA for the years 2015, 2016 and 2017. These years are reasonably representative of average winter weather conditions in Maine.

Natural gas is used by residential consumers to provide space heating and domestic hot water. This usage accounts for approximately 8% of natural gas used in Maine that is not used for generating electricity. Commercial and industrial consumers use natural gas for two purposes – space heating and for process heat. Together, they account for 92% of non-electric generation natural gas usage in the state. Of this total amount, I estimate that about 77% is used for commercial and industrial processes. A small amount of natural gas is used in the transportation sector, primarily to power bus fleets. This amount is very small and included in the modeling of the electrification of the transportation sector.

2.1.1.1 | Heating

Natural gas used for heating purposes is highly correlated with ambient temperatures and associated weather conditions. The vast majority of natural gas used for heating end-use purposes is consumed during the winter months. As noted above, I have defined 100% of residential natural gas usage as usage for heating purposes (space heating and domestic hot water). This ignores gas used for cooking purposes. This amount is very small and its omission will have *de minimus* impacts on the model results.

Unfortunately, EIA does not break down natural gas usage in the commercial and industrial sectors by end use. To estimate the amount of monthly natural gas used for heating purposes in the commercial and industrial sectors, I define 100% of the gas used during the months of June, July, August and September, when facilities are not providing heat due to warm ambient air temperatures, as process related use. The amount of all monthly usage in the remaining eight months of the year in excess of the process amounts is then defined as natural gas used for heating loads.

Figure 2-2 shows the monthly natural gas heating loads for the residential, commercial and industrial sectors, based on the above assumptions. The low residential usage reflects the relatively low degree of natural gas distribution system penetration in Maine. Where natural gas distribution systems are in place, they tend to be designed for and located to serve large end-users. Even where the gas pipelines go past or are close to residential units, the conversion rate of residences to natural gas among those end-users is slow and has remained well below 50%.

2.1.1.2 | Process

I estimate natural gas process loads by calculating the average monthly usage over the months of June, July, August and September for the commercial and industrial sectors. This average is applied across all twelve months assuming that process loads are non-seasonal. The monthly usage levels are shown in **Figure 2-3**. The differences across the months reflect only the differences in the number of days in each month. Not surprisingly, the majority of process load

FIGURE 2-2 | Maine Monthly Gas Heating Loads by Sector

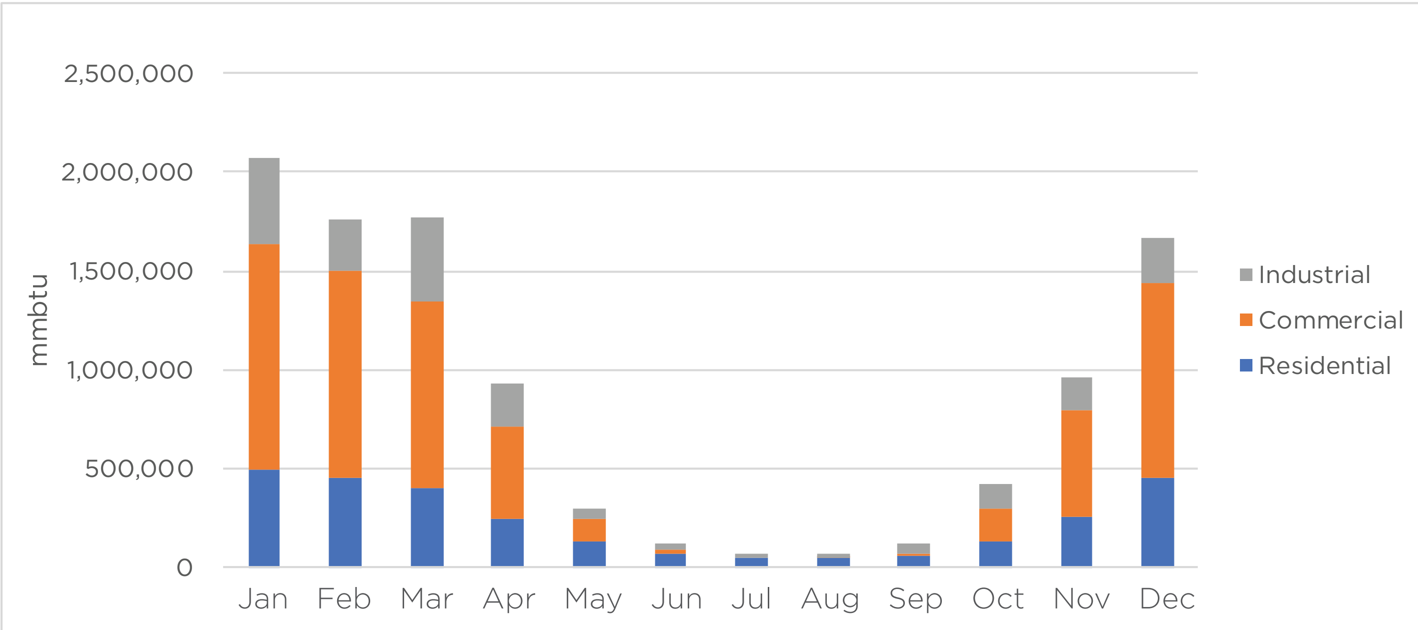
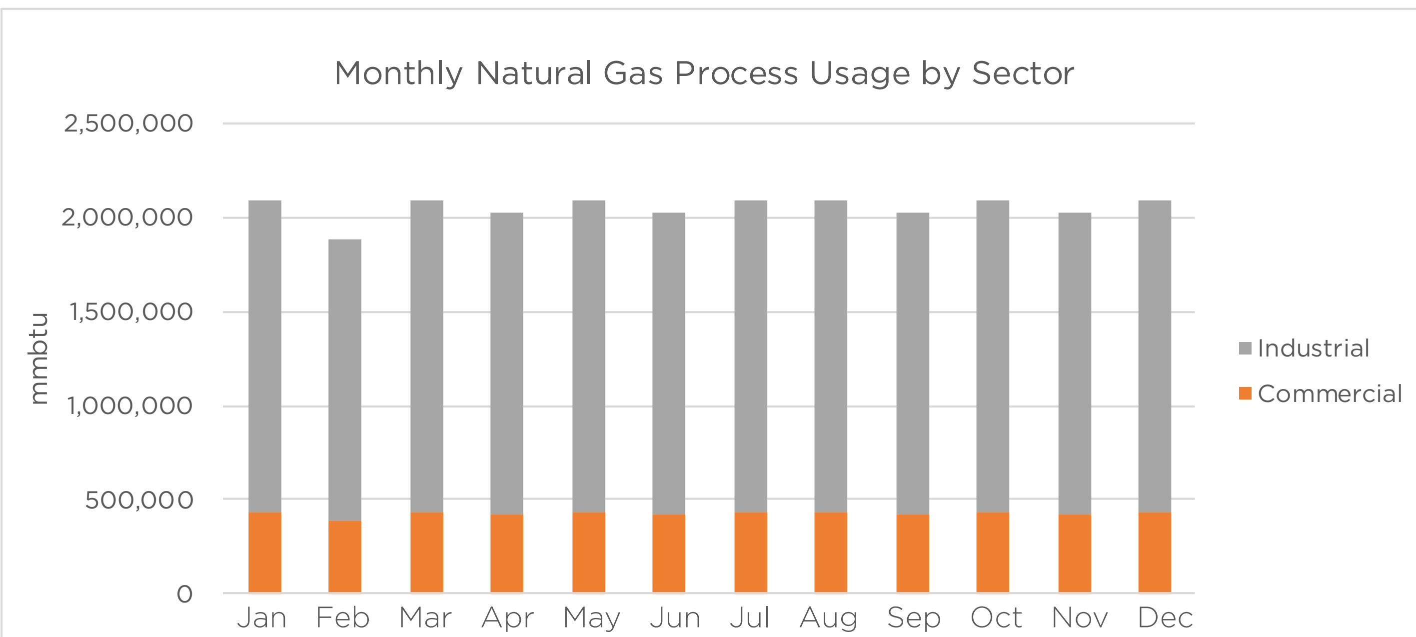


FIGURE 2-3 | Monthly Natural Gas Usage for Process Loads by Sector



is industrial and generally associated with Maine's largest manufacturing facilities, including Maine's remaining paper mills and companies like Bath Iron Works.

2.1.3 | Distillate Fuels

The primary distillate fuel used for heating and process applications in Maine is #2 oil, which is often referred to as heating oil. Distillate fuels also include propane and kerosene as well as Residual Fuel Oil (Resid or #6 oil) that is used in non-residential applications. As shown in **Table 2-2**, Maine uses about twice as much distillate fuel on a btu basis as it uses natural gas for all end uses. The sector use of the fuel is heavily weighted toward residential usage, since approximately 70% of all Maine households use heating oil as their primary heating source. Residential usage of distillate fuel constitutes about 60% of total Maine use, with commercial and industrial usage representing 25% and 15%, respectively. Unlike natural gas, which is delivered through fixed pipelines and where the use of the fuel is metered monthly, the only monthly data on distillate fuels are related to the delivery of the fuels at the wholesale level. This does not provide a good match to monthly consumer usage. Therefore, I have apportioned annual distillate fuels use by month using the monthly percentages of natural gas use by sector. I then used the monthly percentages for natural gas heating and process uses to apportion total monthly distillate fuels use into heating and process end uses. Since the monthly consumption shapes and the relative percent to process versus heating in the commercial and industrial sectors are assumed to be the same as with natural gas, the usage graphs would look the same as those presented in Figue 2-3 and are not presented here.

2.1.4 | Gasoline & Diesel (Over-the-Road)

Total gasoline and diesel use in Maine for over-the-road transportation purposes is just under 93 trillion btus per year. This is equivalent to approximately 780 million gallons of distillate fuels. It represents 36.1% of all energy used in Maine. While there are some monthly data available, these data tend to be based on point of sale information that is not necessarily consistent with actual usage. As I discuss in more detail in Section 2.2., I have relied on a variety of different data sources to apportion this usage by end-use (passenger cars, buses, trucks) and by month to measure when the fuels are actually consumed.

2.2 | Beneficial Electrification

Considerable effort has been and continues to be spent on carbon capture and storage technologies and more recently on concepts for removing CO_2 from the air as a means of reducing CO_2 to address global warming. These efforts have not been able to produce any technologies that can work at the scales necessary to make an impact on global CO_2 levels in the atmosphere, nor have they been able to deliver CO_2 emissions reductions at anything approaching a reasonable cost. On the other hand, passive solar designs for buildings reduce heating and cooling requirements, solar thermal systems displace heating oil and/or natural gas as a source of energy for domestic hot water, increased vehicle efficiencies and other energy conservation efforts reduce CO_2 emissions. These are all important contributors to reducing overall CO_2 emissions, but they cannot bring us anywhere near zero-carbon.

Given the state of technology today, electricity offers the only option for producing usable energy at the scale required and at reasonable costs without creating CO_2 emissions or other forms of greenhouse gases. Further, many end-uses of energy can be displaced by equipment or technologies that run on electricity and that deliver comparable output as oil and natural gas. These technologies include electric vehicles in the transportation sector, air source and ground source heat pumps for space heating and various electronic equipment for producing usable heat to displace oil and natural gas in commercial and industrial processes.

This section focuses on these three end-uses of energy to estimate how much electricity and during what hours of the year that electricity would need to be consumed to displace all fossil-based fuels used in Maine for these purposes. In all cases and for all end-uses, the resulting electric loads have been grossed up by 8% to account for losses on the transmission and distribution grid.

2.2.1 | Space Heating

Using the methodology for apportioning distillate fuels and natural gas use into heating and process end uses described in the previous section, I estimate that fuels used for space heating represent approximately 23% of total annual fuel use in Maine. While some Maine homes, businesses and institutions are heated with wood and wood pellets and some with electric resistance heating, most of the energy used for this end-use across all sectors are distillates (heating oil, propane or kerosene) and natural gas.[18] Recent advances in air source heat pump technologies that enable the delivery of heat at lower winter temperatures have led to an increase in their use in Maine, abetted through promotions by Efficiency Maine Trust. Overall penetration remains very small, however, as these make up less than 5% of total households.

Ground source heat pumps have been around for decades. This technology relies on a relatively constant temperature in the ground to serve as a source of heat in the winter and a sink for heat in the summer. This constant temperature allows ground source heat pumps to operate at higher efficiencies during the winter months than air source heat pumps. However, they tend to cost considerably more to install, especially where drilling through ledge is required for the piping that serves as the heat exchanger.

I make the assumption that by 2050 all Maine residential units are converted to air source heat pumps and that all commercial and industrial facilities switch over to ground source heat pumps to meet their heating requirements. This assumption is convenient; altering the relative percentages of each technology in each sector would not change total electric usage appreciably. I assume that air source heat pumps have a coefficient of performance (COP) that is a function of ambient air temperatures according to the following equation:

$$\mathbf{COP = (0.025 * T) + 1.75} \qquad (1)$$

(where T is ambient air temperature each hour measured in Degrees F)[19]

This means that at a temperature of 50°F the COP is 3.0, and the heat pump uses one-third the amount of electricity as resistance heating would use to provide the same amount of heat.

Based on a general review of the literature, I assume that ground source heat pumps have a constant COP of 3.5 when providing heat.

As homes and businesses electrify by converting to air and ground source heat pumps, these heat pumps are replacing furnaces, boilers and other equipment that burn distillate fuels or natural gas to generate heat. I assume that existing residential heating systems operate at an average efficiency of 82%, commercial systems at 82.5% and industrial systems at 85%. The commercial and industrial levels are consistent with manufacturing specs for new equipment and for older equipment that is well maintained. The figure for residential heating systems reflects actual operating performance across all such systems.[20] Since the air source and ground source heat pumps deliver heat directly, the amount of electric energy required to provide the equivalent levels of heat provided by burning distillate and natural gas is equal to the quantity of those fuels used multiplied by the average efficiency values noted above. I perform the calculation on the monthly distillate and natural gas usage levels to obtain the equivalent amount of electric energy input into air source and ground source heat pumps required to displace fossil fuels.

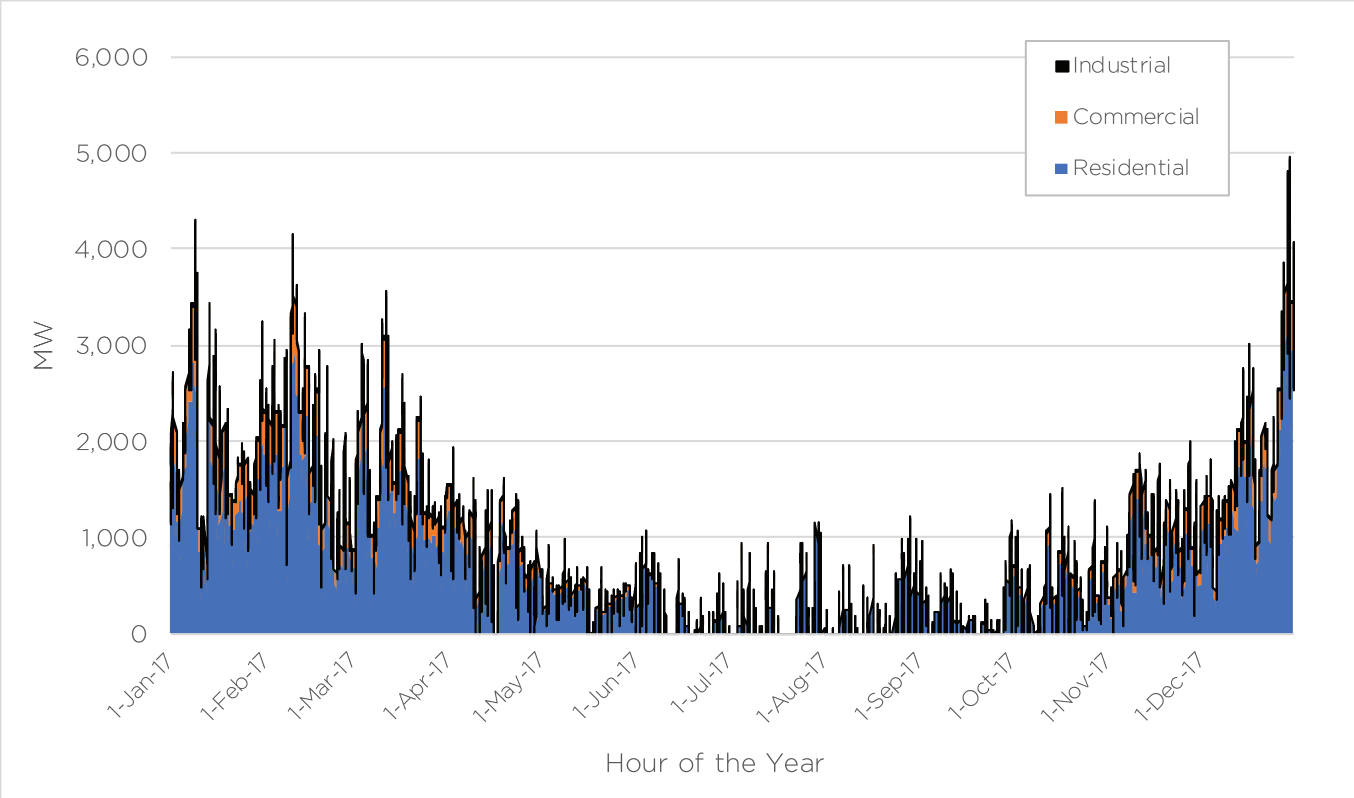
Next, I allocate the monthly distillate and natural gas requirements for each end-use sector to each hour in the month based on the heating degrees for that hour as a percent of total heating degrees for the month. I use 2017 hourly temperatures for Maine as reported by ISO-NE. This hourly fuel amount is then converted to electricity usage using Equation (1) for residential usage and using the COP of 3.5 for commercial and industrial usage. This results in estimates of the hourly electricity loads that would provide equivalent heating for each

[18] I assume that all homes, businesses and institutions that use wood or wood pellets for heat continue to do so. Since these fuels emit no CO_2 on a life-cycle basis, they do not need to be replaced by electrification.

[19] Source: "Natural Gas and Electric Positioning and Gas Technology Update," William E. Liss, gti, Gas Technology, May 2017, p. 33.

[20] Maine Single-Family Residential Baseline Study, NMR Group, Inc., submitted to Efficiency Maine Trust, September 14, 2015.

FIGURE 2-4 | Estimated Hourly Electric Heating Loads by End-Use Sector



end-use sector to that which is currently being provided by combusting distillate fuels and natural gas. The results are shown in **Figure 2-4**.

Not surprisingly, electric load requirements for heating purposes are highly seasonal, with the highest loads occurring during the winter months and on the coldest hours during these months. While the total electric load for heating end-use purposes of 7,500 GWh is only 66% of current electricity usage in Maine, the peak load is 5,321 MW. This is 2.7 times higher than the current peak load of 1,961 MW. This results in a low annual load factor of about 17% for this end use.

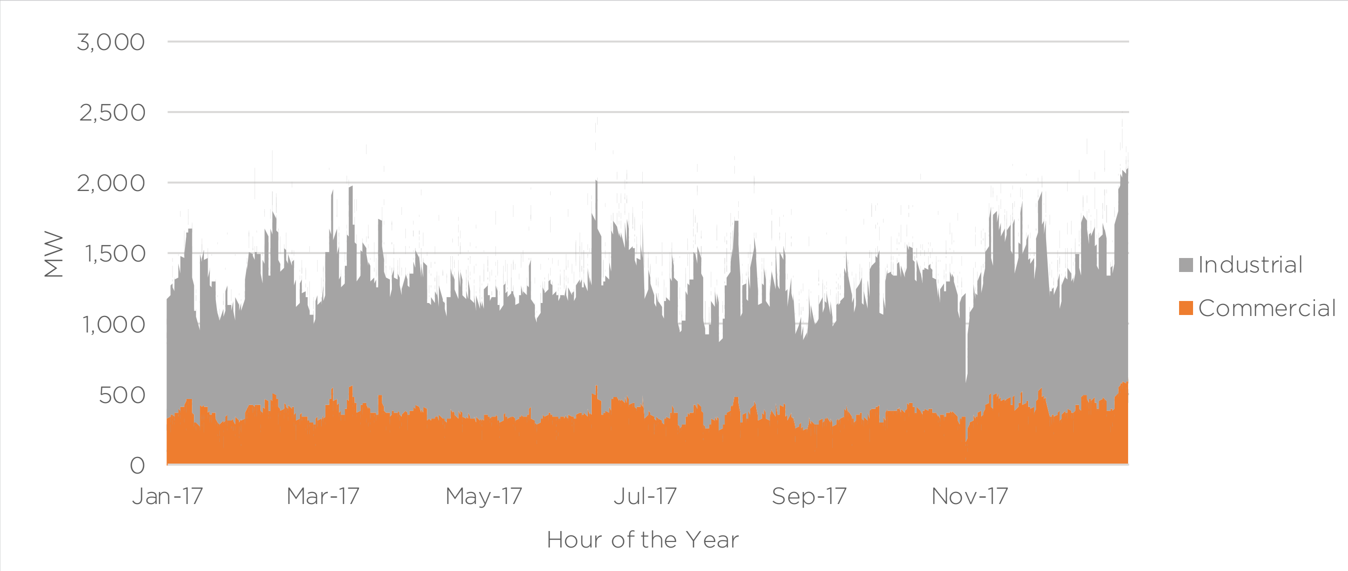
2.2.2 | Non-Space Heating Process Heat

I next compute total electrical requirements to convert all process end-uses in the commercial and industrial sectors from distillate fuels and natural gas to electricity.[21] I assume that the btus of usable heat from current boiler operations is displaced on a 1-to-0.90 basis for industrial customers and on a 1-to-0.825 basis for commercial customers by btus of electricity. I have no direct means of apportioning annual or monthly amounts of distillate fuels and natural gas used by industrial and commercial customers for process purposes into each hour of the year.

As a proxy for this apportionment, I use hourly electricity use in each sector. I assume hourly electricity use is correlated to process intensity, and thus is a reasonable proxy. For the commercial sector, I use an estimate of the hourly loads for the small and medium general service customers of CMP and Emera; for the industrial sector, I use an estimate of the hourly loads for the interval customer classes in each utility. The results are shown in **Figure 2-5**.

[21] I assume that processes that are currently fueled by biomass remain fueled by biomass, as these already meet the zero-carbon emissions target.

FIGURE 2-5 | Estimated Hourly Electric Process Loads by End-Use Sector



The total annual electricity requirement for process loads is just under 12,000 GWh. This is roughly the same as current electricity usage in the state. The annual peak load for this end-use is 2,326 MW – almost 20% higher than current peak loads in Maine. As a result, the annual load factor of this usage profile is 54%.

2.2.3 | Residential Air Conditioning

One of the important advantages that heat pumps offer residential consumers is the ability to operate them in reverse mode to provide cooling for interior spaces during summer months. Today, while most commercial and industrial facilities have air conditioning in areas that impact worker productivity, only about 25% of Maine's roughly 700,000 residences have some form of central air conditioning systems or window units.[22] As all residences convert to air source heat pumps for space heat, they will gain central air conditioning as a side benefit. This represents a net increase in total electricity use by households during the summer months.

As noted, approximately 25% of the 700,000 or so Maine residences have some form of air conditioning. For these residences, the increased electricity usage due to air source heat pumps during the summer will offset the electricity use of their existing air conditioning systems and thus results in no incremental electricity usage.[23] For the remaining 75% of Maine households, I assume that the average air conditioning requirement is for 1,500 sq.ft., requiring 2 tons of chiller capacity. The amount of electricity required to power these units is directly related to ambient air temperatures. This relationship can be approximated using the following linear equation for ambient air temperatures between 70°F and 100°F:

$$\textbf{Multiplier} = .005 * T - 0.15 \qquad (2)$$

(where T is ambient air temperature each hour measured in Degrees F and The Multiplier is multiplied by 4 kW/hour to obtain predicted energy use based on ambient air temperature each hour)[24]

[22] A survey of households performed on behalf of Efficiency Maine Trust in 2015 found that 13 out of the 41 homes visited in the survey had some form of cooling equipment, most of which was room air conditioners. I have reduced the percentage to 25% as an estimate of the households with full-house air conditioning. "Maine Single-Family Residential Baseline Study, NMR Group, Inc., submitted to Efficiency Maine Trust, September 14, 2015, at page 62.

[23] Since heat pumps are more efficient than window AC units, these 25% of households may see a reduction in total energy use. I do not factor this into the analysis as it would be very small in any case.

[24] See for example, https://asm-air.com/airconditioning/much-cost-run-air-conditioner/

I assume that no air conditioning is used when ambient air temperatures are below 70°F.

The increase in residential electricity use due to increased air conditioning is obtained by multiplying the hourly electricity usage for this single dwelling unit by the 75% of 700,000 households assumed to have no air conditioning today.

Total annual electricity usage for this end-use is 598,000 MWh, virtually all of which occurs during the summer months. Peak demand is just over 714 MW, which means the annual load factor is less than 9.5%. This usage, however, is seasonally countercyclical to heating. Even though the total usage is small and has itself a poor load factor, use of heat pumps to provide air conditioning actually improves the overall load factor for the grid as the grid expands to serve beneficial electrification.

2.2.4 | Transportation

Electrification of the transportation sector has been the most visible and most discussed component of beneficial electrification in the U.S. and around the world. Most of the attention has focused on passenger vehicles. Increasingly, we are seeing attention spread to buses, as electric buses are being adopted by cities across the country. We are also beginning to see some attention by Tesla and Volvo, among others, pushing the sector forward with designs and prototypes for trucks, including long-haul tractor trailers. The speed with which the conversion of different classes of vehicles occurs will depend on many factors, including the life-cycle costs of ownership, the range of travel offered, the ubiquity of charging stations and the time it takes to recharge vehicles. For purposes of estimating the amount of electricity required to power the beneficial electrification of Maine's transportation sector, I assume that by 2050 all passenger vehicles, light trucks, buses and trucks in Maine are electric. I also assume that annual vehicle miles traveled for each class of vehicle remain the same in 2050 as today. In addition, I make certain assumptions described below about the efficiencies of the different classes of motor vehicles, measured not in miles per gallon, but in miles per kWh of electricity used.

2.2.4.1 | Passenger Vehicles

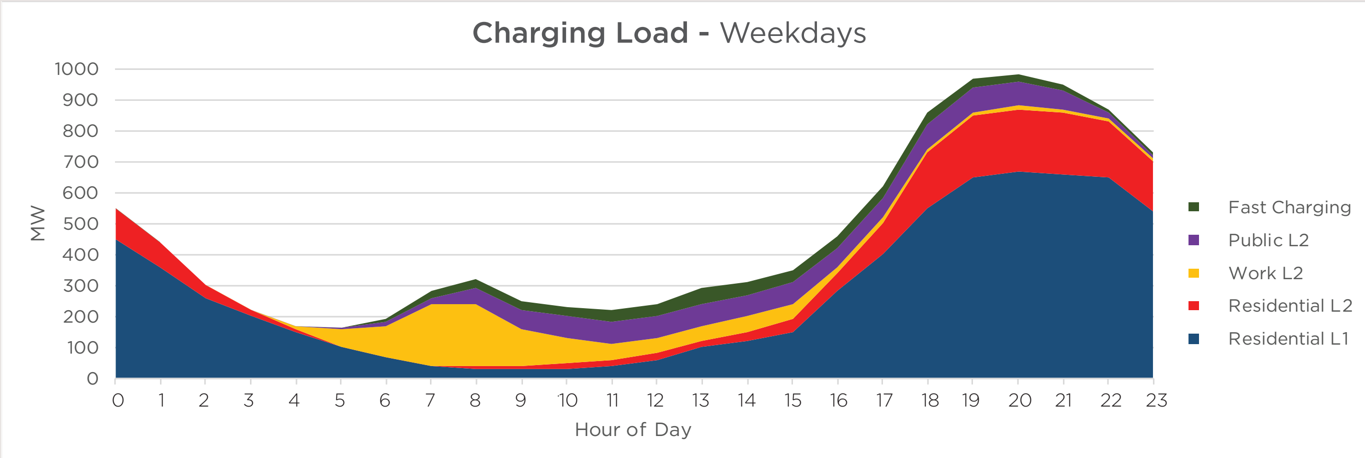
It is relatively straightforward to convert the total annual amount of gasoline and diesel fuel used to power passenger vehicles in Maine to an equivalent annual amount of electric energy required. The difficulty is determining when the electricity will be drawn off the grid and stored in the battery systems of these passenger vehicles. This is necessary to define the hourly profile of electricity use over the course of the year. To the best of my knowledge, there have been no studies of how Maine electric passenger vehicle owners will charge their vehicles. As a result, I am forced to rely on studies from other states and to modify the results of those studies to reflect Maine driving patterns and weather conditions.

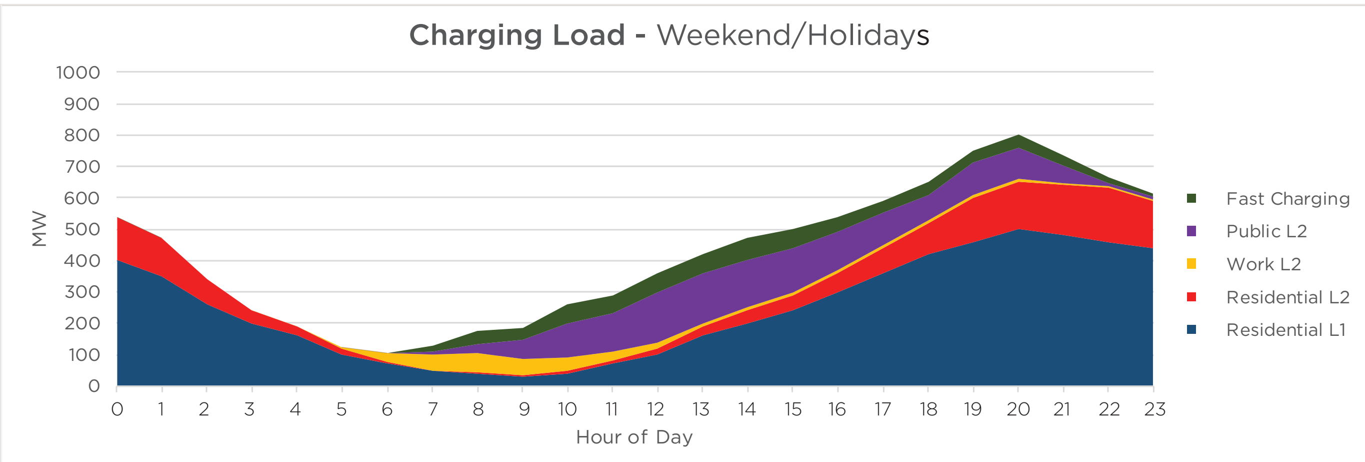
One of the more detailed studies of driver charging behavior is a study done by the California Energy Commission and released in March 2018.[25] A major component of this study involved the survey of travel behavior of households. This survey was used to develop a simulation of passenger vehicle travel for 1.3 million passenger vehicles across California. These results were combined with assumptions about the number and location of electric vehicle chargers to create hourly charging profiles for typical weekdays and weekends. I extracted these profiles and present them in **Figure 2-6**.

The study assumes that electric passenger vehicle charging is done at four types of chargers. The most widely used are Level 1 (L1) and Level 2 (L2) chargers located at each vehicle owner's residence. This charging generally occurs during the evening hours, extending into the overnight hours. Some amount of charging is done during the day at L2 chargers located either at the workplace or at public facilities such as parking garages, shopping malls, and similar types of locations.

[25] "California Plug-In Electric Vehicle Infrastructure Projects: 2017-2025," California Energy Commission Staff Report, March 2018 | CEC-600-2018-001.

FIGURE 2-6 | California Study Results – Electric Charging Profiles for Passenger Vehicles





This charging tends to be concentrated during morning workday hours for charging done at the workplace and during afternoon hours at the other locations. Fast chargers that are located on highways and other heavily traveled routes account for the remaining charging that occurs. This charging occurs during the day and evening hours. The charging pattern for weekdays and weekends is similar, with a few notable differences. The first difference is the electricity load shape for weekday charging is more peaked than for weekends. Second, there is less charging done at the workplace on weekends. Finally, there is more charging done at fast chargers and at public L2 charging locations on weekends.

These two graphs can be used to estimate the hourly electricity consumption in 2050 required to charge electric passenger vehicles in Maine by applying the results of the California Study to Maine. I do this by making a number of modifications to reflect differences between the two states. First, I scale the California results down based on the ratio of the number of Maine passenger vehicles (928,132) to the number of passenger vehicles in the study (1.3 million). Second, I scale the results up slightly to reflect the fact that the number of miles driven per vehicle in Maine is higher than in California.

Finally, I adjust the results to reflect differences in monthly travel in Maine, measured in vehicle miles driven per month, and for the fact that miles/kWh of electricity consumption tends to be lower in Maine during cold months when the battery in electric vehicles is called upon to provide heat to the passenger compartment. With respect to this latter adjustment, I assume that passenger vehicles get 4 miles/kWh during the summer months, 3 miles/kWh during the months of January and February and somewhere in between for the other months. The average miles/kWh over the course of the year is 3.60. This is comparable to what is reported by owners of the Chevy Bolt in New England, but higher than the Tesla models achieve today. I use this higher value to account for improvements in vehicle efficiency over the next couple of decades as more and more electric vehicles are produced. The adjustments result in total electricity usage of about 4.18 million MWhs, with a peak charging load of 1,125 MW.

2.2.4.2 | Buses

The Maine Secretary of State reports that there are 4,455 buses registered in Maine, 3,000 of which are classified as school buses. These buses drive over 120 million miles a year. This is just under 28,000 miles per bus. I assume that the 70% of buses that are school buses operate only on weekdays, while the remainder operate over the entire seven-day week. This translates into an average miles driven per day of approximately 100 miles across the entire bus fleet. Assuming the average efficiency of electric buses is 0.465 miles/kWh,[26] the total annual electricity use of Maine's bus fleet is calculated to be 280,000 MWhs.

To estimate the charging profile of the buses, I assume that each bus charges overnight to replenish the electricity used the prior day in driving the 100 miles. I further assume that the charging occurs during the hours from midnight to 5 am, and that the amount of electricity consumed is evenly distributed over these five hours.[27] Finally, I add a round-trip charging loss of 12.5%. This is in addition to the 8% loss factor applied to grid electricity, generally. The total charging load, including losses, is 340,000 MWhs, with a peak load of 233 MW.

2.2.4.3 | Trucks

The category "trucks" includes vans, single-unit and combination trucks. It does not include pick-up trucks and SUVs, as these are included in passenger vehicles. There are about 76,000 registered trucks in Maine. These vehicles logged a total of 1.2 billion miles in Maine in 2015, for an average of 15,862 miles per truck per year. I assume that all trucks operate on weekdays, but only 67% of them operate on weekends. This results in an average of 50 miles of travel per day per truck.

To obtain the amount of fuel used, I assume that the average efficiency of the current truck fleet is 12 miles per gallon, since the ratio of van registrations to tractor trailer registrations is about 10-to-1. When the heat content of the fuel used is converted to electricity, this is equal to 0.328 miles per kWh. This is well below the passenger vehicle miles/kWh of 3.6 and also below the 0.465 miles/kWh assumed for buses.

I next assume that each truck recharges over a 7-hour period from 11 pm through 6 am. As with buses, I assume that the charging is evenly distributed across these 7 hours and that round-trip inefficiency of the charging/discharging cycle is 12.5%. The total amount of electricity use by trucks (including transmission and distribution losses of 8%) is calculated as 3.7 million MWh, with a peak demand of 1,622 MW.

2.2.5 | Total Electricity Use

Table 2-3 provides a summary of the amount of electricity that is required to continue to power Maine homes and businesses at their current levels, plus (a) convert all space heating and domestic hot water use in all residential, commercial and industrial facilities to electricity, (b) extend air conditioning to all residential units in Maine, (c) convert all fuels used in commercial and industrial processes to electricity and (d) electrify our transportation sector (passenger vehicles, buses and trucks).

[26] See, for example, http://www.nrel.gov/docs/fy17osti/67698.pdf, Table ES-1.

[27] This charging schedule will require chargers with the capacity to deliver 43 kW per hour of charge. A longer charging window is available for school buses. I use this shorter 5-hour window to reduce the amount of overlap between charging buses and residential charging of passenger vehicles.

TABLE 2-3 | Summary – Electricity Use by End-Use Sector Under Beneficial Electrification

LOAD TYPE	TOTAL LOADS (GWh)	MAXIMUM DEMAND (MW)	MINIMUM DEMAND (MW)	AVERAGE DEMAND (MW)	CAPACITY FACTOR (%)
Current Use (RNS)	12,048	1,961	789	1,375	70.10%
Total Heating	7,453	4,954	0	851	17.20%
Residential AC	598	714	0	68	9.50%
Total Process	11,910	2,512	135	1,360	54.10%
Total EV Charging	8,272	2,486	102	944	38.00%
Passenger Vehicles	4,177	1,125	102	477	42.40%
Buses	340	233	0	39	16.70%
Trucks	3,755	1,622	0	429	26.40%
TOTAL LOADS	**40,280**	**9,893**	**1,449**	**4,598**	**46.50%**

The first row of **Table 2-3** shows current electricity use in Maine. This is referred to as Regional Network Service (RNS) loads, in keeping with ISO-NE notation. It is measured at the generator, so is already grossed-up for transmission and distribution losses. Maine currently consumes 12,048 GWh of electricity. Annual peak demand is just under 2,000 MW. This provides a good benchmark for the generation capacity required plus the size of the transmission and distribution system necessary to serve current loads across all sectors of the economy and all towns in Maine. To achieve beneficial electrification requires a grid that is capable of transmitting and distributing a more than 3-fold increase in total electricity usage, plus, more importantly, a 5-fold increase in peak loads. As a result, total grid utilization falls from a very high 70% today to about 46.5% with full beneficial electrification.

While the total amount of end-use energy in the beneficial electrification case is the same as current energy use in Maine, the conversion of heating, transportation and process to electricity reduces the primary energy required. As shown in **Table 2-3**, Maine currently uses 260 trillion btus of energy net of those fuels I am not including. Of this total only 41 trillion btus or 16% is electricity. In contrast, by 2050, assuming full beneficial electrification, Maine will only consume electricity. The amount will be 40,280 GWh as shown in T**able 2-3**. This is just under 140 trillion btus and represents a 47% reduction in total energy used, measure in btus consumed.

Figures 2-7 and **2-8** present the estimated hourly loads by end-use over the course of a year, assuming beneficial electrification as described above. **Figure 2-7** presents the results for an entire year. Since it is difficult to see daily fluctuations in electricity use in **Figure 2-7**, **Figure 2-8** provides the same information but only for the first week in January.[28]

These graphs provide useful illustrations of just how electricity use changes as Maine moves to beneficial electricification. The first thing to note from **Figure 2-7** is the impact of converting heating to electricity. This not only increases total electricity use, but more importantly it shifts Maine's peak electricity demand to the winter.

The second thing to note is best seen in **Figure 2-8** and is the impact of converting both process heat and transportation to electricity. While process loads tend to be relatively evenly distributed over the course of the week, the EV charging load shows the

[28] Since this is for the first week in January, there is no residential air conditioning load.

FIGURE 2-7 | Total Hourly Electricity Use Under Beneficial Electrification

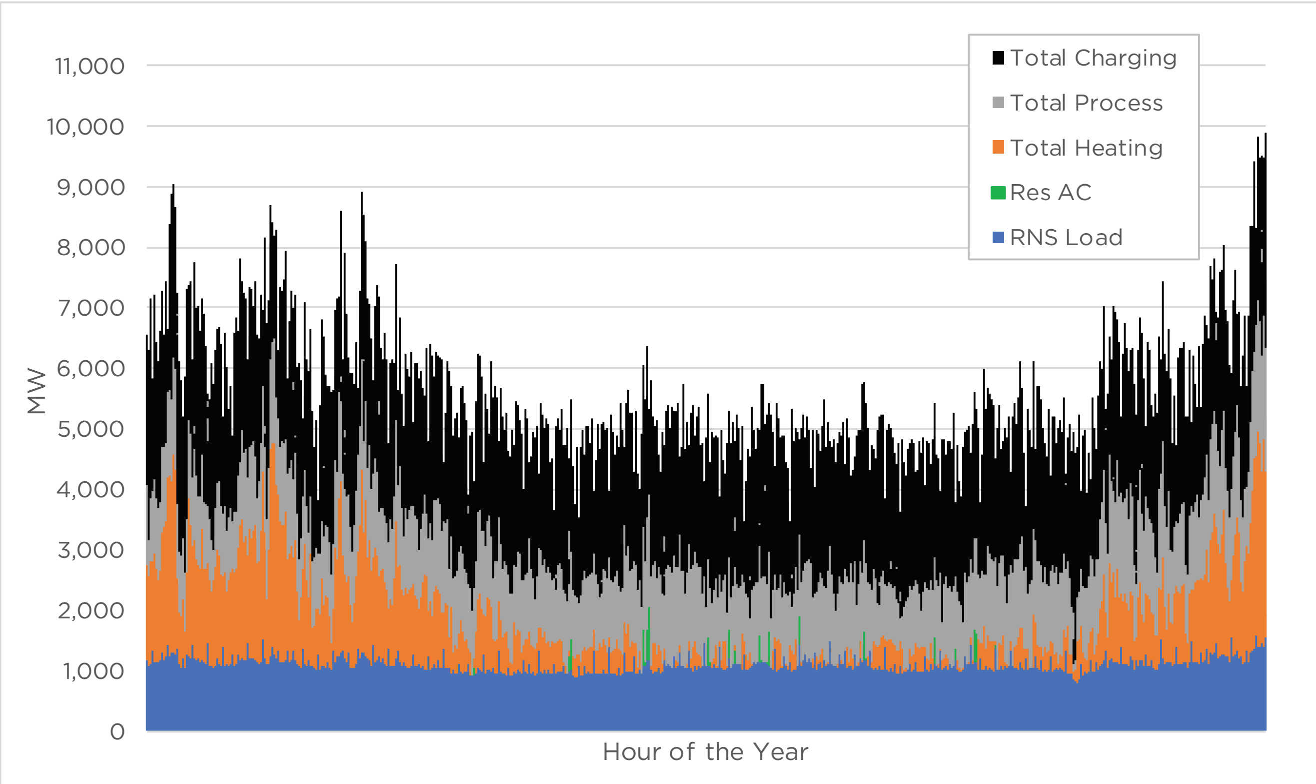
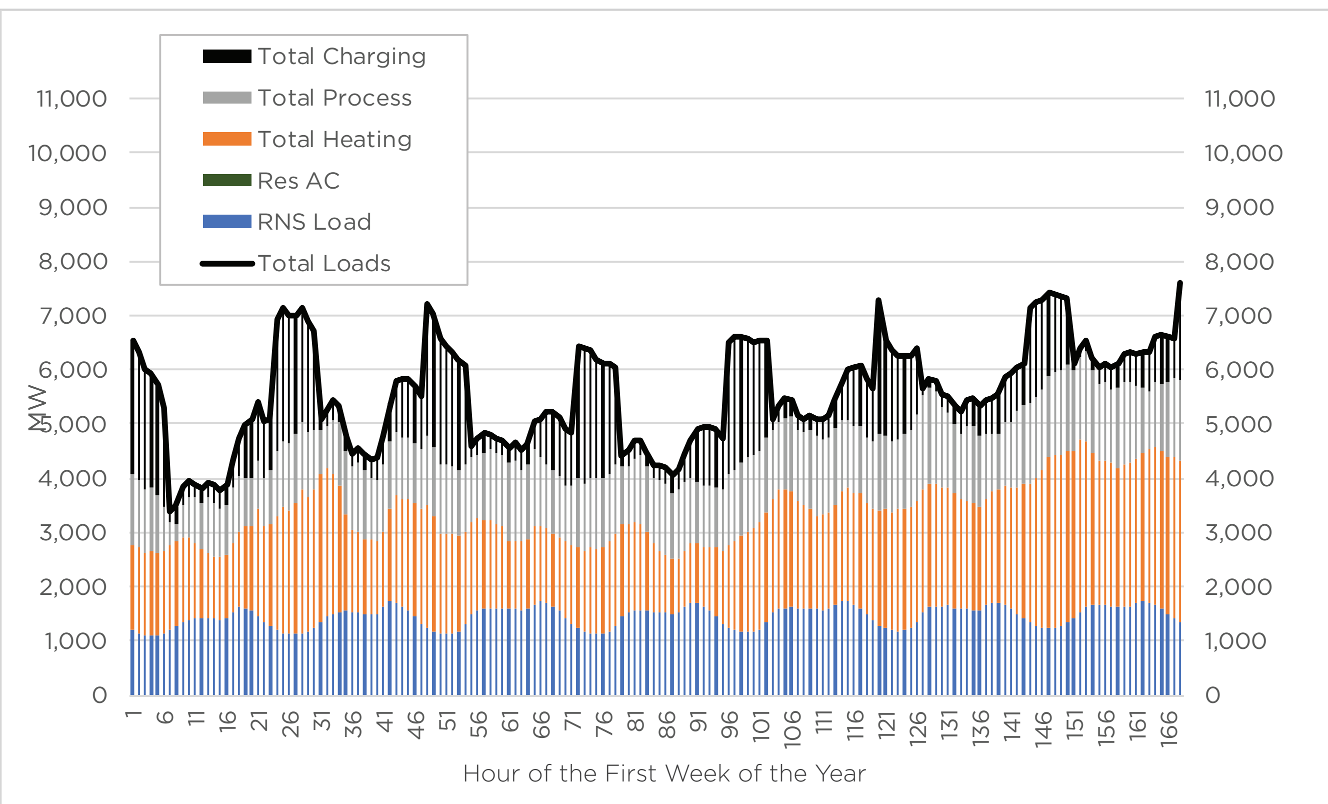


FIGURE 2-8 | Total Hourly Electricity Use Under Beneficial Electrification (week)



effect of assuming that truck and bus charging occurs during the overnight hours, while most of the electricity used to charge passenger vehicles occurs during the evening hours.

The most important thing to note about these two figures is the distinct difference between daily load cycles and seasonality, especially as it relates to meeting these electricity requirements with renewable energy. As I will discuss in more detail in the next section, the daily cycle in **Figure 2-8** is on the order of 3,000 MW for about 10 or so hours each day. If there were no heating loads and if we could charge a system of battery storage each day and discharge it during periods of high demand, the size of the battery storage system required would be on the order of 30,000 MWh. The heating loads, however, create strong seasonality in electricity use. As a result, the seasonal storage requirement is between 10 times and to up to 100 times larger than the daily storage requirement, depending on the type of renewable generation available, as I discuss in the next section.

2.3 | Electricity Supply Requirements

In this section, I focus on a variety of renewable electric generation options for supplying electricity to meet hourly electric loads, assuming full beneficial electrification as shown in **Figure 2-7**. Since a primary objective of beneficial electrification is to enable deep decarbonization thereby virtually eliminating CO_2 emissions across all sectors of society, I consider only those generation technologies suitable for Maine that are capable of producing electricity at the scale required. These are solar PV systems, on-shore wind and off-shore wind. In addition, I have assumed that Maine's existing hydroelectric generating plants continue to operate, and that their collective energy is delivered to meet Maine's electricity requirements. I do not consider tidal, ocean wave or ocean current technologies, biomass, nuclear or geothermal, as I believe these will remain either politically unacceptable, technologically infeasible or economically unviable through 2050 compared to the other alternatives.[29]

I note that my focus on only Maine-based generation resources is an artificial construct given the interstate transmission grid that enables generating resources located outside of Maine to serve Maine load. I have imposed this constraint to demonstrate the feasibility of meeting Maine electric loads with Maine-based zero-emission renewable generation so as not to impose on other political jurisdictions any perceived negative consequences of achieving deep decarbonization. In reality, I would expect states to meet as much of their own electric loads with distributed energy resources and larger-scale utility size plants located within their boundaries before relying on imported energy flows.

The four renewable generation technologies are "intermittent" – that is, they produce electricity when the sun is shining, the wind is blowing, or the rivers are flowing. The hourly outputs of these technologies over the course of the year do not match the hourly electricity requirements shown in **Figure 2-7**. During some hours, they will produce too much electricity; during other hours, they will produce too little electricity. As I discuss below, I assume that balancing hourly loads with generation is done using battery storage.

I estimate hourly generation for solar PV using standard P50 solar conditions for solar projects in Maine, scaled to a 23% annual capacity factor to account for improved technology over time. I expect that most of this generation will be from ground-mounted, utility-scale solar PV.[30]

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[29] These same constraints may not apply to other regions. In fact, I would expect to see zero-emission renewable generation resources developed in other regions consistent with the availabilities and relative costs of the underlying resources. By omitting nuclear, I am assuming that the region's three remaining nuclear plants – Seabrook, Millstone I and Millstone II – do not operate beyond the terms of their current licenses.

[30] I do not discount rooftop solar PV. If one-third of Maine households install solar PV on their roofs and the average size system is 6 kW, the total capacity will be close to 2,000 MW. My modeling of electric loads, energy generation and total energy costs treats these units as generation and for cost purposes on the same basis as the ground-mounted

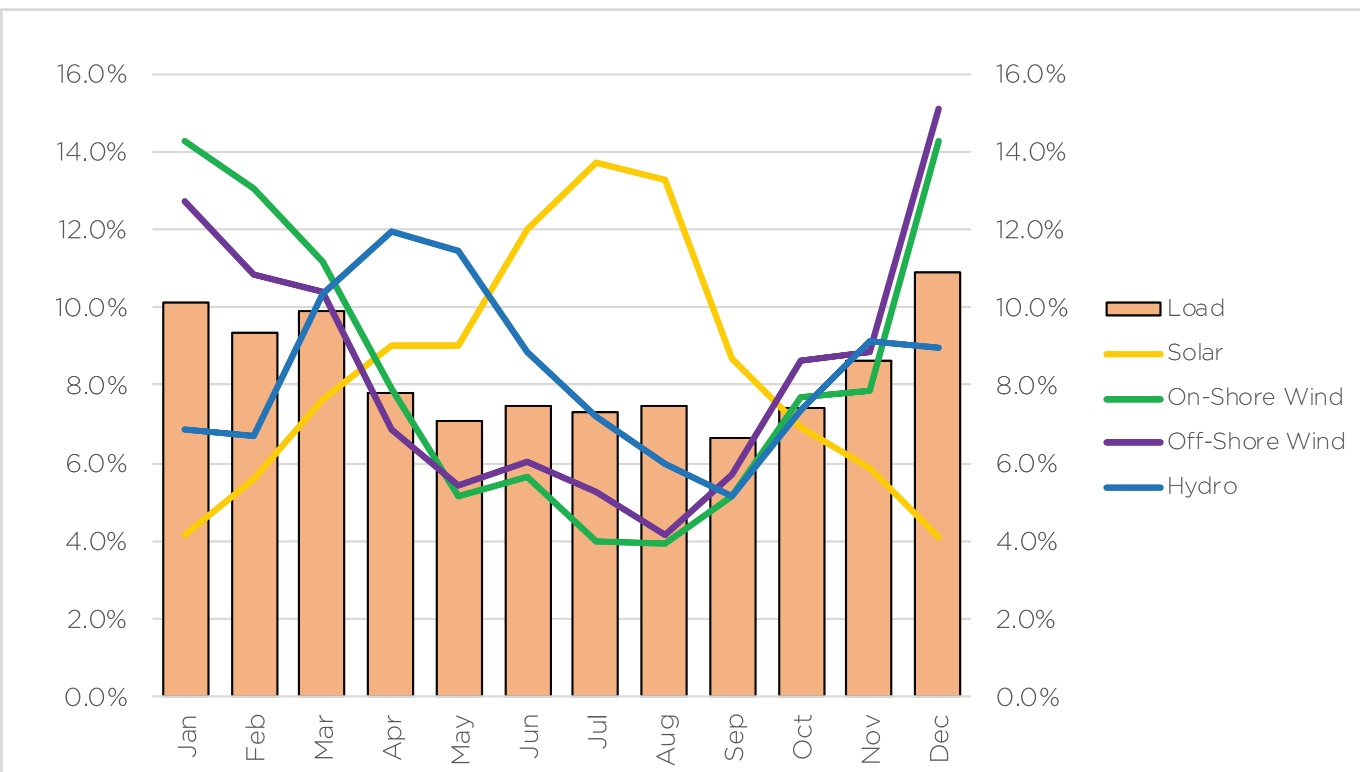
Hourly on-shore wind generation is estimated using P50 wind conditions for western Maine and generator performance curves for 3.0 MW turbines. The hourly generation is scaled to an annual capacity factor of 42.55% to account for improvements in wind turbine technology likely to occur over the next couple of decades. I estimate hourly generation for off-shore wind using average wind speed measurements from buoys in the Gulf of Maine over a ten-year period and the performance curve for new GE 8.0 MW wind turbines. This results in an annual capacity factor of 53.6%, which is in line with various industry estimates. Next, I estimate hourly hydroelectric generation output by using the average annual generation over the past 20 years (3,500 GWh). I apportion this annual generation to each month using the relative percentages of such generation in each month to account for the seasonality of rainfall and snow melt as well as the extensive storage reservoir systems for Maine's three major rivers – the Kennebec, Androscoggin and Penobscot. Finally, I apportion the monthly totals evenly across all hours in each month. This approximates the hourly generation distribution under a P50 weather scenario.[31]

Figure 2-9 shows the percent of total electricity generation in each month for each of the four generation technologies compared to the percentage of estimated 2050 electric load in each month. On balance, the generation technologies work well together to meet load requirements. Both on-shore and off-shore wind generate higher percentages of their output during the winter season, tracking the seasonal distribution of loads. During the summer, when wind generation diminishes, solar fills in the gap. Hydro is less well-aligned with load. While it does produce higher energy outputs during the winter, its time of maximum production coincides with the spring snowmelt

units. To the extent that their installation costs are higher, I assume that this cost premium represents non-monetary benefits received by the system owners.

[31] This apportionment does not capture the daily cycling capacities of a few of the hydroelectric stations such as Harris, Wyman and Williams on the Kennebec River. This is a small percentage of total annual generation and does not materially affect my results.

FIGURE 2-9 | Monthly Loads and Generation Output by Generation Type



when electric loads are relatively low.[32] Since hydro is meeting only 8% of total loads, this mismatch has only a small impact.

The seasonal counter-cyclicity of wind and solar helps match generation output to loads. However, even with this benefit, wind generation exceeds loads during the winter months, while solar exceeds loads during the summer months. Balancing generation and load requires either relying on surplus wind in the winter to be stored to meet summer loads, surplus solar in the summer to be stored to meet winter loads or a combination of both.

To understand the relationship among generation technologies, loads and storage requirements, I examine three generation scenarios. Each generation scenario includes hydroelectric generation plus one or more of the other three generation types – solar, on-shore and off-shore wind. Initially, I size the capacities of these generation types so that their total annual energy generation matches total annual electricity usage. Where the scenario includes wind as well as solar PV, I size the wind equal to what is generally viewed as the longer-term capacity that can be built in Maine and use solar PV to meet the remaining amount of annual electric load. Under each scenario, I assume that battery storage is used to balance the grid. Thus, during hours when the generation exceeds load, surplus electricity is stored in batteries. This electricity is released during those hours when generation is less than loads. I further assume that the battery storage units experience round-trip cycle losses of 12.5%; that is, in order to obtain 1 MWh of energy from the battery, 1.125 MWh must be used to charge the battery. This process creates a maximum deficit and a maximum surplus for battery storage over the year. The amount of storage required to balance the grid and meet all electricity requirements is equal to the greater of these two amounts.

In the next section, as an alternative to increased storage, I relax the constraint that the total generation at nameplate ratings must equal total loads. Specifically, I allow for overbuilding of wind and solar generation. This introduces another tool to balance the grid in addition to battery storage. This provides the ability to throttle back generation from these wind and solar generating plants, i.e., dispatching generation off when it exceeds loads, in addition to using battery storage to balance the grid.

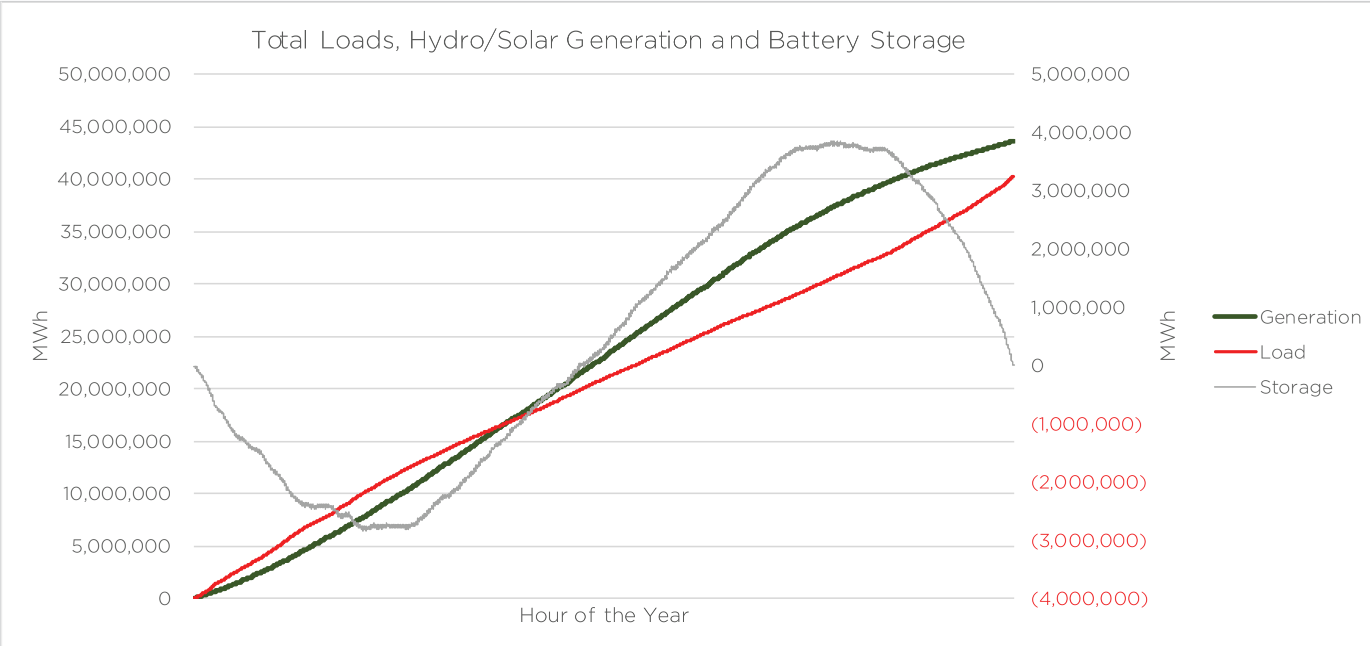
The first electricity generation scenario I examine is one where the full electricity requirements shown in **Figure 2-7** are met with 100% solar PV, beyond what is met by hydroelectric generation. At a 23% annual capacity factor, Maine needs about 19,860 MW to meet total electricity usage of 40.28 million MWh a year plus the round-trip losses of the battery storage system.[33] **Figure 2-10** shows cumulative loads and generation over the year on the left axis. The graph shows the seasonal mismatch between solar PV generation and total electric load.

Beginning January 1st, heating loads impose electrical requirements well in excess of solar generation, resulting in a drawn-down of electricity stored in batteries. As spring arrives, the situation changes – solar PV generation exceeds loads and the accumulated deficit slowly turns into a surplus, with electricity being stored in the batteries. The surplus continues through mid-fall, when storage reaches a peak. With the onset of fall, the situation changes again, repeating the annual cycle. The amount by which generation exceeds load at the end of the year is equal to the energy lost in charging and discharging the battery storage units. The total amount of this lost energy is 3.34 million MWhs, which represents 8.3% of total annual load.

[32] Maine achieves a relatively high capacity factor for its hydroelectric generating plants because of upstream storage on its major river systems. However, under both federal and state clean water regulations, the hydroelectric plants must balance energy generation with other public benefits such as flood control, fisheries management and recreational activities. As hydroelectric generation becomes a smaller and smaller component of Maine's energy generation, I expect these other benefits to become more significant. This could cause financial pressures on the hydroelectric plants due to restrictions on operating regimes and increased capital requirements.

[33] At this stage, I do not include any capacity for reserves to meet electricity requirements when some of the solar PV units are off line.

FIGURE 2-10 | Generation Scenario - 100% Solar PV



The state of the battery storage is shown on the right axis of **Figure 2-10**. The curve shows the state of charge of the batteries equal to zero on January 1st and returning to zero on December 31st, net of the cycling losses noted above. The maximum deficit over the course of the year is about 2.84 million MWh; the peak storage level is 3.84 million MWh. The larger of the two – 3.84 million MWh, is the size of the battery storage system required to support meeting Maine's electric requirements with 100% solar PV generation.

The second electricity generation scenario I examine is one where the full electricity requirements are met with a combination of the existing hydro, on-shore wind and solar PV. I set the capacity of the on-shore wind at 3,500 MW. The output from these wind generators meets about 31% of the total load. The balance that is not met by hydroelectric generation is met by 12,845 MW of solar PV. **Figure 2-11** shows the same load, generation and storage curves as **Figure 2-10**.

The maximum electricity deficit in this configuration is about half that of the 100% solar PV scenario, while the peak storage level is about 2.45 million MWh. This is because the seasonal generation profile of on-shore wind is counter-seasonal to that of solar and more in line with winter heating loads, as shown in **Figure 2-9**. Therefore, less battery storage is required to balance the grid seasonally to meet total electricity requirements. This lowers total round-trip efficiency losses to 2.2 million MWhs, or about 5.5% of total loads.

The third electricity generation scenario I examine adds off-shore wind to the mix. I set the capacity of the off-shore wind at 4,000 MW and keep on-shore wind capacity at 3,500 MW. These two sources generate enough electricity to meet 46% and 32% of the total electricity load, respectively. The balance not met by hydroelectric generation is met by 2,930 MW of solar PV. **Figure 2-12** shows the results for this generation configuration.

Because off-shore wind has such a high annual capacity factor and has a different seasonal profile than both on-shore wind and solar PV, the amount of storage required is lower than under either of the first two options. The maximum deficit is only about 175,000 MWh; however, the peak storage level is still 1.87 million MWh. Total round-trip losses are just below 1 million MWhs, or about 2.4% of total load.

FIGURE 2-11 | Generation Scenario – On-Shore Wind Plus Solar PV

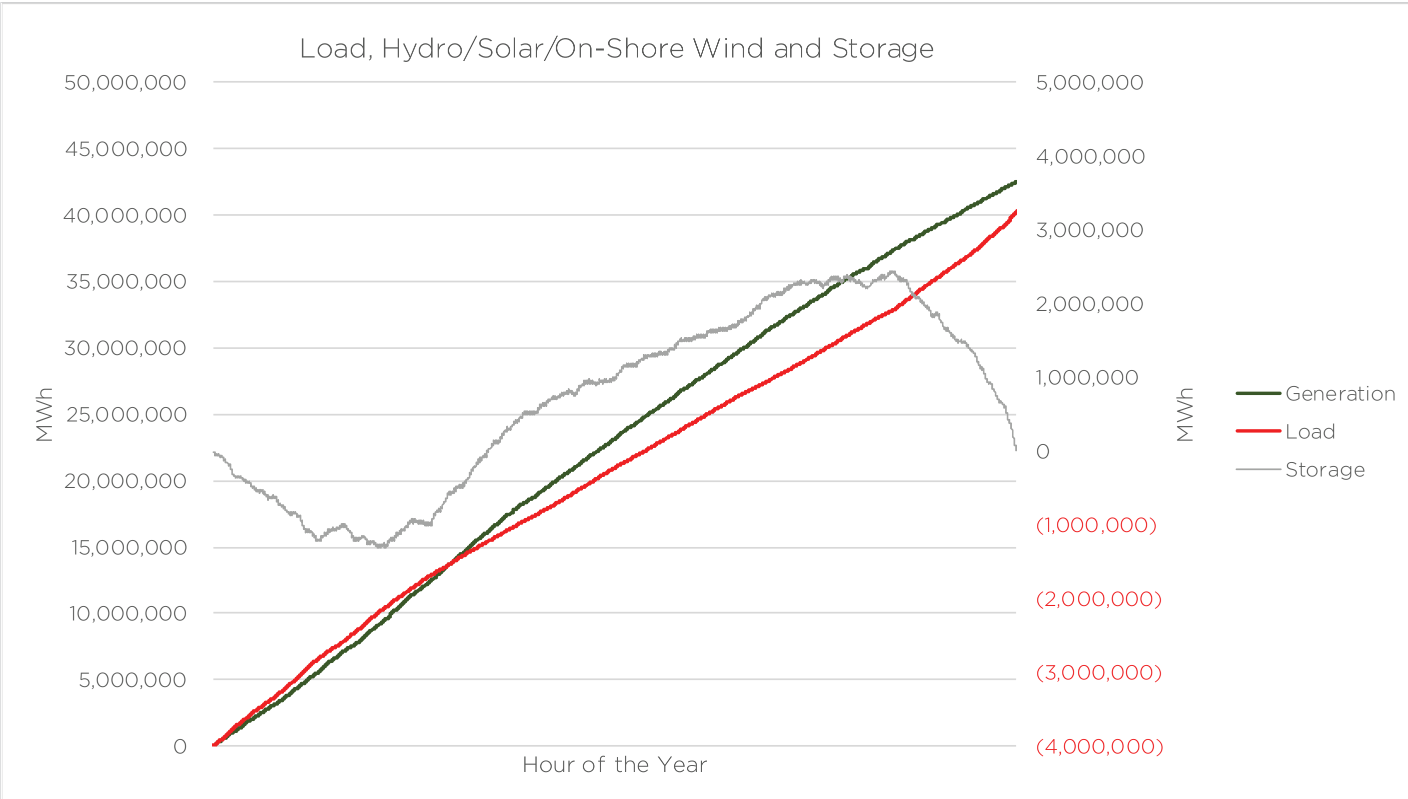


FIGURE 2-12 | Generation Scenario – Off-Shore plus On-Shore Wind plus Solar PV

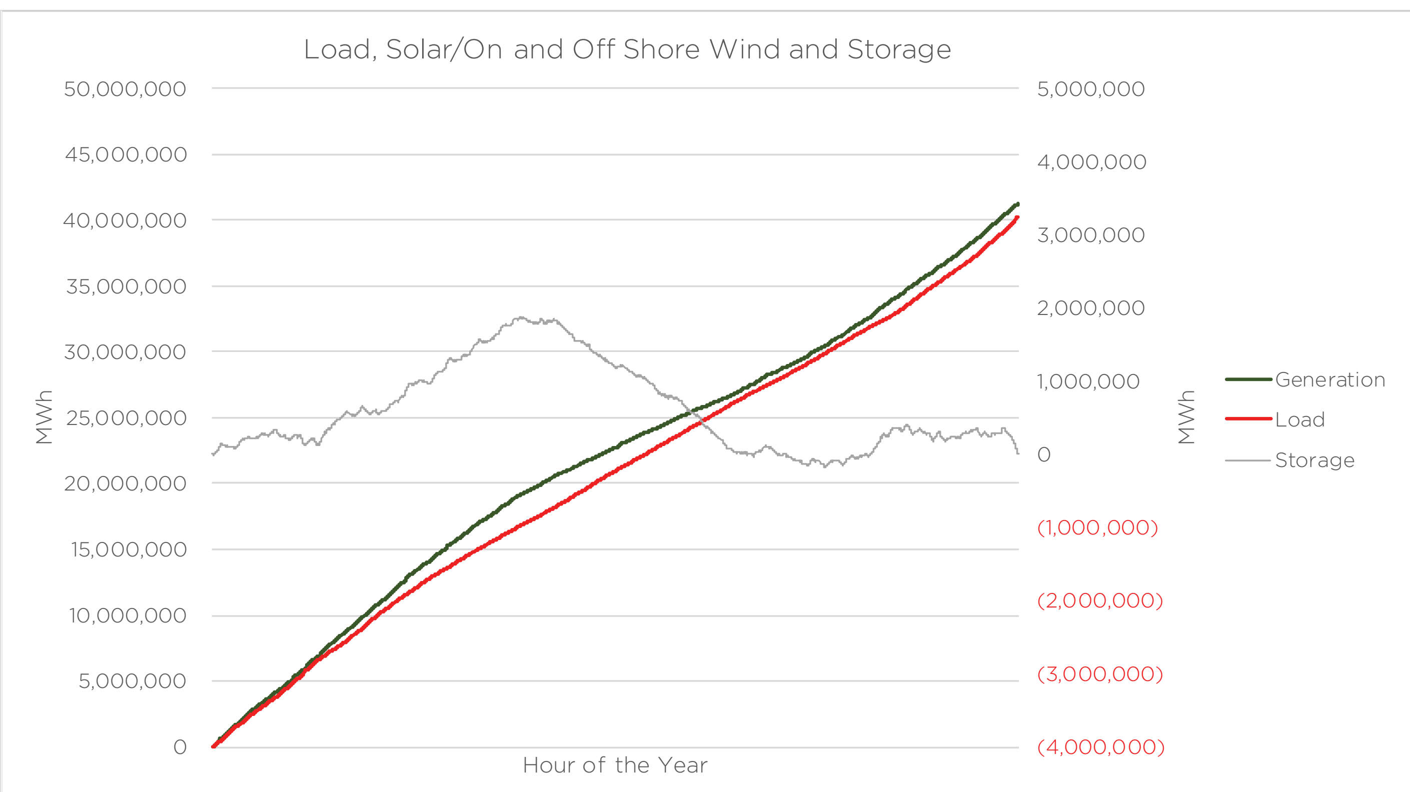


FIGURE 2-13 | Battery Storage Requirements for Different Generation Scenarios

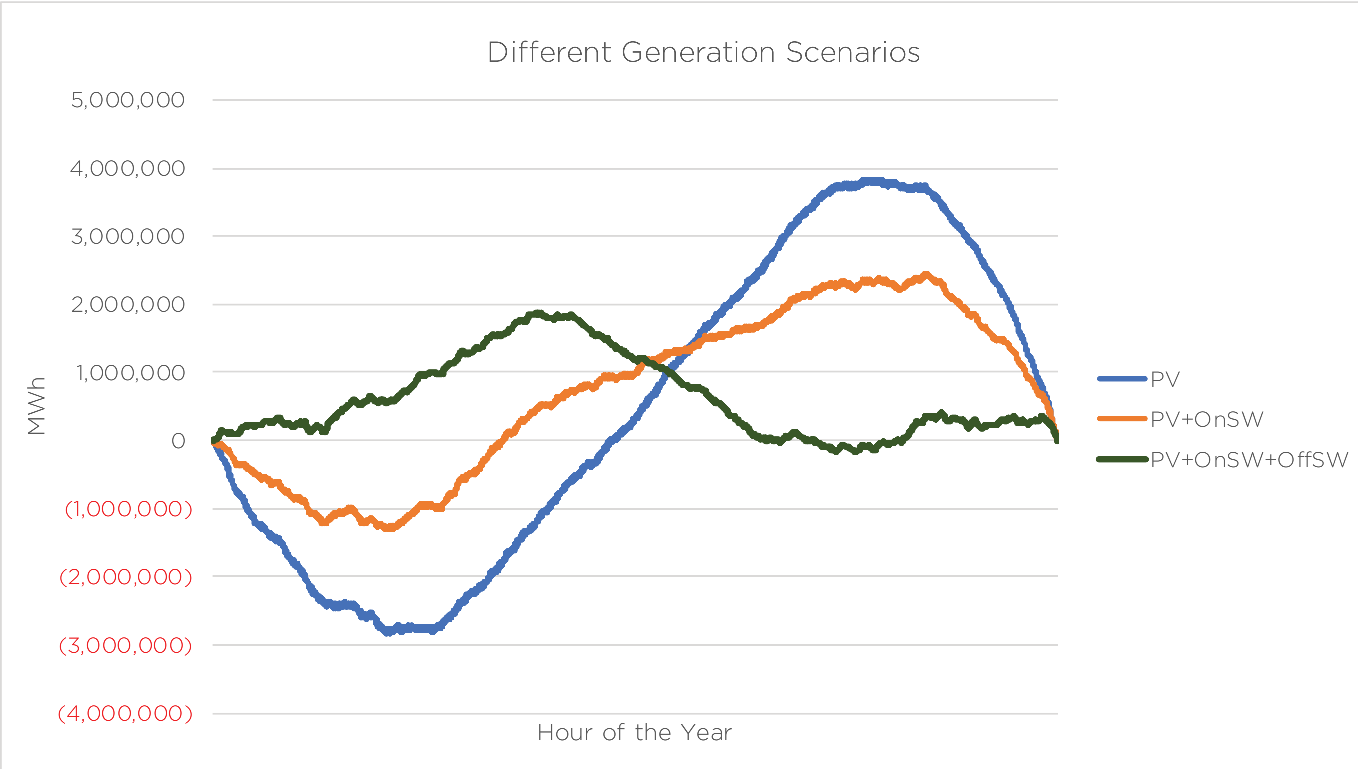


Figure 2-13 shows the storage requirements for each of these scenarios on the same chart for easier comparison. This chart shows the value of off-shore wind generation for Maine to meet its 2050 electric requirements with renewable generation resources. Each MW of off-shore wind is equivalent to 2.3 MW of solar PV in terms of the amount of electricity generated over the course of the year and reduces the amount of storage capacity required by 50%.

The electricity storage requirements in all three generation scenarios are driven by the seasonal nature of electricity loads and primarily by the electrification of space heating across all sectors of the economy. The 2 million to 4 million MWh of annual storage requirement for these different generation scenarios dwarfs any diurnal storage requirements that arise from the generation profile of solar compared to, for example, the charging pattern for EVs. The maximum daily storage deficit or surplus over the course of the year under the third of the generation scenarios presented is approximately 100,000 MWh. The total storage required to meet this maximum diurnal differential is only 5% of the total seasonal storage requirement of the hydro plus solar PV plus on-shore and off-shore wind generation scenario.

This result is driven by heating loads and is therefore more pronounced in the northern climates such as Maine. This means that considerations such as when people charge their cars or otherwise use electricity over the course of the day has only a small impact on the amount of total storage required. To illustrate this, I changed the behavior of how people charge their passenger vehicles from the curves shown in **Figure 2-6** to a perfectly flat charging schedule by distributing the total MWh of charging equally across the 24 hours of the day. Doing this resulted in a reduction of about 2,000 MWh of battery storage in the solar PV plus on-shore plus off-shore wind scenario. This is a reduction of one-tenth of one percent of the total storage requirement for that generation scenario.[34]

[34] I do not model this relationship where winter seasonal use is much lower or near zero, as it would be, for example, in places like San Diego. In these locations, I

2.4 | The Costs of Meeting Beneficial Electrification

EIA reports that Maine spent about $5.44 billion on energy in 2016. The breakdown of this total amount by fuel and by sector is shown in **Table 2-4**.

Eliminating spending on those fuels not included in **Table 2-2** and eliminating spending on fuels used in the generation of electricity reduces this amount to $4.96 billion. **Figure 2-14** shows this same total (that is, net of those fuels not included in **Table 2-2** and the amount spent on fuels used to generate electricity) for each year since 2000. These amounts are expressed in 2016 dollars. Total spending ranged from a high of $8 billion in 2008 to a low of $4.3 billion in 2001 and averaged close to $6 billion.

In this section, I estimate the costs to Maine of the third generation scenario described above, where beneficial electrification of the transportation, space heating and process sectors of Maine's economy is met through a combination of existing hydro, solar PV, on-shore wind, off-shore wind and battery storage. **Table 2-5** presents the assumptions I have made about the installed capital costs and fixed and variable operating costs of each of these technologies in 2020 and 2050, as well as the annual revenue required to support the capital costs of each. I have assumed that the

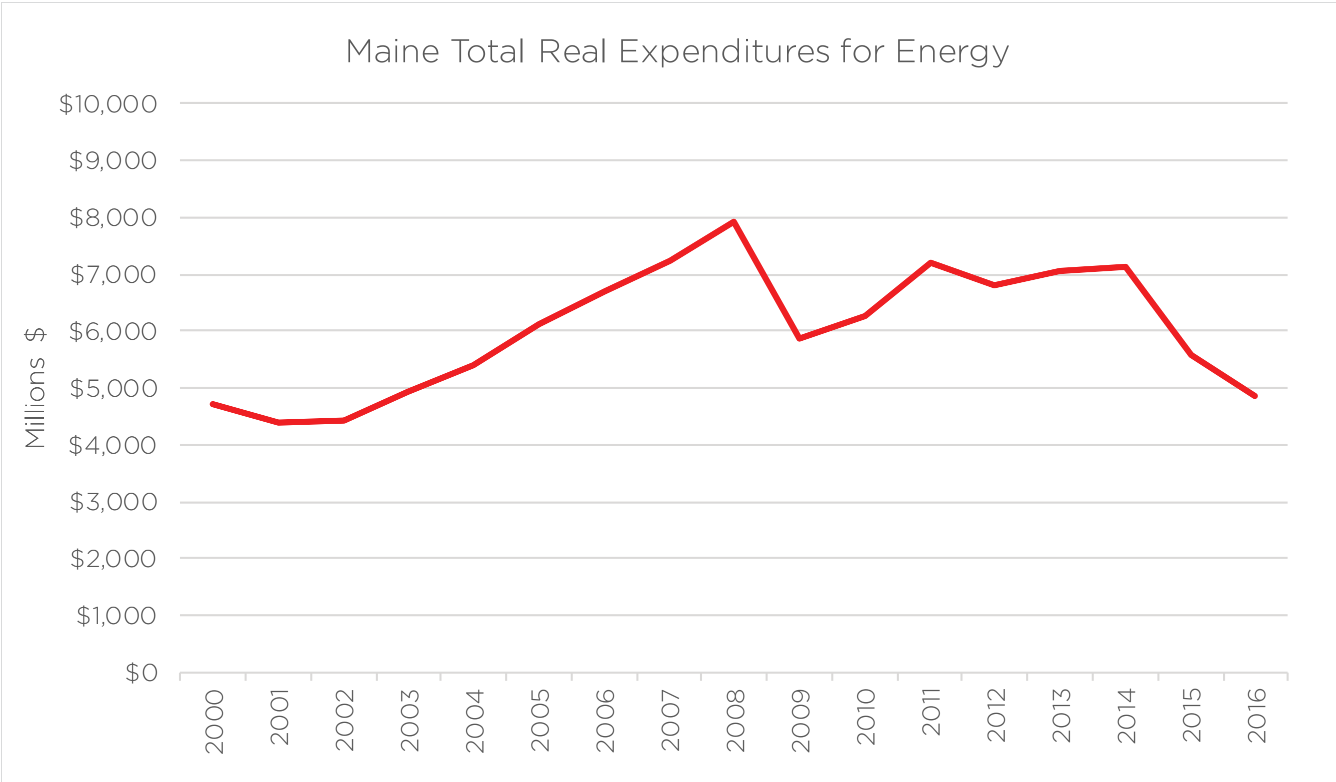
expect that diurnal storage requirements are much more important. This means that EV charging schedules will have a larger impact on the total amount of battery storage required to balance the grid.

TABLE 2-4 | Total Annual Energy Costs in Maine

	ECONOMIC SECTORS					
COMMODITY	RESIDENTIAL ($millions)	COMMERCIAL ($millions)	INDUSTRIAL ($millions)	TRANSPORTATION ($millions)	ELECTRIC ($millions)	TOTALS ($millions)
Aviation Gasoline	-	-	-	3	-	**3**
Asphalt & Road Oil	-	-	37	-	-	**37**
Coal	-	-	2	-	7	**9**
Distillate Fuel Oil	488	106	43	493	-	**1,130**
Electricity	726	482	258	-	-	**1,465**
Jet Fuel	-	-	-	68	-	**68**
Kerosene	26	3	-	-	-	**28**
Propane	158	88	4	1	-	**251**
Lubricants	-	-	15	51	-	**66**
Motor Gasoline	-	29	21	1.735	-	**1,786**
Natural Gas	36	91	146	7	72	**352**
Residual Fuel Oil	-	2	6	7	11	**27**
Wood & Waste	34	9	110	-	64	**218**
TOTALS	**1,466**	**810**	**643**	**2,366**	**155**	**5,440**

TOTAL ENERGY EXPENDITURES ($millions)	5,440
less Fuels Used in Electricity	(155)
less Wood & Wood Waste	(154)
less Jet Fuel, Asphalt & Road Oil, Lubricants	(174)
	4,958

FIGURE 2-14 | Total Annual Energy Expenditures from 2000 – 2016 (2016$)



*The above cost figures do not include expenditures for fuels used in generating electricity, wood and wood waste, jet fuel, asphalt and road oil and lubricants.

TABLE 2-5 | Cost and Financing Assumptions

	INSTALLED CAPACITY COST			FIXED O&M		
ASSET	**UNIT**	**2020**	**2050**	**UNIT**	**2020**	**2050**
Existing Hydro	($/kW)	$-	$-	($/MWh)	$20	$20
Solar PV	($/kW)	$1,500	$602	($kW/yr)	$10	$10
On-Shore Wind	($/kW)	$2,000	$2,000	($/MWh)	$10	$10
Off-Shore Wind	($/kW)	$4,000	$4,000	($/MWh)	$20	$20
Battery Storage	($/kWh)	$500	$41	($kW/yr)	$10	$10
Battery Storage- Round Trip Efficiency Losses					12.5%	12.5%

FINANCING COSTS			
Weighted Average Cost of Capital	3.0%	3.0%	
Financing Term (Years)	30	30	
Debt Service Cost per Million	$51,019	$51,019	
EFFECTIVE PROPERTY TAX RATE	$0	$0	(per thousand of valuation)

installed costs for all generation categories are financed through government using a 3% cost of debt, as this is the most cost-effective and tax efficient way to build out this very significant infrastructure. (I discuss this assumption in more detail in Chapter Four.) Since all generation will be owned by government, I have set property taxes equal to zero.[35]

I have assumed that the fixed and variable operating costs for each generation technology are constant in real terms over the entire 30-year transition period; that is, they change on average by an amount equal to the underlying rate of inflation in the economy. The costs shown in year 2020 for hydro, solar PV and on-shore wind are based on cost figures provided in the general literature, including studies performed by entities such as Lazard, the U.S. Department of Energy (EIA and NREL), Bloomberg New Energy Finance and the International Renewable Energy Agency (IRENA). The costs for off-shore wind are based on published reports of the Avangrid project selected in the Massachusetts solicitation.[36] The battery storage O&M costs are at reference prices of around $10/kW-yr. This figure has been quoted for daily cycling applications, where wear and tear and degradation factors are important considerations that need to be managed. In my model, most of the battery storage capacity is being used to address seasonal imbalances between renewable generation and electric load involving far fewer cycles over the course of the year. This should result in lower O&M costs. I have used the $10/kW-yr. figure to be conservative.

I have modeled the installed capital costs for each of the technologies differently. I have assumed that the installed costs of on-shore wind remain fixed in real terms over the transition period. I posit that any technological progress with respect to this technology is given up to cost increases in excess of the rate of inflation imposed by permitting authorities to mitigate environmental siting issues.

The assumptions I have made with respect to off-shore wind are different, even though the net result is the same. I assume that the installations during the early years in the transition period will be entirely shallow water projects similar to those proposed in the Massachusetts solicitation. I have modeled the installed cost of these projects at $4,000/kW. This is $500/kW higher than the installed costs for the Avangrid bid referenced above. Over time, as experience is gained with both shallow water and deep-water wind projects, I expect to see the installed costs fall as the technology matures and the support systems are built out to facilitate this type of generation. By holding the installed costs at $4,000/kW over the entire transition period, I am assuming that reductions in the costs of shallow water generation will offset the higher costs of the small quantity of deep-water generation brought on by the middle of the transition period. By the later years in the transition period, when a higher percentage of the off-shore wind is deep water generation, I expect the costs for this technology to fall to the $4,000/kW range.

I assume continued technological improvements in the solar PV and battery storage sectors that result in falling real costs over the transition period. I model the rate of technological progress for battery storage systems at 8% per year. This is approximately half the rate we have seen over the period 2010 to 2016 during which costs for lithium-ion batteries fell by just under 75%. I use a starting value of $500/kWh in 2020. This figure is conservative for storage systems that are being installed today in combination with solar PV or on-shore wind projects. The 8% figure over the transition period is consistent with a recent forecast of battery system by Bloomberg. Bloomberg is forecasting battery cell costs to fall to $74/kWh by 2030. Continuing this forecasted cost curve to 2050 results in a cell cost of $20/kWh. Since the battery cell represents about 50% of the costs of the

[35] This will certainly be true for off-shore wind, since it will be located outside of Maine's territorial waters and therefore not subject to municipal taxation. I present the case for exempting all other renewable resource generation projects from municipal property taxes in Chapter 5.

[36] Bank of America Merrill Lynch Analyst Report – Avangrid, issued October 4, 2018.

TABLE 2-6 | Energy Costs Under Beneficial Electrification

TOTAL LOAD/SOLAR+ ON & OFF-SHORE WINED + STORAGE/SCALED				
TYPE	**UNIT**	**TOTAL LOAD**	**% ENERGY**	**CAP FACTOR**
Load to Serve	MWh	40,279,909		
Hydro Generation	MWh	3,500,000	8.7%	
Solar Requirement	MW	2,930		
Solar Generation	MWh	5,918,608	14.4%	23.1%
On-Shore Wind Requirement	MW	3,500		
On-Shore Wind Generation MWh	MWh	13,046,246	31.6%	42.6%
Off-Shore Wind Capacity Requirement	MW	4,000		
Off-Shore Wind Generation	MWh	18,777,043	45.5%	53.6%
Maximum/Minimum Storage Deficit	MWh	1,872,881	173,562	

TOTAL COST							
TYPE	**UNIT**	**CARRYING COST**	**FIXED O&M**	**FUEL COSTS**	**PROPERTY TAXES**	**TOTAL**	**$/MWh**
Hydro	$million	-	$70	-	-	$70	$20
Solar PV	$million	$90	$29	-	-	$119	$20
On-Shore Wind	$million	$357	$130	-	-	$488	$37
Off-Shore Wind	$million	$816	$376	-	-	$1,192	$63
Storage Costs	$million	$3,916	$6,243	-	-	$10,159	
TOTAL COST	**$million**	**$5,197**	**$6,778**	**-**	**-**	**$12,028**	
	$/MWh	**$128.59**	**$168.28**	**-**	**-**	**$298.60**	

storage system, this would be about $150/MWh in 2030 and $40/kWh in 2050.[37]

Since solar PV is a more mature technology than battery storage, I assume a lower rate of technological progress for this technology at 3% per year. Starting at a 2020 installed cost of $1.50 per watt, this rate of cost decrease results in a cost of $0.602 per watt in 2020 dollars by 2050.

Table 2-6 provides details of the load, generation and costs for the third electricity generation scenario, which includes both on-shore and off-shore wind and solar. The table shows the amount of generation capacity and energy for each technology as well as their average capacity factors. It also shows the maximum storage surplus and minimum storage deficits required to balance the grid. The last column in the table shows the average costs of generation for each of the generation technologies utilized, expressed as $/MWh. The average costs for solar PV and on-shore wind are $20 and $37/MWh, respectively. These are consistent with where these industries appear headed by 2050, assuming continued technological advancements in each technology and low financing costs of 3%. The average cost of off-shore wind is in the range of the recent bids received by Massachusetts for shallow-water off-shore wind, but well above the costs for floating off-shore wind like the systems proposed by the University of Maine. However, even for floating off-shore wind, the $63/MWh value is within the 20-year

[37] See https://data.bloomberglp.com/bnef/sites/14/2017/07/BNEF-Lithium-ion-battery-costs-and-market.pdf

cost range forecasted by NREL, when a lower cost of capital is used.[38] The total debt service and operating costs in 2050 for these three technologies plus hydro, but not including storage costs is $1.87 billion a year. This is equal to $45.31/MWh.

These costs are only for the generation of electricity. They do not include the costs of transmission and distribution of the electricity - that is, what end-users must pay to the electric utilities for "delivery service". The current amount of such costs in Maine for CMP and Emera combined is roughly $780 million a year.[39] As noted earlier, the transmission and distribution grid will need to be expanded considerably to support the five-fold increase in peak loads under beneficial electrification. The grid expansion required is moderated somewhat, however, because these new higher peak loads occur during very cold weather conditions when the ratings for many of the transmission and distribution system components are much higher. Rather than a five-fold increase in system size, the net increase may be on the order of three and a half times the size of the grid today. Assuming the expansion is relatively linear with respect to costs, a 3.5x increase in costs for this much larger grid will cost Mainers about $2.8 billion a year in real terms by 2050. Therefore, the total cost of the generation components, not including the costs of battery storage, plus the total cost of the grid is about $4.67 billion. This is considerably less than the $6 billion Mainers have paid on average each year for all their energy requirements since 2000.

The problem is seasonal storage. Assuming the cost of battery storage falls to $41/kWh by 2050 (roughly one-twelfth of the cost today for a utility-scale fully installed facility), the 1.87 million MWh storage requirement represents an estimated cost of $76.8 billion. This has an annual revenue requirement of about $10.1 billion, when fixed O&M are included. The costs of storage alone are more than twice the combined costs of all other components of the electric system to meet the electricity requirements of beneficial electrification.

What can Maine do about this? First, I note that seasonal storage must be sized to meet the maximum cumulative difference between electric loads and generation over the course of a year. This creates an important diseconomy of scale. While the costs of battery storage systems are virtually linear as the amount of such storage increases (assuming raw materials are available at a relatively constant price), the utilization of the battery storage units decrease with scale. This is because the first storage units are cycled daily to meet diurnal loads and generation mismatches; the next set of units are cycled over a more limited set of two-to-three-day periods, for example, in response to weather conditions; the next set of units even less frequently; and the last set of units only once – when they are called upon to meet the hour of maximum deficit. Importantly, the last two sets of units represent the majority of the battery storage capacity. In effect, a technology that is very capital intensive is being used in an application with a very, very low annual load factor, and in the limit, to meet one hour out of the year's 8,760 hours. This is not a cost-effective solution. We need to focus on solutions with lower capital costs that can handle seasonal storage more effectively.

One option that has been discussed is to mirror how we now handle the seasonal storage requirements related to the use of natural gas to provide space heating. During the summer months, natural gas is injected into deep storage wells and withdrawn during the winter months to meet demands from heating loads. This is done very efficiently and at low cost. The same type of storage, withdrawals and pipeline systems could be developed for hydrogen. The hydrogen would be produced using the electricity that would otherwise have been put into battery storage. This hydrogen would be stored underground and released during the heating season to generate electricity through fuel cell technologies or

[38] See, for example, Musial, Walter (2018), "Offshore Wind Resource, Cost, and Economic Potential in the State of Maine, NREL/TP-5000-70907, February 2018, Table 4 at Page 11, https://www.nrel.gov/docs/fy18osti/70907.pdf

[39] My estimated breakdowns for CMP and Emera are – CMP transmission $340 million/distribution $280 million and Emera transmission $90 million/distribution $50 million.

simply burned to create space heating or meet industrial process requirements. While there are some technological hurdles that must be addressed to pipe hydrogen, this type of system is technically feasible. However, it would also be very expensive given the cost and efficiency of current electrolysis technologies to separate hydrogen from water molecules. It could, however, be considerably less expensive than the units of battery storage that are cycled once over the course of the year to meet seasonal requirements, since the electrolysis equipment would operate at a high annual load factor.[40]

A second alternative is to overbuild renewable generation in lieu of adding large amounts of battery storage. This will mean that some of the renewable generation will operate at levels below designed annual capacity factors. This may be a less expensive option if the cost of renewable generation capacity is sufficiently lower than the cost of battery storage.

I turn now to examine how overbuilding of generating capacity impacts storage requirements and total costs. In an overbuilt scenario, it is necessary to dispatch off some portion of generation to match annual load requirements. Once dispatch of generation is permitted, there are countless combinations of solar, on-shore wind, off-shore wind and battery storage that result in an annual matching of total generation with total loads. I look at one representative configuration in which I add an additional 1,000 MW of off-shore wind, reduce the on-shore wind capacity by 1,000 and increase solar to 7,500 MW. The results are shown in **Table 2-7**. This combination of generation would produce 11 million MWh more electricity than load if it is operated without dispatch at its full capacity factor, 1.1 million MWhs of which would meet the round-trip efficiency losses of the battery storage units.[41]

[40] It also has the secondary benefit of enabling renewable generation to be located far removed from load centers where environmental conditions are more favorable, yet not suffer the very high losses associated with the transmission of that electricity.

[41] This amount of excess energy potential represents a form of reserve on the system that can be called upon to meet outages of solar and wind generating units. The amount of reserve is approximately 25%.

To match generation with load each hour and over the course of the year, I need to dispatch off certain percentages of each generation type (except hydro) each month. I made adjustments to these monthly dispatch percentages on a trial-and-error basis until I reduced the total amount of storage required to below 250,000 MWh.

The overbuilt generating capacity costs more to support. Total annual costs increase from $1.87 billion to $2.07 billion a year, and the annual capacity factors fall to 20.5%, 32.0% and 40.0% for solar, on-shore wind and off-shore wind, respectively. This increases the average costs of generation from $45.31/MWh to $49.93/MWh.[42] However, reducing the output of the three generation types by different percentages during different months over the course of the year, results in meeting total electricity loads with far less battery storage.

This is shown in **Figure 2-15**. This is the same graph as **Figure 2-13** with the exception that a fourth-generation scenario (Hydro + Solar PV + Onshore Wind + Offshore Wind with Overbuild) is added that incorporates overbuilding. The amount of storage in this scenario falls from 1.8 million MWh to 230,000 MWh and shows virtually no seasonality. This results in a reduction in storage costs from $10 billion to $1.26 billion a year, bringing the total cost of supplying Maine's energy requirements with 100% zero carbon electricity to $6.13 billion, inclusive of the costs of storage and delivery service. This is very close to the $6 billion annual average total cost of energy in Maine since 2000.[43]

[42] To put this in perspective, ISO-NE reports that average costs (inclusive of energy, capacity and ancillary services) in New England were approximately $60/MWh over the 5-year period from 2012-2016.

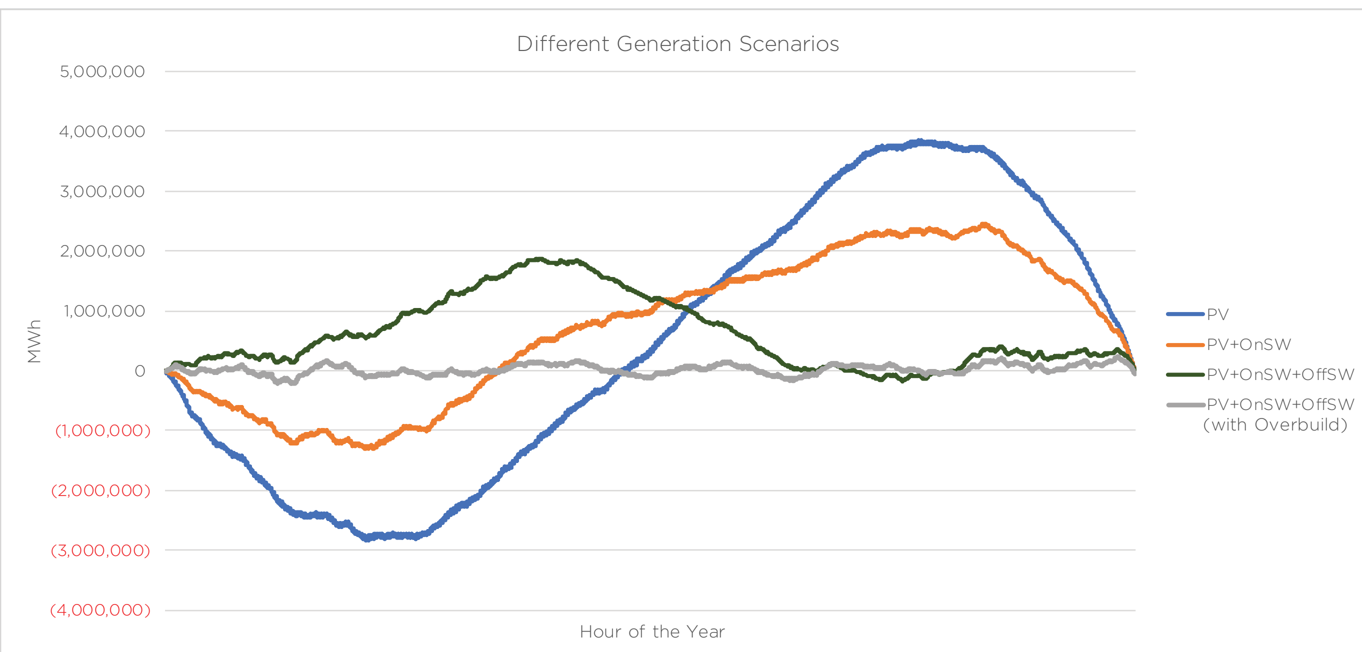
[43] This conclusion is consistent with similar findings in other studies. One example is a recent report issued by the Energy Watch Group. This study found that a global transition of the electric generation industry to 100% renewable electricity by 2050 is feasible, and that the total levelized cost of electricity (LCOE) in a global average for 100% renewable electricity in 2050 is 52 €/MWh (including curtailment, storage and some grid costs), compared to 70 €/MWh in 2015. Global Energy System Based on 100% Renewable Energy – Power Sector, LUT Lappeenranta University of Technology and Energy Watch Group, November 2017. http://energywatchgroup.org/wp-content/uploads/2017/11/Full-Study-100-Renewable-Energy-Worldwide-Power-Sector.pdf

TABLE 2-7 | Energy Costs Under Beneficial Electrification– Generation Overbuild Scenario

TOTAL LOAD/SOLAR+ ON & OFF-SHORE WINED + STORAGE/OVERVBUILD				
TYPE	**UNIT**	**TOTAL LOAD**	**% ENERGY**	**CAP FACTOR**
Load to Serve	MWh	40,279,909		
Hydro Generation	MWh	3,500,000	8.7%	
Solar Requirement	MW	7,500		
Solar Generation	MWh	13,456,815	32.4%	20.5%
On-Shore Wind Requirement	MW	2,500		
On-Shore Wind Generation MWh	MWh	7,003,334	16.9%	32.0%
Off-Shore Wind Capacity Requirement	MW	5,000		
Off-Shore Wind Generation	MWh	17,512,554	42.2%	40.0%
Maximum/Minimum Storage Deficit	MWh	232,254	222,854	

TOTAL COST							
TYPE	**UNIT**	**CARRYING COST**	**FIXED O&M**	**FUEL COSTS**	**PROPERTY TAXES**	**TOTAL**	**$/MWh**
Hydro	$million	-	$70	-	-	$70	$20
Solar PV	$million	$230	$75	-	-	$305	$23
On-Shore Wind	$million	$255	$70	-	-	$325	$46
Off-Shore Wind	$million	$1,020	$350	-	-	$1,371	$78
Storage Costs	$million	$486	$774	-	-	$1,260	
TOTAL COST	**$million**	**$1,991**	**$1,269**	**-**	**-**	**$3,331**	
	$/MWh	**$49.44**	**$31.52**	**-**	**-**	**$82.69**	

FIGURE 2-15 | Battery Storage Requirements (with overbuild)



Incurring an additional annual cost of $0.32 billion a year by overbuilding renewable generation, saves more than seven times that much in lower battery storage costs to meet seasonal electricity requirements. At this level of total storage, the amount required for diurnal cycling is now a large percent of total storage needs. This means that further reductions in storage might be possible by altering charging patterns for electric vehicles, by adopting other demand-side measures and by more finely-tuning the dispatch of renewable generation.

2.5 | Concluding Observations

The elimination of CO_2 emissions associated with energy use by Maine's households and businesses over the next 30 years through deep decarbonization and beneficial electrification across all sectors of Maine's economy is technologically possible. Advances to date and those that are likely to occur over the next three decades in heat pump technologies, electric vehicles, solar photovoltaic generation and wind turbine technologies make it possible to seriously consider a Maine without fossil fuels. Further, if we focus on only the amount of generation required to meet beneficial electrification and not the coincidence of that generation and electric load, it appears economically feasible to achieve this objective at a lower total cost than Mainers pay for energy each year, even after including the costs necessitated by expansion of the transmission and distribution networks to enable that generation to be delivered to all Maine households and businesses.

This is an astonishing conclusion – one that was unthinkable a decade ago. However, this conclusion must be moderated somewhat as the elimination of CO_2 from Maine's energy future through beneficial electrification and renewable energy generation must address the issue of electricity storage, and, specifically, the very large seasonal deficit that is caused by Maine's winter heating load. Given current battery storage technology and costs, it is prohibitively expensive to rely exclusively on batteries to provide the required seasonal storage. We need to look elsewhere. Hydrogen offers one potential option; however, it too suffers from high capital costs and conversion inefficiencies. A better option may be to simply overbuild renewable generation capacity. While this option adds capital costs to the energy sector, it provides a zero-carbon solution that is within politically and economically acceptable cost parameters. In addition, once the overbuilt capacity reduces seasonal storage requirements, it is possible to consider other additional strategies and incentives, such as demand-response, vehicle charging programs and other smart grid capabilities to reduce storage needs further. This could reduce further the total cost to meet Maine's total energy requirements to less than what it currently costs Maine to meet those same energy requirements using today's technologies and fuel mixes.

This chapter presents results only for the end state in 2050, where Maine has achieved deep decarbonization through beneficial electrification met with 100% renewable energy and battery storage. It does not include any consideration of the transition from today's energy situation to this end state. I turn to this issue in the next chapter.

Chapter 3

The Transition to a Carbon Free Energy Sector in Maine by 2050

3.0 | Introduction

In the previous chapter, my focus was on the end state – Maine's energy sector in 2050 – and specifically on whether Maine could achieve beneficial electrification, support it through deep decarbonization and do so at a reasonable cost. The answer to all three components is yes; such an end state in the year 2050 is technologically feasible and economically viable. In this chapter, I focus on the transition to that end state. Specifically, I examine how the conversion of the heating, industrial and commercial process and transportation sectors and the development of renewable generation resources and battery storage units can be accomplished over the 30-year transition period and at what costs to Maine residences and businesses.

At the outset, I need to emphasize that there are an infinite number of potential pathways along which Maine's energy sector can be transformed through beneficial electrification and deep decarbonization to an end state in 2050 where Maine is essentially carbon free. Each of these pathways would achieve both objectives of beneficial electrification and deep decarbonization by 2050 but might result in very different electric generation and energy use configurations each year until 2050. More importantly, each might do so under very different assumptions about the speed with which heating, process and transportation end uses convert to electricity and the speed with which zero carbon, renewable generation solar, on-shore and off-shore wind and battery storage are developed. These conversion rates, in turn, would have implications for capital investments, energy costs and CO_2 emission levels during the transition period.

That said, there are certain aspects of the various pathways that we know to be true. For example, the slower the electrical conversion and renewable generation development rates are during the early portion of the transition period, the faster they will need to be later during the transition period. On the other hand, the prices of energy during the transition, the costs of the investments necessary to accomplish the objectives of beneficial electrification and deep decarbonization and the costs to Maine residents and businesses each year from 2020 to 2050 will be a function of technological developments over this 30-year transition period. These, in turn, may themselves be determined by the rates of electrical conversion and renewable generation development in the United States and around the world, as these factors among others will drive the rate of innovation and technological development in this sector. Further, since Maine's electric grid is interconnected with the electric grids of the other New England states and eastern Canadian provinces, the speed of electrical conversions and renewable generation developments in these other states and provinces will impact electricity costs and CO_2 emission levels in Maine.

What this means is that there is no way to determine in 2019 an optimum pathway for the State of Maine to transition its entire energy sector from its state in 2020 to the desired end state of zero CO_2 emissions by 2050. While such an optimum pathway may be identifiable in hindsight from a vantage point in 2050, no such optimum can be found today. Instead, it is necessary to make a number of different assumptions regarding the rates of electric conversions for each energy end use, the rates at which renewable energy generation will be developed, the prices for various energy sources at their point of consumption and the costs of the different forms of renewable generation and battery storage over this thirty-year transition period. These and other related assumptions will determine a pathway. The reasonableness of that pathway will be determined by the plausibility of the assumptions that underlie it.

3.1 Electrical Converstion Rates

Beneficial electrification requires the conversion of end uses of energy from one or more fossil fuels to electricity. My focus is on the three end-uses in Maine that account for almost all energy use in Maine – space heating, commercial and industrial processes and transportation, not including marine vessels or airplanes.[44] **Figure 3-1** shows the assumed conversion rates for each of these end-uses, and within transportation for passenger vehicles, buses and trucks.

It is important to emphasize that these conversion rates are designed to be consistent with the achievement of 100% penetration of electricity in each of the end-use sectors by 2050. They are not necessarily what is likely to occur over the next thirty-years.

[44] I have omitted marine vessels and airplanes because the data on fuel use and the costs of conversions to electricity are unknown or highly uncertain. In any case, this represents a very small percentage of total fossil fuel use in Maine.

I have assumed that the conversion rates for each of the transportation sub-sectors follows a standard S-curve model for the adoption of new technologies, products or processes. This pattern begins with a relatively slow up-take over the first 10-years of the transition period, where adoption of each type of EV is primarily driven by a small set of the population for whom such adoption provides non-economic benefits. This early adoption period is followed by rapid conversion over the next 10 years, as the economics of EV ownership becomes more favorable, and EVs become the dominant vehicle type offered for sale. Finally, the last 10 years exhibit a slowing down of the conversion rate where laggards and more conservative consumers switch to EVs as these are the only vehicles available for purchase in the market. These conversion assumptions result in EVs representing approximately 50% of all vehicles on the road by 2040,[45] at which point much of Maine's rolling stock would have been replaced twice, based on the average age of Maine's passenger vehicles.[46]

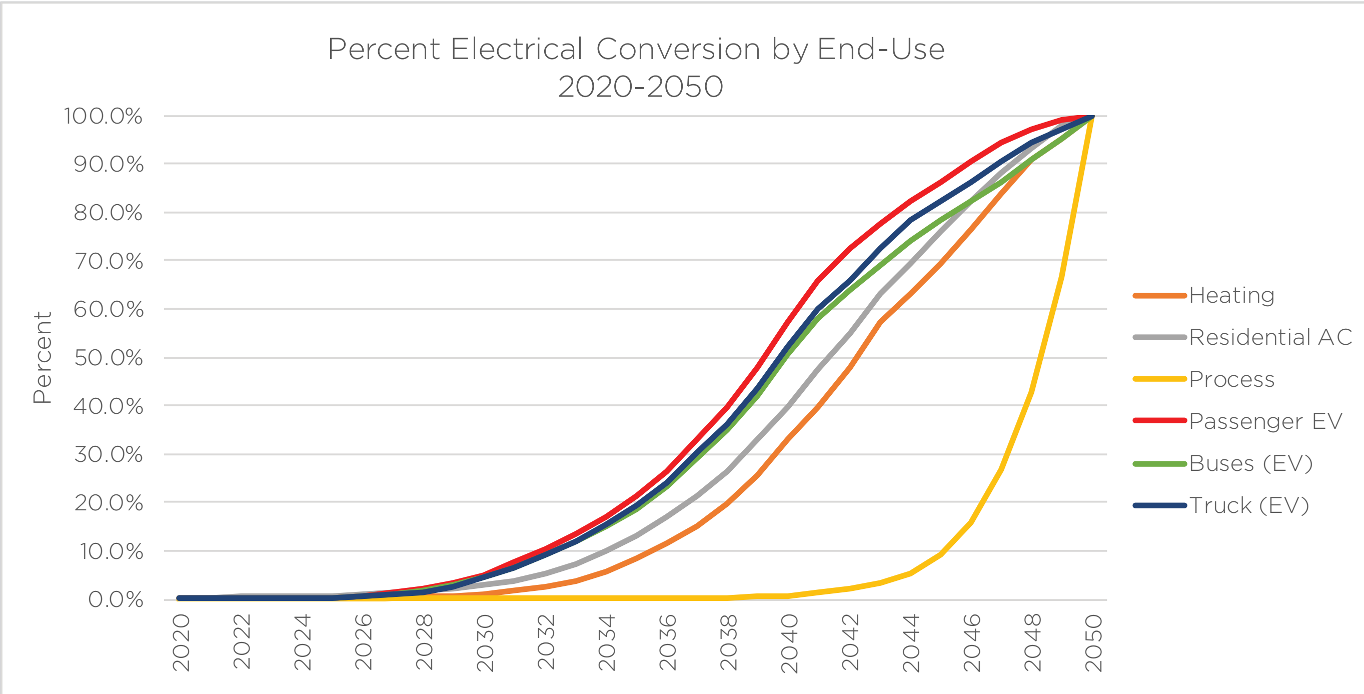
I assume that the percent of EVs among passenger vehicles is higher across the entire period than for buses and trucks, reflecting the likelihood that the conversions of passenger vehicles will be advantaged by government incentives of one form or another, e.g., rebates, charging station construction, favorable electric rates, to a more significant degree than trucks and buses. I assume that EV trucks and EV buses are adopted at essentially the same rate over the first 20-years, but that school districts, in particular, lag and need to catch up over the last 10 years.

Heating end uses include residential, commercial, industrial and institutional facilities, buildings and residences. Unlike passenger vehicles, trucks and buses, all of

[45] There are various estimates for how quickly EVs will be adopted in the U.S. and worldwide. One analysis by Bloomberg suggests that EV penetration will be 35% by 2040, while other studies indicate the number will be much higher. See, https://news.nationalgeographic.com/2017/09/electric-cars-replace-gasoline-engines-2040/

[46] The average age of passenger vehicles on the road in Maine is just over 11 years. See, https://autoalliance.org/in-your-state/ME/pdf/?export

FIGURE 3-1 | Rates of Electrical Conversion for Heating, Processes and Transportation



which have a relatively short-lived economic and physical lives, the life expectancy of heating equipment is much longer, often well-over 30 years if properly maintained. As a result, I do not believe we will see as rapid a conversion rate for this end use as for transportation. Early adoption will likely be confined in the residential sector to instances in which the customer must replace an existing system, is installing the conversion to capture its air conditioning benefits, or is receiving a subsidy from government, most likely through a program offered by Efficiency Maine Trust. I would expect to see early adopters in the other two sectors among those customers that are constructing new facilities, are replacing aging heating systems, or are trying to achieve corporate or institutional CO_2 emissions reduction targets. Accordingly, most of the adoption of technologies to convert space heating to electricity are anticipated to occur in the second half of the transition period.

Residential air conditioning does not represent a conversion from a fossil fuel to electricity, but rather it is an additional energy use that is incremental to energy use in Maine today. As noted in the previous chapter, I assume that approximately 75% of all Maine households lack either central air conditioning or window units, and that these households add central air conditioning as they adopt air source heat pumps. This results in a somewhat more rapid adoption curve than heating for two reasons. First, the residential sector represents about 80% of all heating loads in Maine. The slower adoption rates for ground-source heat pumps or other electric heating technologies in the commercial and industrial sectors slows the overall conversion process. Second, I assume that many of the early air-source heat pumps that are adopted for air conditioning reasons are used to provide heat as a secondary source, at least until the primary heat source needs to be updated or replaced. Together, these factors result in a more rapid rate of increase in electric loads to provide air conditioning than to provide heating.

Industrial and commercial process energy use is assumed to be the slowest end use to convert to electricity. The primary reason for this is that the economics of this conversion are likely to be much less attractive, because there are no major performance efficiencies that are being achieved, unlike with the transportation and heating end uses. Input fuel btus that are being supplied to create steam or other forms of process heat are being replaced by btus of electricity at a rate equal to 1 x the efficiency of the boilers or other heat producing equipment. Thus, if a boiler uses 100 mmbtu of fuel and is 80% efficient, the amount of electricity required to provide the same useful energy is 80 mmbtu. Therefore, I assume that most of this conversion will occur later in the transition period when more of the electricity generated is from renewable technologies, and electricity prices are more advantageous to higher load factor end users. This leads to a very steep conversion pattern, with most of the conversion occurring over the last 5 years of the transition period, perhaps as a result of government mandates or simply the inability to source fossil fuels as the economy-wide use of such fuels shrinks over the period. [47]

Electricity use for each of these end uses as well as current electricity use are shown in **Figure 3-2** for each year over the period 2020 to 2050. Current use is held flat over the period at just above 12,000 GWh a year. Each of the other end uses increases as the percentage of the end use that is converted to electricity increases as shown in **Figure 3-1** until each end use is at 100% conversion by 2050. At this point total electricity use in Maine is 40,280 GWh. The top graph shows the amount of energy each year associated with each of the end uses. The bottom graph shows the relative percentages of total annual electricity that each end use represents.

These graphs are specific to the conversion rates I have assumed. A different set of conversion rates over the 30-year transition period would produce different graphs. However, in each instance, the first and last years of the graph would look the same, since all conversion rate profiles would begin at 12,000 in 2020 and would result in the same amount of electricity use in year 2050. Accordingly, faster conversion rates would tend to flatten out the relevant area shown in the bottom graph, while slower conversion rates would create more of a wedge shape similar to that shown as Process in that graph.

3.2 Renewable Generation Development Rates

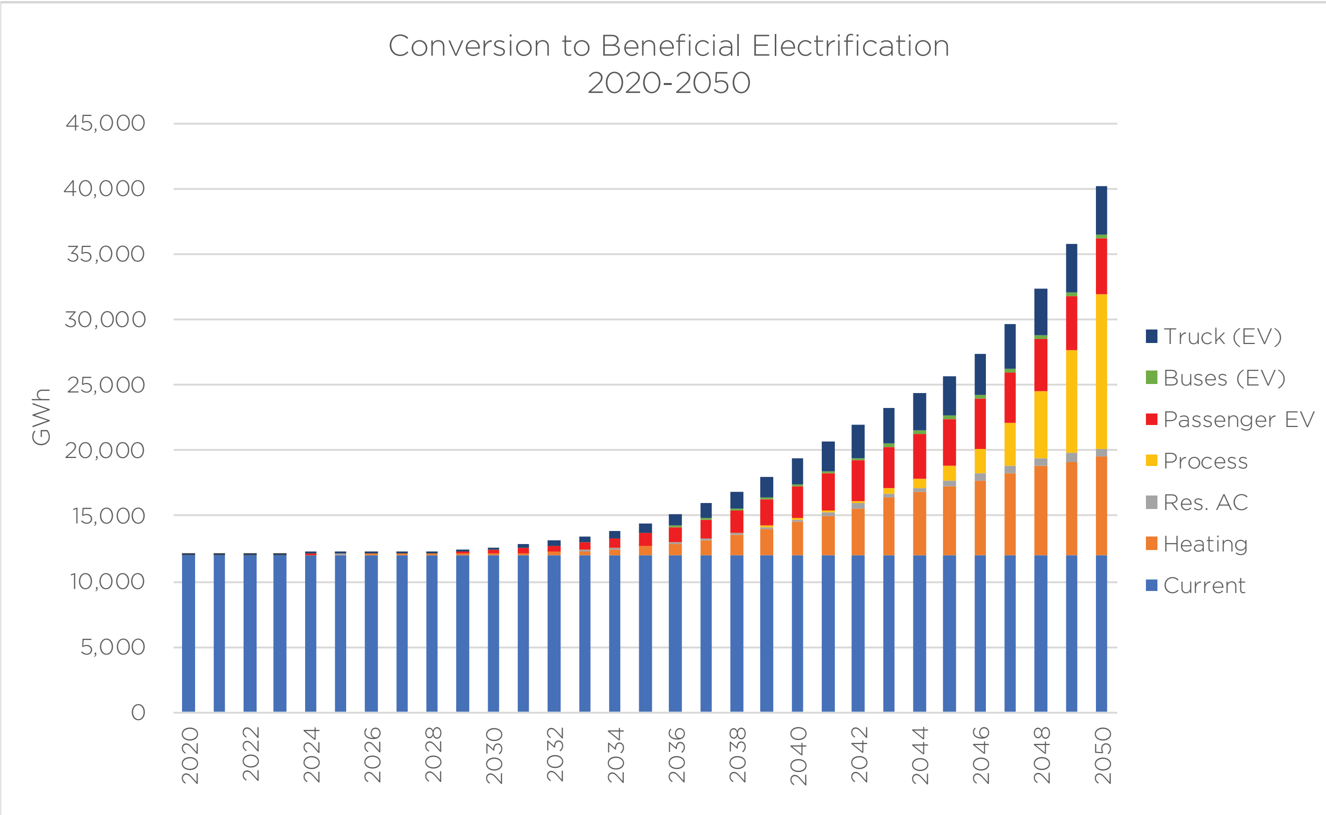
In the previous chapter, I identified four types of renewable generation that I believe are technically, economically and politically possible to generate electricity in Maine to meet beneficial electrification – hydro, solar, on-shore wind and off-shore wind. As discussed in the previous chapter, I have assumed that all existing hydroelectric generation will remain in place through 2050, and that no additional hydroelectric generation will be brought on line. The existing hydroelectric generation is roughly 3,500 million MWh a year. This represents just under 30% of current electricity use in Maine but only 8.7% of full beneficial electrification loads in 2050. In addition, I assume that no modifications in the regulation or use of seasonal and weekly hydro storage will be possible to accommodate different storage requirements of full decarbonization. [48]

For purposes of this transition analysis, I focus on the last of the generation scenarios described in the prior chapter, where electric loads are met with hydro, solar, on-shore and off-shore wind plus battery storage, and where the generation capacities are overbuilt to reduce the amount of battery storage required. The year 2050 capacities of solar, on-shore and off-shore wind are 7,500 MW, 2,500 MW and 5,000 MW, respectively. If operated at 100% of their nameplate capacities, these generation

[47] This may be an area where the secondary effects of beneficial electrification become important. Mandated conversion of industrial processes away from fossil-fuels may result in the heat-intensive manufacturing processes in Maine shutting down. If this were to happen, the transformation process would speed up, electricity loads would fall somewhat and the Maine economy would look more like the economies of New Hampshire and Massachusetts, as discussed in Chapter One.

[48] It may be attractive to forego draw-down from storage in the fall and early winter to maximize the draw-down from storage in January and February when battery storage is the most expensive per MWh. I do not attempt to model such changes in this analysis. In addition, it may be technically feasible and economically attractive to expand seasonal storage, but I do not believe that the environmental constraints on such additions can be surmounted.

FIGURE 3-2 | Rates of Electrical Conversion for Heating, Processes and Transportation



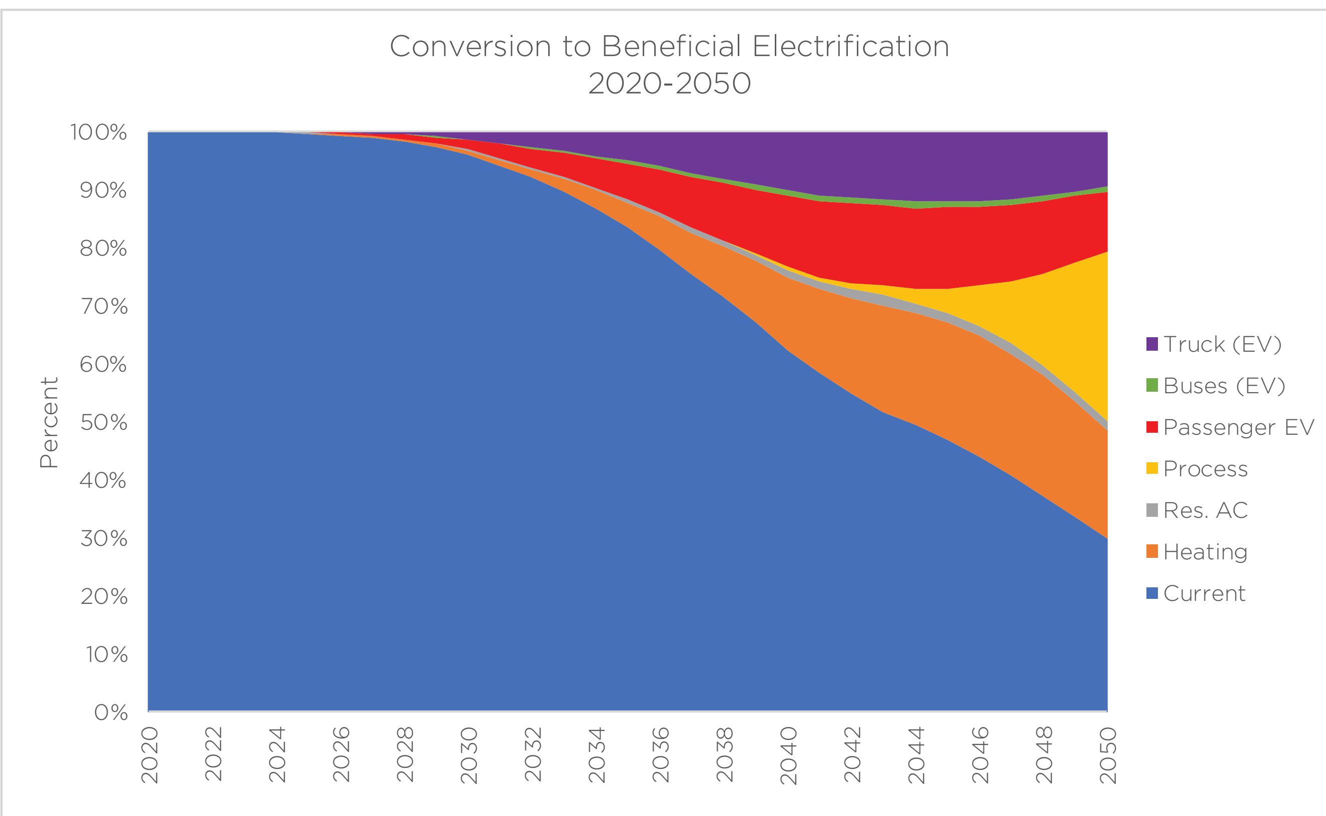
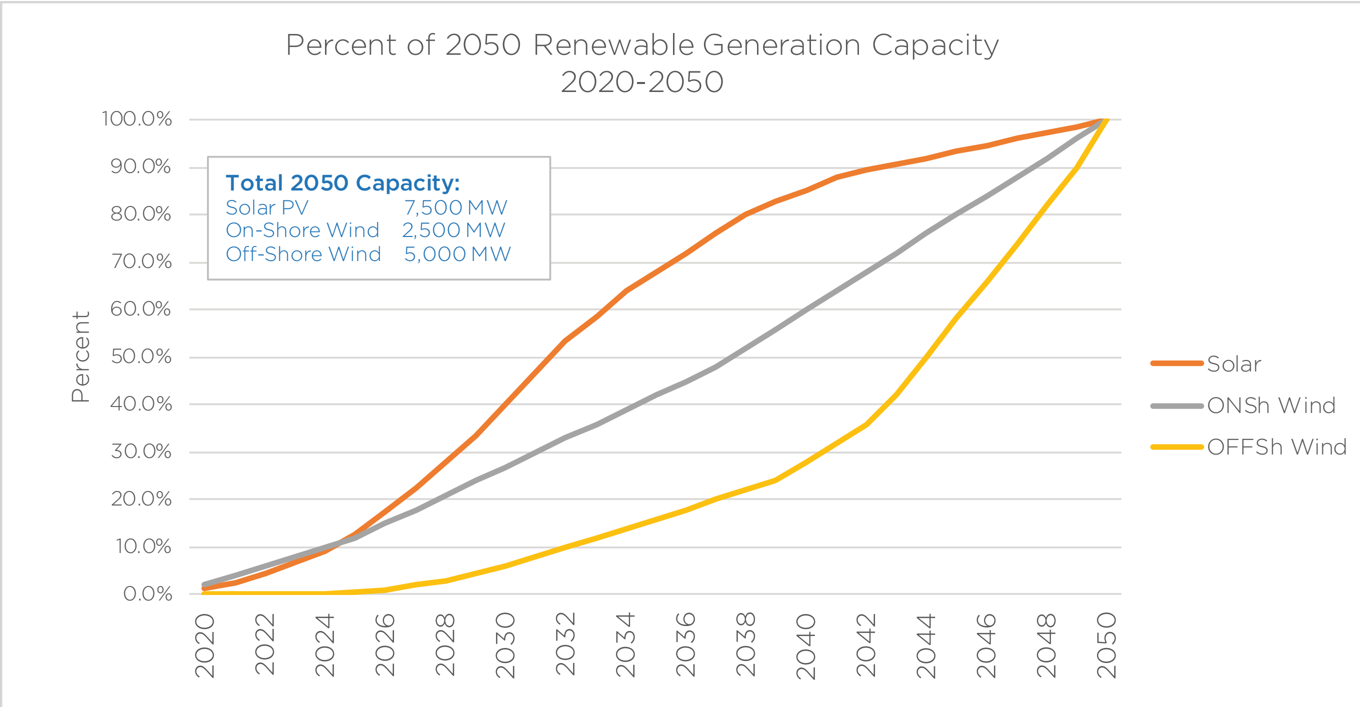


FIGURE 3-3 | Renewable Generation Development Rates



sources would produce approximately 11 million MWh more than Maine's 2050 load under beneficial electrification. Therefore, a percent of these generation resources will need to be dispatched off during certain hours of the year once the grid approaches full build out.[49]

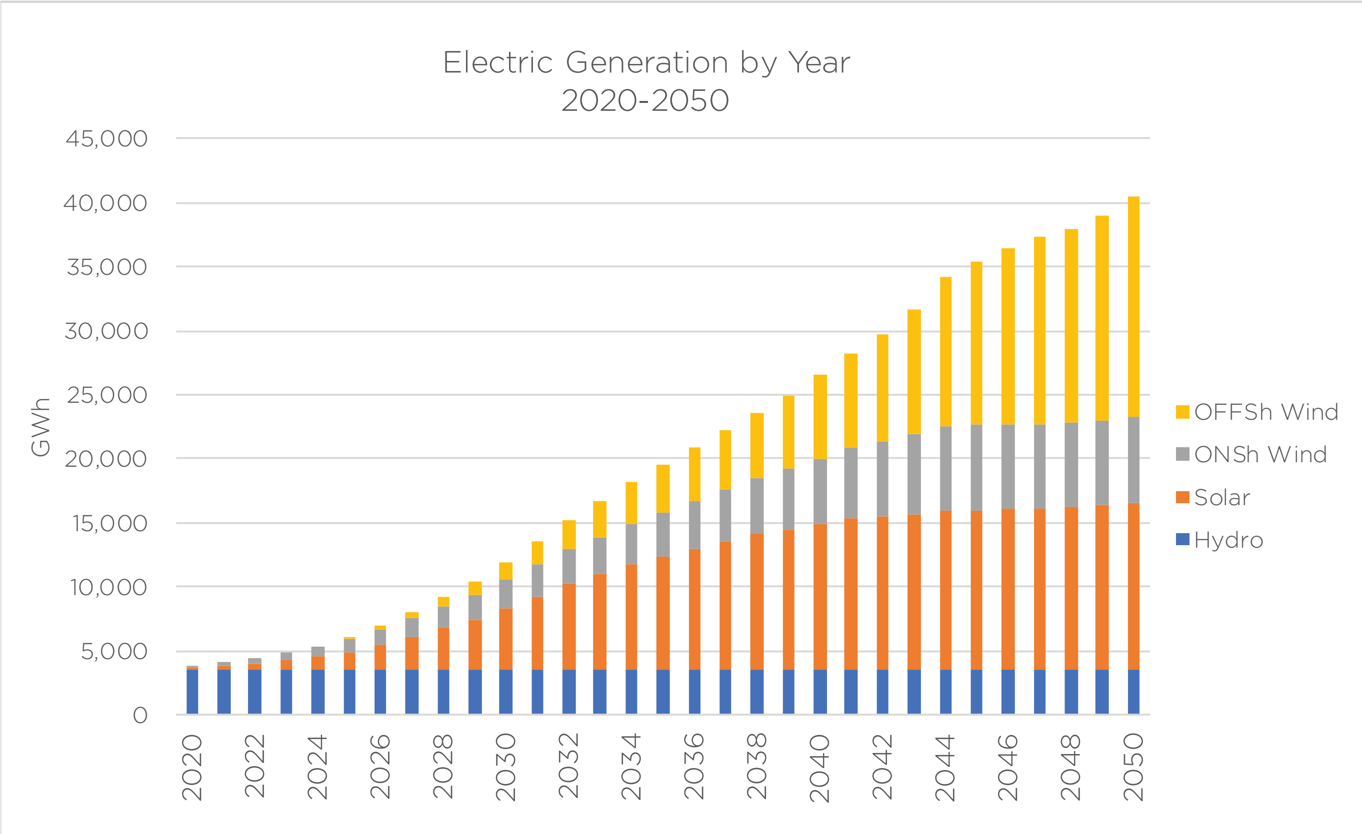
The generation development curves that I have modeled for solar, on-shore wind and off-shore wind are shown in **Figure 3-3**. I assume that on-shore wind capacity is developed almost linearly over this 30-year period. Even though Maine currently has close to 1,000 MW of installed on-shore wind generation capacity, I make the conservative assumption that this is replaced in its entirety over the transition period. Accordingly, the full amount of the 2,500 MW is developed over the 30-year transition period.

On the other hand, I assume that solar is developed more rapidly over the first two-thirds of the transition period, while off-shore wind is developed most rapidly over the last one-third. I have done this to account for two factors. First, I do not want to completely back-end generation development, as this would put significant financial pressures on Maine consumers to support the incremental capital requirements in the later years associated with such a development pattern. In addition, the IPCC Report and virtually every other scientific study emphasize the need to make consistent progress in reducing CO_2 emissions between now and 2050. While a pathway that back-end loads CO_2 reductions may be technically feasible, I do not think that such a delay will be politically acceptable, as it will result in higher atmospheric concentrations of CO_2 over the entire transition period and beyond.

Second, I assume that the early off-shore wind development will be shallow-water, but most of the 5,000 MW will be deep-water developments as opposed to shallow-water development, because the near shore, shallow-water locations are limited. Therefore, by delaying these projects until later in the transition period, I am able to capture technological advances and accompanying cost reductions in deep-water wind technology.

[49] A small amount of this surplus is used to offset the round-trip charging losses of 12.5% on the battery storage units.

FIGURE 3-4 | Renewable Generation Development Rates



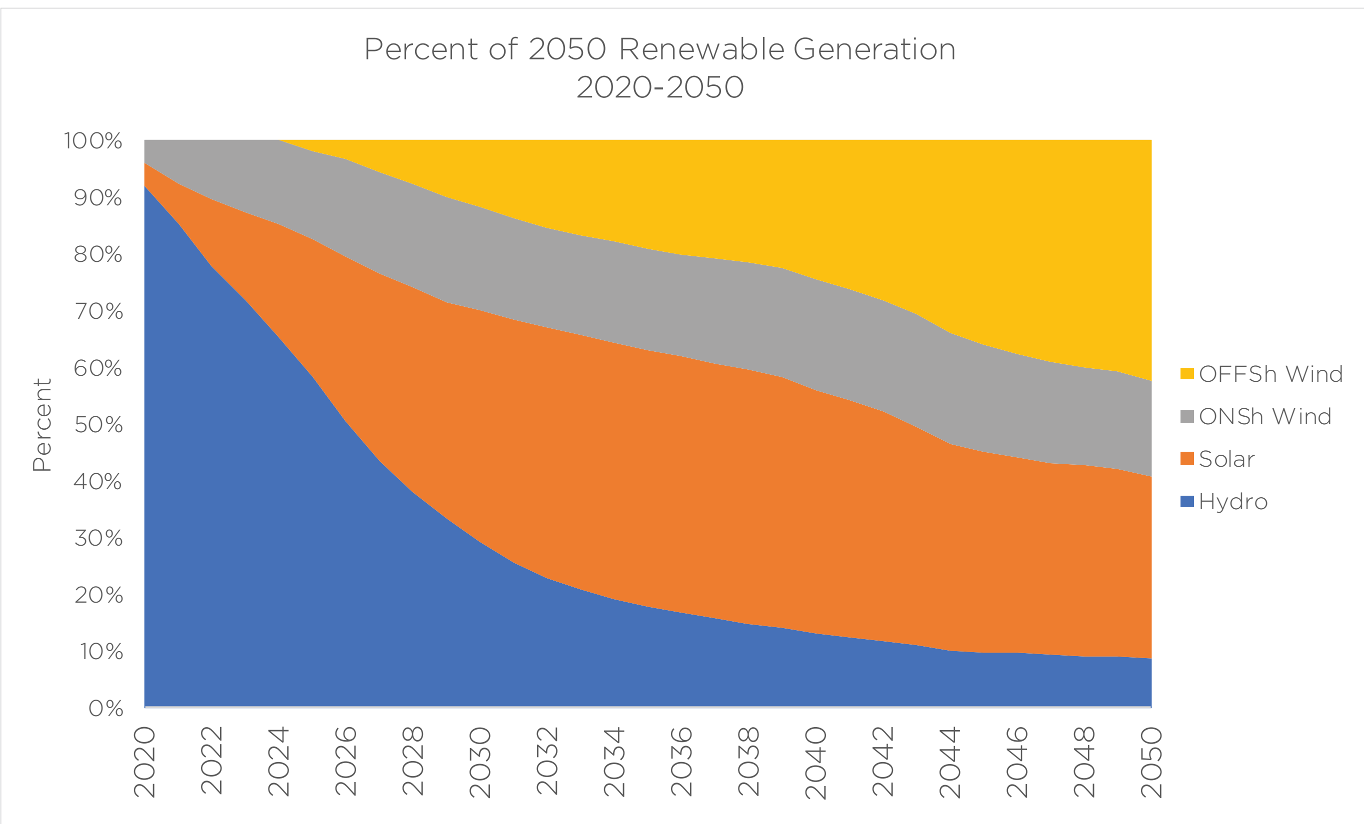
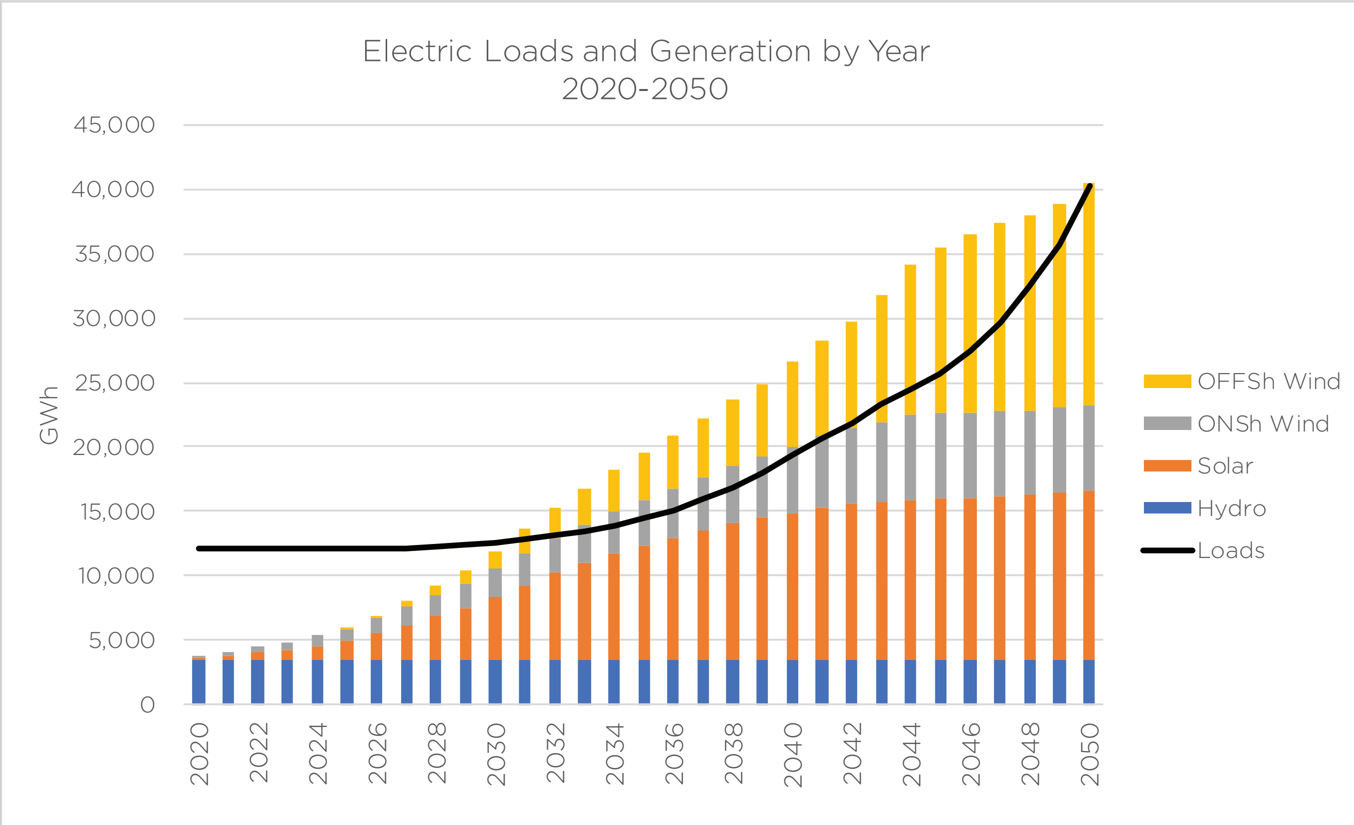


FIGURE 3-5 | Renewable Generation Development Rates and Electric Loads



The generation output of this renewable generation development pattern (including hydroelectric generation) is shown in **Figure 3-4**. The top graph in this exhibit shows the annual amount of generation by generation type, measured in GWh. The bottom graph shows the percentage of generation represented by each generation type during each year of the transition period. These graphs would be different for each generation development scenario, depending on the relative ratios of generation capacity in year 2050 and the total amount of battery storage required to balance the grid in that year.

Figure 3-5 is the same as the top graph in **Figure 3-4** with annual electricity loads superimposed on it. This graph shows renewable generation expanding more rapidly to catch up to loads over the first third of the transition period and continuing to expand more rapidly than load over the second third, albeit at a slower rate. I have assumed that all shortfalls in the early years of the transition period are made up by purchases of electricity from non-renewable generation resources located in Maine and the rest of New England.[50]

Beginning around 2030, Maine is generating more renewable electricity than it can use. I have assumed that this excess generation can be delivered to the grid and absorbed by other states or provinces through power flows over the grid. In the last third of the transition period, load increases much more rapidly as industrial and commercial process loads convert from fossil fuels to electricity. During this period, I have introduced annual dispatch factors to moderate total generation output

[50] It is possible that some of these purchases could be from renewable generation through, for example, the purchase of RECs. During the early years of the transition period, however, such REC purchases would almost certainly result in the transfer of environmental attributes from one location to Maine and would offer no net reduction in CO_2 emission benefits in the region. Accordingly, my modeling of CO_2 emissions makes this assumption; that is, I have assumed no net CO_2 emission reductions from meeting Maine electricity loads with any generation except renewable generation located in Maine.

so that it converges relatively smoothly to total load in 2050. One way to think about this surplus generation capacity, in addition to its beneficial effect on reducing battery storage requirements, is as capacity reserves that are available to offset generation outages.

3.3 Energy Prices & Capacity Costs

The previous two sections of this chapter have defined conversion rates for energy end uses and renewable generation development rates for three renewable generation technologies for each year over the transition period from 2020 to 2050. In this section, I change focus to look at the costs Mainers will incur for energy during each of these 30 years compared to Maine's current total expenditure on energy. Before I can do the calculations that underlie this comparison, I need to define prices for each form of energy and the costs for installing and operating each type of renewable generation technology. Once I have this information, I can calculate the annual amount Maine will spend on energy each year over the 2020 to 2050 period, based on the specific load and generation levels shown in **Figure 3-5**.

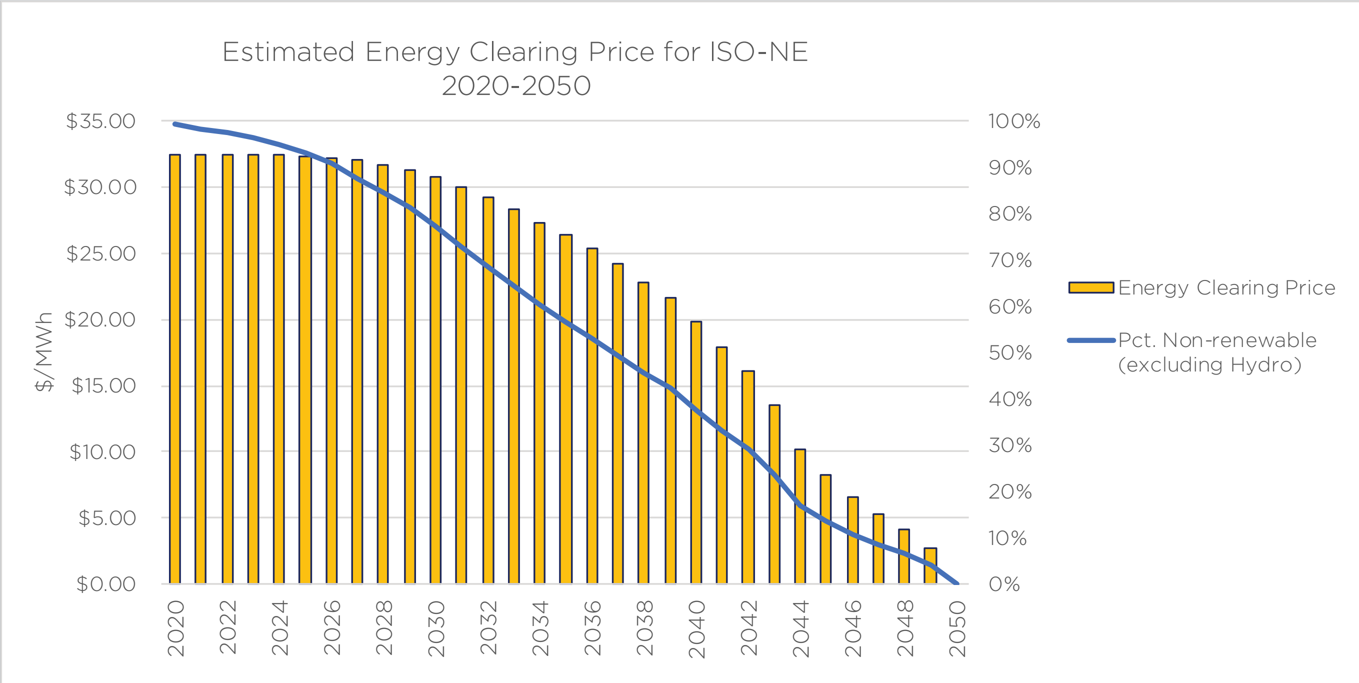
I begin with distillate fuel prices. As noted earlier, all prices are in real dollars. I assume that heating oil, diesel and gasoline prices delivered to the point of end use and net of any state or federal taxes are each $2.50 per gallon over the entire 30-year transition period. I have made a similar assumption that real natural gas prices remain flat over the transition period, except here I have included a seasonal component to reflect its use as a heating fuel. I have assumed that commodity prices are $2.75/mmbtu for serving year-round process loads but are a higher $3.00/mmbtu for serving heating loads. The comparable prices for New England basis are $2.00/mmbtu and $3.50/mmbtu, respectively; Maine basis prices (where applicable) are $1.00/mmbtu and $2.50/mmbtu, respectively; and delivery service rates are $3.00/mmbtu and $4.00/mmbtu, respectively. These price components result in annual average delivered natural gas price for process loads of $8.75/mmbtu and for heating loads of $13.00/mmbtu. I hold all distillate and natural gas prices constant in real dollars over the term. This assumption is generally consistent with U.S. EIA long-term forecasts that have fossil fuel prices increasing at close to the expected rate of inflation.

This assumption of constant real prices however, does not factor in any feedback loops that arise due to economy-wide or even world-wide decarbonization. All things being equal, one would expect electrification to lead to falling demand for fossil fuels, and this to result in falling real prices for distillate fuels and natural gas. On the other hand, as demand falls the utilization of fossil fuel drilling, processing and delivery capacity shrinks, which, again all things being equal, would lead to increasing prices. For example, it is hard to imagine that real prices of jet fuel can be sustained, where jet fuel is the only distillate fuel that is used across the U.S. economy. Similarly, at some point in the conversion of each end use to electricity, the remaining usage is likely to be too small to physically support the existing infrastructure related to its use without price increases, due to the fixed costs of the production, refining and delivery infrastructures. I do not know how these competing forces will impact prices over time. I make the simplifying assumption that these will offset each other and thus that real prices remain flat.

Estimating the price of electricity, however, does require taking into consideration feedback loops. We know from current experience that, as renewable generation increases as a percentage of total generation in New England, the energy clearing price falls,[51] and, in the limit where 100% of the generation is renewable with no fuel price or

[51] This relationship has been referred to as the price suppression effect and has been estimated most recently by London Economics International in its evaluation of the impact that CMP's NECEC transmission line to deliver up to 1,200 MW of Hydro Quebec energy to Massachusetts will have on energy clearing prices in ISO-NE. "Independent Analysis of Electricity Market and Macroeconomic Benefits of the New England Clean Energy Connect Project," London Economics International, LLC, prepared for the Maine Public Utilities Commission, May 21, 2018.

FIGURE 3-6 | Energy Clearing Price – 2020-2050



marginal generation cost, the energy clearing price will fall to zero. This does not mean that electricity will be free; it only means that the economically efficient price to charge for the use of an additional MWh of electricity at that time is zero. Consumers will still need to pay for the capital and fixed operating costs of any renewable generation resources developed, as I discuss later in this chapter.

To address the feedback relationship between prices and renewable generation resource penetration rates, I make the simplifying assumption that the average annual clearing price of electricity in New England (including Maine) will fall in proportion to the percentage of renewable generation compared to total generation on the grid, although less rapidly. The impact of renewable generation on market clearing prices is assumed non-linear – the larger the percentage of renewable generation (that is, the smaller the percentage of non-renewable generation), the more downward pressure this generation will exert on market clearing prices for energy. The result is shown in **Figure 3-6**. As the percentage of non-renewable generation falls from 100% to 0%, the average annual electricity price falls because the number of hours that a marginal unit natural gas plant must operate to serve load falls each year as the amount of renewable generation capacity is developed and delivers electricity to the grid. This reduces the average annual implicit heat rate, and assuming constant real prices for natural gas, reduces the average clearing price.

Figure 3-6 shows the estimated average clearing price to meet a flat annual load, what is sometimes referred to as a 24x7 block of energy. Since the price of natural gas is higher in the winter, the energy clearing price will also be high in the winter. Therefore, the average price of electricity to meet heating loads will be higher than to power the transportation sector or to meet process requirements. I assume that this heating load premium is 100%. No other adjustments are made for any of the other end uses.

It is not just the clearing price of electricity that is impacted by the development of renewable generation. The market price at which the electric output of renewable generation can be sold is also impacted. As more and more of each form of renewable energy is developed, the clearing price at which the output of these different forms of renewable energy can command in the market will fall, and in the limit, when there is not enough load to absorb the full amount of such output, the price will fall to zero. [52] I have computed the generation weighted price for each of the different forms of renewable generation. This is the average price at which the energy output can be sold in the market. I do this by assuming that this price falls in proportion to the amount of such generation that is developed and reaches zero when that form of generation is dispatched down. I set this zero-price point to occur in 2041 for solar, 2043 for on-shore wind and 2045 for off-shore wind.

The capacity and fixed operating costs for each of the renewable generation types for years 2020 and 2050 are shown in the previous chapter in **Table 2-5**. I have assumed that the fixed operating costs in real dollars are constant over the entire 30-year transition period; that is, they change on average by an amount equal to the underlying rate of inflation in the economy. I have made this same assumption for the installed costs of on-shore wind. This means that any technological progress with respect to this technology is given up to cost increases in excess of the rate of inflation for such considerations as environmental siting issues, and because the best wind locations are likely to be developed first.

The assumption with respect to off-shore wind is different. As noted above, I assume that the early capacities developed are shallow-water monopole installations and that in the later years of the transition period, more of the capacity is floating deep-water. The changing composition of the technology from shallow water installations in the early years to deep water installations in the later years, enables deep water technology to mature, thus lowering its costs. While deep water wind is initially more expensive than shallow water wind, there is effectively no limit on the availability of sites and thus no offset to the long-term decline in price as discussed above for land-based wind.

Finally, I assume that continuing technological progress in both solar and battery storage result in falling real costs for each technology over this period. I assume the rates of technological progress for these two technologies are 3% and 8%, respectively, reflecting the fact that battery storage is a much newer product with the opportunity for more rapid advancements. These assumptions result in falling real installed costs for solar from $1,500/kW in 2020 to $600/kW by 2050, and for battery storage from $500/kWh to $40/kWh over the same period as noted in the prior chapter.

3.4 | Total Energy Costs

We now have in place the building blocks for calculating the total costs Mainers will incur for all their energy use each year from 2020 to 2050. These costs can be broken down into the following six components:

- **Fossil Fuel Costs** These costs include the costs of all fossil fuels used to provide heating (natural gas and heating oil), industrial and commercial processes (natural gas and heating oil) and transportation (gasoline and diesel). Since the amount of fossil fuel use will decrease over this period and the real cost of such fuels is assumed constant, this cost component will fall over the transition period and will equal zero in 2050.
- **Electricity Delivery Service Costs** These costs represent the revenue requirement of the electric utilities that provide electric service across the entire State of Maine. These costs grow in direct proportion to the expansion of the distribution and transmission grid necessary to support both beneficial electrification and the development of renewable generation resources. Electric Delivery Service costs are set at $780 million in 2020 and 3.5 times that level, or $2.8 billion, in 2050.

[52] In fact, prices could turn negative as occasionally occurs during low load/high renewable generation output hours in New England. One reason this occurs is that renewable generation receives REC revenues and/or production tax credits today. Since I am not using either a Renewable Portfolio Standard or RECs, and do not include any tax incentives to support the pathway, I ignore this possibility in the modeling.

- **Electricity Supply Costs** These are the costs of the non-renewable electricity used by Mainers to meet their current electric usage plus incremental electric usage associated with the conversion of heating, process and transportation to electricity. They are calculated as the product of total MWh use times the price per MWh for energy, then grossed by 30% to include ancillary services and capacity costs.[53]

- **Renewable Generation Resources Costs** These costs represent the revenues necessary to support the development and ongoing operation of all the renewable generation resources brought on line to meet electricity load requirements. They include financing and fixed O&M costs.

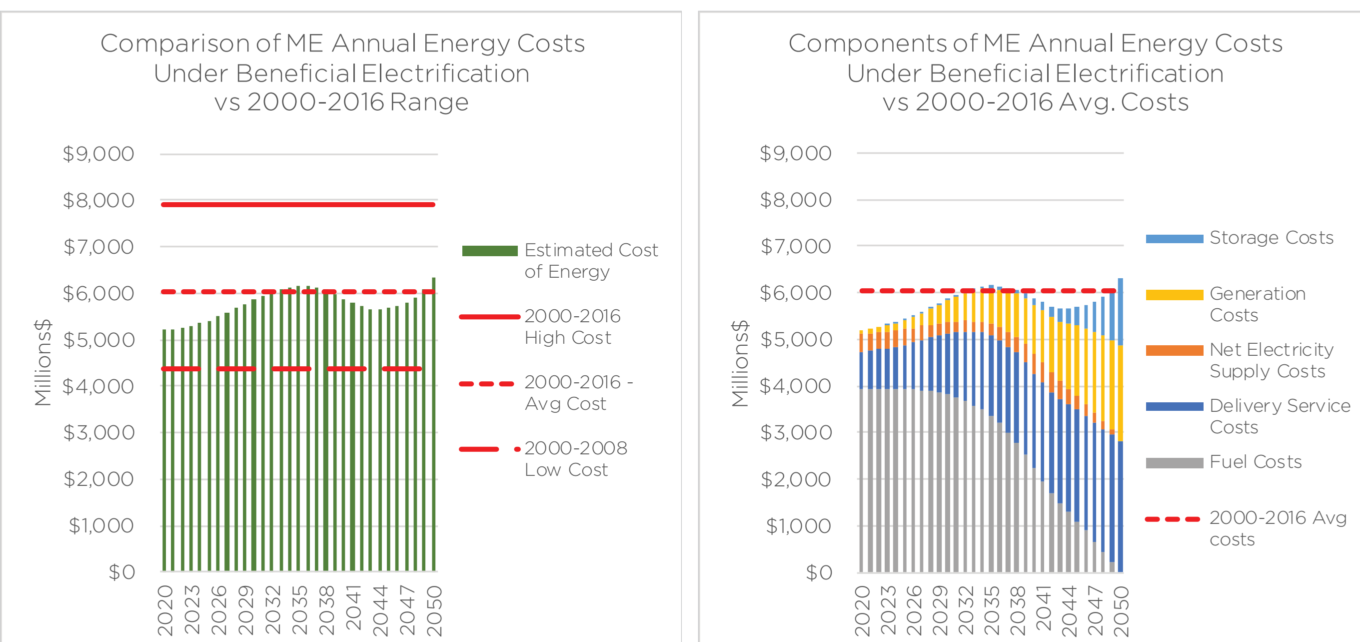
[53] The usage levels include transmission and distribution losses. Therefore, losses are not included in the 30% figure. It is possible that the 30% figure increases over the transition period (a) to offset revenue losses related to falling energy prices due to the price suppression effects of increased renewable generation and (b) an increase in ancillary service requirements associated with ensuring grid stability and reliability as the percentage of intermittent renewable energy generation increases. These factors would be likely but for the fact that the capital costs of the new renewable generation and battery storage systems (that can provide grid stability and reliability) is assumed to be covered through a non-market revenue stream, as I discuss in more detail in Chapter Four.

- **Storage Costs** These costs represent the revenues necessary to support the development and ongoing operation of all the battery storage resources brought on line to meet electricity load requirements. As with renewable generation source costs, these include financing and fixed O&M costs.

- **Value of Generation** These are negative costs that represent the value of all electricity generated by the renewable generating resources at their respective generation weighted prices per MWh that is not used by Mainers. I have assumed that these resources do not provide any capacity or ancillary services value. The only revenues they receive are from the sale of generation output into the energy market. This revenue stream represents an offset against electricity supply costs, but it is broken out and treated separately for exposition purposes. I have treated it as an offset in all the exhibits and refer to electricity supply costs as "net."

These cost components are shown in **Figure 3-7**. The graph on the left shows the estimated total annual energy expenditures for Maine each year over the 2020 – 2050 transition period. Also

FIGURE 3-7 | Total Annual Maine Energy Costs by Component



shown in red horizontal lines are the highest, average and lowest total annual expenditures for energy in Maine during the period 2000 through 2016. In each year of the transition, total expenditures are estimated to be less than or incrementally above the average annual amount spent in Maine on energy since 2000.

The graph on the right shows the estimated total annual energy expenditures broken down by expenditure category. Fossil fuel costs, shown in gray, fall as a share of total costs as the conversion of heating, process and transportation from natural gas and distillate fuels to electricity occurs. At the same time, the total costs of electricity increase, since more electricity is being used by Mainers. The largest component of electricity costs are utility delivery service costs that increase to support the 3.5-fold increase in the total size of the grid. With respect to the supply of electricity, the graph shows the substitution of capital costs tied to the development of renewable generation resources for fuel costs related to the marginal cost of energy. The result is that net electricity supply costs fall to zero, while the fixed costs of renewable energy resource generation capacity increase significantly. Finally, the graph shows the costs of battery storage in the later years that are necessary to balance the grid seasonally over the course of the year.

The excess, along with very significant battery storage resources, is assumed to provide the capacity reserves and ancillary service requirements to operate the electric grid. Since each generating unit is so small relative to the total capacity of the grid, reserve margins should be very small for this type of system. While the intermittent nature of renewable generation will likely impose higher ancillary service requirements, the total capacity of the battery storage systems installed dwarfs even these higher ancillary service capacity requirements.

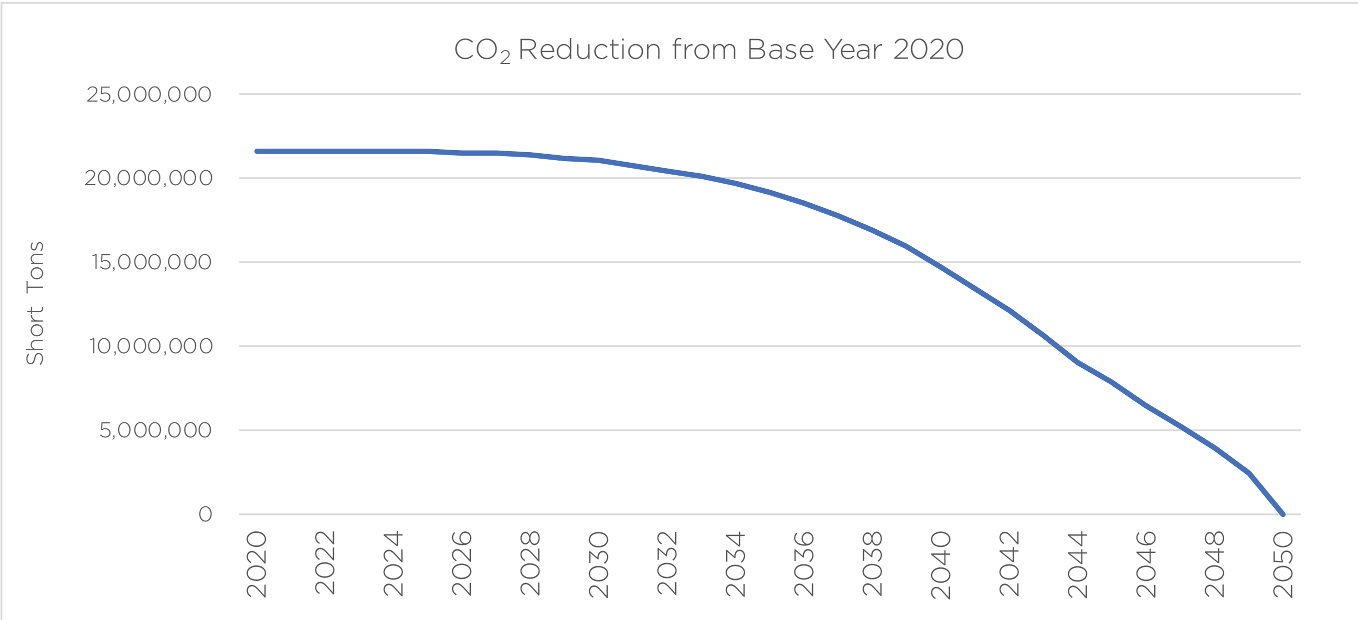
The most compelling result of **Figure 3-7** is that the total annual costs incurred by Mainers for all their energy requirements under the transition are very similar to the amount Mainers have paid on average for the same amount of energy since 2000. Further, having achieved a zero-carbon state by 2050, ongoing costs beyond 2050 should remain relatively flat in real terms as new generating plant, battery storage units and delivery service facilities are brought on-line to replace those that have exceeded their useful physical lives. Without any fuel costs, total cost volatility in Maine's energy sector is reduced considerably.

The environmental benefits from this transition are profound. **Figure 3-8** shows annual CO_2 emissions each year from 2020 through 2050. This graph shows that emissions fall each year, but that the rate of decline over the first 10 years is below that over the next 20 years. During the transition period, the combination of beneficial electrification and deep decarbonization reduces CO_2 emissions to zero by 2050, accomplished, as noted above, without burdening Maine residents or businesses with higher energy costs.

A second noteworthy result is that the composition of total energy costs in 2020 is very different from that in 2050. At the beginning of this period, approximately 75% of Maine's energy costs are fuel costs. By the end of the period, there are no fuel costs – virtually all of Maine's energy costs reflect carrying costs associated with major capital investments in the electric grid, renewable generation resources and battery storage units. The transition of Maine's energy sector to zero carbon is best characterized as a substitution of capital investments for fuel and related operating costs.

While the underlying electric loads and transmission and distribution grid structures and costs in this analysis are specific to Maine, there is no obvious reason why the above two conclusions would not be applicable outside of Maine. Some regions will have greater opportunities with respect to the development of solar, on-shore wind and/or off-shore wind; some regions may be better positioned to develop other zero-emission renewable energy opportunities such as new hydroelectric, geothermal and ocean-based resources; some regions will have greater electric load density (e.g., New York City) that may require more in-bound transmission to move electricity

FIGURE 3-8 | Cumulative Percentage Reductions in CO_2 Emissions

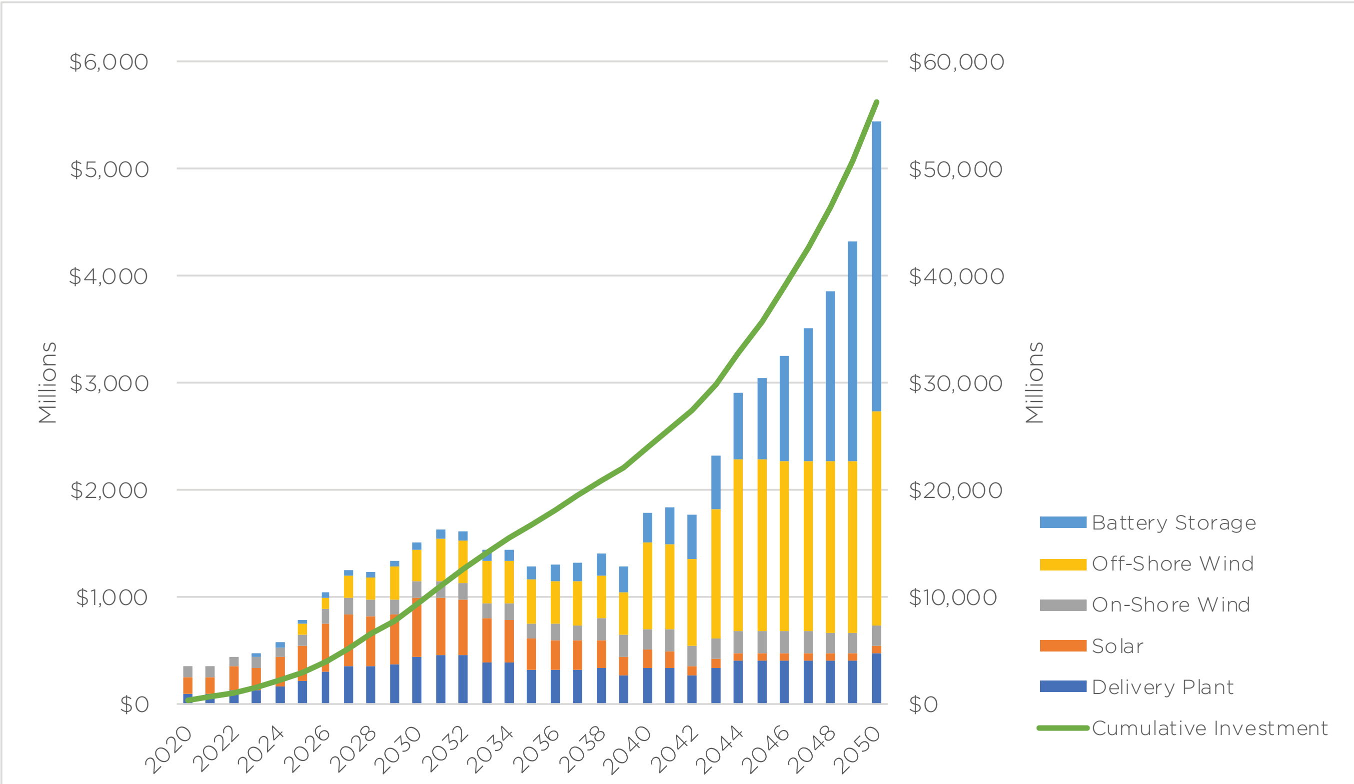


from generation to loads; some regions that are more temperate and even tropical will have less heating loads relative to total energy consumption, thus reducing the need for seasonal storage. However, in all cases, the basic principles apply. Beneficial electrification and deep decarbonization will reduce total primary energy use, will require the development of zero-emission renewable generation, will necessitate the build-out of the transmission and distribution grid and the conversion of that grid into a network capable of supporting multi-directional electricity flows, and will require huge capital inflows into the sector, as capital is substituted for fuel and operating costs.

Figure 3-9 shows the annual investments in Maine's energy sector that are required to achieve a transition to zero-carbon emissions in Maine by 2050 along the pathway laid out. The investment amounts are in real dollars and include only investments in energy related equipment and facilities. They do not include any investments by the customer to enable beneficial electrification. In particular, they do not include any end-use conversion costs. For many of the end uses, the conversion will be gradual and occur as existing technology or equipment needs replacement over the next 30 years. In this case the conversion costs to the end-user will be zero or very small. This is certainly the case for transportation, as Maine's entire transportation fleet will be replaced at some point (and perhaps at multiple points) over this period. It is probably also true for much of the process conversions as older technologies are superseded by newer ones forcing companies to modernize to remain competitive. It is more problematic, however, with heating and especially residential heating, where systems and equipment have longer lives. The conversion of all such systems to electric will undoubtedly impose additional costs on some end-users, depending on the price and availability of natural gas and heating oil as less and less of each fuel is burned in Maine.

Annual investments exceed $1 billion a year beginning in year 6 of the transition, driven primarily by increases in solar and on-shore wind generation and by expansion of the electric grid. By 2040, annual investments begin to accelerate as increasing amounts of off-shore wind and battery storage are brought on line. These investments reach $6 billion a year by the end of the transition period. Total investment in this sector over the entire 30-year period is $56 billion. This is a little

FIGURE 3-9 | Annual Investment and Total Capital Requirements to Achieve Zero CO_2 Emissions



below Maine's total personal income today.[54] This means that Maine can accomplish the conversion of its economy to a zero-carbon economy over the 30-year period from 2020 – 2050 by investing roughly 3.3% of its total annual income each year in this effort.

An investment of 3.3% of total personal income each year may not seem like a difficult accomplishment, until it is put into perspective. The average annual amount of about $2 billion a year is more than twice the amount of money that has been invested in all new (single family homes, apartments and condos) housing in Maine each year during each of the last ten years. Viewed through a different lens, the total capital requirements of $56 billion dwarf the State's current debt obligations of just under $10 billion. Raising the necessary capital will not be easy. However, as shown in **Figure 3-7**, the debt service on such an enormous investment will not impose a financial burden on Maine's businesses and residences. That chart shows that the total energy cost to Maine is essentially unchanged from what it is today. Further, an argument can be made that on balance Maine's economy will be better off, because a portion of the dollars that now flow out of Maine on expenditures for fuel will remain in the state in the form of construction and ongoing operating activities related to the renewable generation resources.[55]

Figure 3-9 shows investments increasing as Maine approaches 2050. It is important to note that this increase in investment is to achieve a zero-carbon state by 2050. At that time, the

[54] The Federal Reserve Bank of St. Louis reports Maine's seasonally adjusted annual personal income in 2017 as just over $60 billion. https://fred.stlouisfed.org/series/MEOTOT. Also http://www.bea.gov/system/files/2018-08/spi0618.pdf

[55] The balance of payments effects of this transition will depend to a large degree on whether Maine is able to develop the equipment manufacturing capabilities for solar PV, wind and battery storage. I do not see this as likely for solar PV or battery storage. There is some possibility that this could occur with respect to off-shore wind in light of the University of Maine's technology lead and companies like Cianbro and BIW with strong maritime engineering capacities.

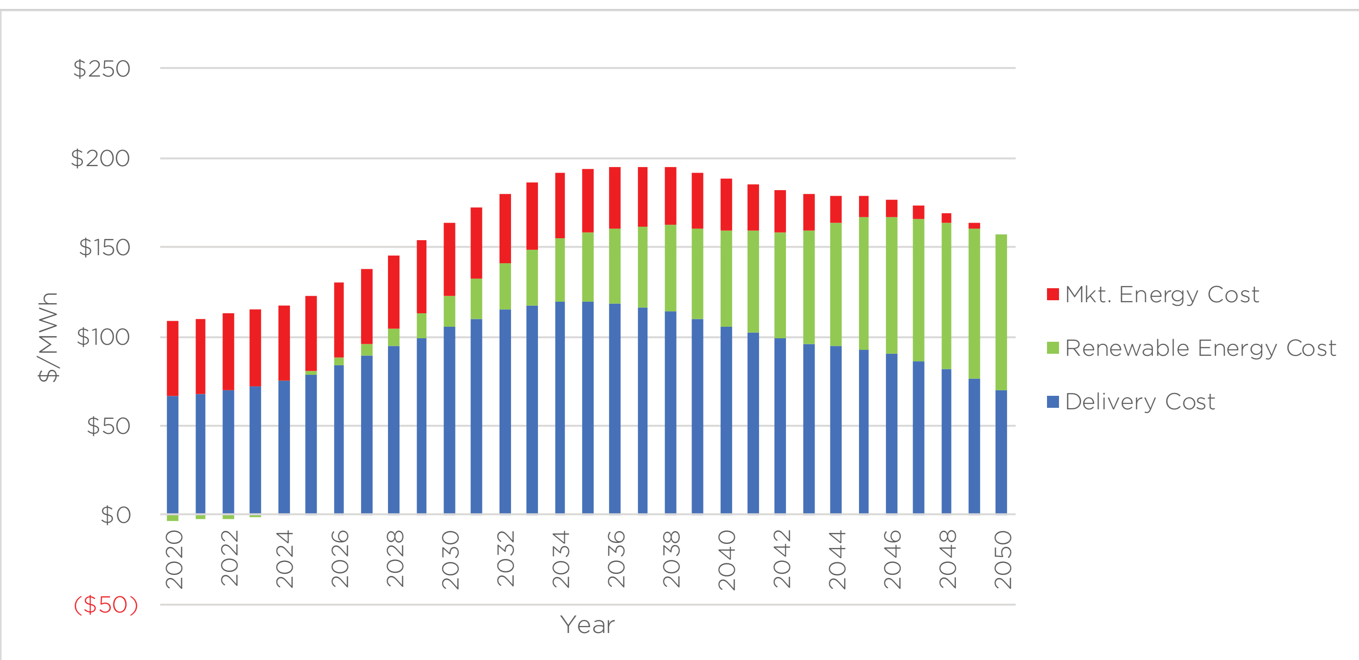
total amount invested in generation plant and battery storage systems will be $56 billion. On a going forward basis, new investments will accommodate growth in overall energy demands and will replace portions of the generation and battery storage capital stock as it wears out. Assuming these assets have useful physical lives of 10 to 15 years for battery storage systems and 25 years for each of the generation technologies (except hydro, which I assume lasts for well beyond the thirty-year transition period given repairs, renewals and maintenance), I estimate ongoing investments for replacement purposes to be around $2.2 billion in real terms. When total debt service costs are added to the annual fixed operating costs and the $2.8 billion annual revenue requirement for transmission and distribution, Maine's total energy costs will remain relatively flat in real terms at 2050 levels once full decarbonization has occurred.

A third feature of the transition to a zero-carbon economy by 2050 is less obvious, as it is masked by the aggregate results discussed previously. In **Table 2-2**, I showed that Maine currently uses approximately 260 trillion Btus of energy a year, net of fuels used to produce electricity and wood and wood waste. The annual cost for this energy has ranged from just under $4 billion to almost $8 billion, as shown in **Figure 2-14** in the prior chapter, and has averaged roughly $6 billion. This average annual cost results in an average fuel weighted cost of just over $23/mmbtu, as the higher delivered cost of electricity per mmbtu is offset by lower costs for fossil fuels.

One important effect of beneficial electrification is that the substitution of electricity for gasoline and diesel fuels in transportation and the substitution of electricity for a range of fossil fuels in space heating and process applications results in a reduction in the total quantity of primary energy consumed. By 2050, with full beneficial electrification, the total energy consumed (all of which is electricity) falls to just under 140 trillion Btus – an almost 50% reduction from 2020 levels. Since the amount spent in 2050 for energy is roughly the same $6 billion, the cost of the energy on an mmbtu basis almost doubles to $44/mmbtu. Further, since all of the energy is now electricity, this means that the average cost of delivered electricity rises from just over $100/MWh in 2020 to $150/MWh by 2050.

Figure 3-10 shows the estimated average costs per MWh for electricity each year during the 30-year transition period. The average cost

FIGURE 3-10 | Delivered Electricity Prices by Component



per MWh is comprised of three components – the cost for delivery (transmission and distribution), the market costs for energy (energy plus capacity plus ancillary services) and the costs for renewable generation (financing plus operating costs less any revenues received from the sale of energy into the markets). Average delivery costs increase during the first half of the transition period, as the grid is being built out to accommodate increased renewable generation ahead of increased usage due to beneficial electrification. During the second half of the transition period, beneficial electrification of transportation, heating and process accelerates resulting in increased electricity usage. While grid buildout continues over this period, the net effect is a lowering of average costs.

The other two components depict the declining clearing prices for energy in electricity markets as fossil-fuel and other non-renewable generation plants are replaced by renewable generation. These curves reflect the assumptions discussed previously in this Chapter.

The important point is not the shape of the average cost curve and its components in **Figure 3-10**; the shape is a function of the rates of beneficial electrification and development of zero-carbon generation. The important point is that average costs of electricity increase over the transition period, regardless of the assumptions about how quickly beneficial electrification occurs or zero-carbon renewable generation is developed. A second point is that at the same time that the price of electricity is rising, we can expect the price of fossil fuels to fall.[56] The reason is that beneficial electrification results in lower demands for fossil fuels, and as demand falls, fossil fuel producers will shut-down their most expensive wells first. Since the costs of production at marginal wells determine prices in the market, fossil fuel prices will fall as the most expensive wells are decommissioned.[57] I would expect this cycle to continue as demand for fossil fuels falls further until such point as the production cost decreases are offset by rising average fixed costs related to pipeline and other plant and equipment charges.

The divergence between the price of electricity and the prices for fossil fuels will act as a brake on voluntary actions of businesses and residents to switch from fossil fuels to electricity. Therefore, all other things being equal, the effect will be to slow the transition to a zero-carbon economy. This is an important result. The divergence between electricity prices and fossil fuels during the transition period results from the transition process itself. It is not a result of any anti-competitive actions by big oil companies to undercut renewable generation technologies. Technological advances may help, especially those that reduce the costs of expanding the transmission and distribution grid that are necessary to accommodate increased development of zero-emission generation plants and beneficial electrification.[58] However, it is unlikely that these will be significant enough to overcome the transition-induced price divergence.

There are only three ways to address this problem. The first is to use general revenues[59] to subsidize either the cost of renewable generation or the equipment that is necessary to enable beneficial electrification. This first approach underlies U.S. policies such as the Investment and Production Tax Credits for wind and solar and research monies for the development of new and advanced technologies. These efforts have borne fruit;

[56] As noted earlier, the model holds real fossil fuel prices constant over the entire transition period. I made this assumption to err on the conservative side with respect to the total cost of energy. Had I allowed fossil fuel prices to fall, total energy costs would have been lower than those shown in Figure 3-7.

[57] There will likely be a secondary compounding effect with respect to refining capacity. As demand falls, refiners are likely to shut-down their most expensive refineries, as well. This should contribute to falling fossil fuel prices.

[58] It should be remembered that our model already incorporates technological changes in solar PV, on-shore and off-shore wind generation and battery storage that result in falling real prices of electricity generated by these technologies over the transition period.

[59] The revenue source must not come from utility assessments such as systems benefit charges or resource portfolio standards, as these will just exacerbate the rising price of electricity.

the problem is that the former incentives are being phased out, while the latter research monies are already factored into the model through assumed technological changes in generation and battery storage technologies over the 30-year transition period. In Maine, the only general fund revenues committed to beneficial electrification and decarbonization were the one-time monies allocated to biomass plants out of state surplus funds. Accordingly, I do not see much room for expanding general government subsidies to address this problem at the federal level and even less opportunity in Maine.

The second approach is to use governmental powers to mandate the development of renewable generation as well as beneficial electrification. This can be done, for example, by requiring all new or redeveloped residential or commercial construction to install solar PV systems, vehicle charging systems and/or heat pumps. While there are some examples of such mandates today, they are the exception – and in any case, would never create the level of investments required to achieve zero-carbon by 2050.

The third approach is to raise the prices of fossil fuels to offset the price divergence from electricity prices that will occur during the transition. This can be done in any number of ways, but the one that has received the most attention is a carbon tax. Carbon taxes have been shown to have relatively low implementation costs and, by placing a price on carbon, to promote overall economic efficiency. Further, they can be fine-tuned to increase over the transition period as the divergence between the price of electricity and the prices of fossil fuels increase.

Table 3-1 illustrates the computation of the required carbon tax per ton of CO_2 necessary

TABLE 3-1 | Implied Price of CO_2 ($/ton)

TRANSPORTATION				
#	**FACTOR**	**UNIT**		**TOTAL**
1	Efficiency of Internal Combustion Engines	%		25%
2	Heat Content of 1 MWh of Electricity	mmbtu		3.413
3	1 MWh Electricity - Diesel Fuel Equivalent	mmbtu	(2)/(1)	13.652
4	1 MWh Electricity - Diesel Fuel Equivalent	gallons	(3) X 7.143	97.514
5	Price Increase - Electricity	$/MWh		$10.00
6	Equivalent Price Increase/Gallon of Diesel Fuel	$/gallon	(5)/(4)	$0.10
7	CO_2 Emissions - Diesel	lb/mmbtu		160
8	CO_2 Emissions - Diesel	lb/gallon	(7) X 7.143	22.40
9	**Implied Price per Ton of CO_2**	**$/ton**	**(6) X 2,000/(8)**	**$9.16**

SPACE HEATING				
#	**FACTOR**	**UNIT**		**TOTAL**
10	Average COP for Heat Pumps			3.00
11	Efficiency of Boiler Systems	%		80%
12	Heat Content of 1 MWh of Electricity	mmbtu		3.413
13	1 MWh Electricity - Heating Oil Equivalent	mmbtu	(12) X (10)/(11)	2.799
14	1 MWh Electricity - Heating Oil Equivalent	gallons	(13) X 7.143	91.420
15	Price Increase - Electricity	$/MWh		$10.00
16	Equivalent Price Increase/Gallon of Heating Oil	$/gallon	(15)/(14)	$0.10
17	CO_2 Emissions - Heating Oil	lb/mmbtu		160
18	CO_2 Emissions - Heating Oil	lb/gallon	(17) X 7.143	22.40
19	**Implied Price per Ton of CO_2**	**$/ton**	**(16) X 2,000/(18)**	**$9.77**

to offset the financial impacts of each $10.00/MWh increase in the price of electricity for the transportation and space heating sectors, assuming there is no change in the prices of diesel and home heating oil fuels. (In this illustration, I have focused only on diesel fuel and home heating fuels. The results would be comparable for gasoline, natural gas and propane.) The calculations adjust for the different efficiencies with which electricity and fossil fuels are converted into useful energy in each of the two sectors.

Based on these parameters, it would be necessary to levy a carbon tax at the rate of $9.00 - $10.00 per ton of CO_2 to offset the financial consequences of each $10/MWh increase in the price of delivered electricity, and therefore divergence between the prices of electricity and fossil fuels. This level of carbon tax would raise the price of diesel fuel and home heating oil by about $0.10 per gallon.[60] Thus, to offset the largest increase of $90/MWh shown in **Figure 3-10** would require a carbon tax of around $90/ton. This, in turn, would increase the price of fossil fuels by about $0.90 per gallon. While these are significant impacts, the levels of carbon taxes required to mitigate the impact of price divergence are within the range of values being discussed as the social cost of CO_2 emissions and therefore the rate of taxation of CO_2.

3.5 | Concluding Observations

This chapter presents a pathway to move Maine's energy sector and economy away from fossil fuels to an end state by 2050 with effectively zero CO_2 emissions. The pathway defines rates of conversion of heating, process and transportation from fossil fuels to electricity and the development of renewable generation resources and battery storage capable of meeting Maine's annual electricity requirements. In addition, the pathway incorporates a three and a half-fold expansion of Maine's electricity transmission and distribution grid to support this much higher use of electricity. The result is that Maine is able to make this transition at what is essentially the same total annual cost as Maine is paying for all of its energy today. This bears repeating. There is a pathway that enables Maine to reduce its CO_2 emissions to zero by 2050 yet does so in a manner that imposes no additional costs on Maine residents and businesses for all of the energy consumed each year over the thirty-year transition period from 2020 to 2050 compared to what they are spending today.

The defining of any pathway to a point thirty-years in the future is a highly uncertain exercise in any situation. In the case of an economic sector as essential to the functioning of the economy and as dynamic as the energy sector, the degree of uncertainty is that much higher. This means that the plausibility of the pathway depends fundamentally on the assumptions that underlie it. In this case, I believe that the assumptions I have made are reasonable, given that the end state in 2050 must meet the zero-carbon emissions requirement through beneficial electrification and deep decarbonization. The pathway achieves the goal in a manner that spreads the actions that must be taken by all sectors of the economy over the 30-year transition period so as not to impose too significant a strain on any one sector, while at the same time recognizing the cost advantages associated with innovation and technological progress that may accrue through delays.

The transitioning of the electricity sector and the economy more broadly through the process of deep decarbonization raises the interesting policy question of whether the electric grid should be designed and built out to accommodate beneficial electrification or whether it should lag demands and investments made as constraints or choke points arise on the electric grid. Good arguments can be made on both sides as different risks are evaluated and weighed. Ultimately, however, I think that the monopoly

[60] The carbon tax is only applied to fossil fuels not used in the generation of electricity. Applying the tax to those fuels would increase the price of electricity, thereby exacerbating the divergence between electricity and fossil fuel prices.

nature of the transmission and distribution grid and the complexity of delivering electricity to end users as flows of electricity begin to resemble network flows and the grid becomes "smarter" will necessitate build out to facilitate electrification rather than in response to it.

The pathway illustrates key aspects of transitioning Maine from a fossil fuel-based economy to a zero-carbon economy. The first is that fuel-related costs are replaced by very large capital investments requirements – on the order of an average $2 billion a year for each of the thirty years in the transition period. This substitution of capital for operating costs places a very high premium on the cost of capital. My assumption that the $56 billion of necessary investments in renewable energy resources and battery storage units can be undertaken using 30-year debt at a cost of 3% is perhaps the most important assumption underlying the results of the pathway. This requires that the debt be issued by some form of tax advantaged government entity. In the next chapter, I turn my attention to this issue to examine whether there are organizational structures and financing mechanisms that can meet this requirement.

The second is that, while overall energy spending remains relatively flat over the transition period, as more and more energy is consumed as electricity, the price for that electricity increases at the same time as we might expect the price of fossil fuels to decline with demand for those fuels. This creates an impediment to voluntary actions by residents and businesses to substitute electricity for fossil fuels in the transportation, space heating and process sectors. Absent any intervention by government, this price divergence between electricity and fossil fuels is likely to slow down the pace of beneficial electrification. This issue provides yet one more reason for adopting carbon taxes. When carbon taxes are levied on fossil fuels not used to generate electricity, the prices of those fossil fuels will increase, thereby mitigating the divergence between electricity prices and fossil fuel prices that is essential for voluntary actions to facilitate the transition process.

Chapter 4

Deep Decarbonization Requires Deep Pockets

4.0 | Introduction

As I discussed in the previous two chapters, achieving the elimination of CO_2 emissions from our state will require a near complete transformation of our energy sector and indeed our entire economy. The capital investments to accomplish this transformation are enormous - $56 billion over the next 30 years in the energy sector alone. Maine is not unique in this regard. As I discuss further in this chapter, one nationally noted scholar estimates that the costs to retool our country's generation of electricity exceed $12 trillion. Trillions more will be required to convert all sectors of the economy, including transportation, space heating and industrial processes to electricity. While we are making more progress at the national level than in Maine in building out renewable generation, the total cumulative accomplishments over the past two decades represents a very small fraction of what is required in each of the next thirty years.

One serious shortcoming in our efforts to achieve deep decarbonization is that the mechanisms we have in place today to raise the vast sums of capital necessary to retool our electric sector and broader economy are woefully inadequate. The voluntary efforts undertaken thus far by some of our country's largest companies and institutions to procure zero emission electricity are barely enough to keep up with the growth in electricity usage, let alone result in a net reduction of CO_2. The alternative mechanism of calling upon our electric utilities to raise capital through equity offerings and debt markets based on their access to their captive ratepayers could provide the necessary capital but would likely do so at the expense of competition and the dynamic efficiency that only competitive forces can bring. I discuss this tradeoff later in this chapter, and whether it is good public policy to ask private companies and their shareholders to function as the primary agents for implementing a social policy of deep decarbonization. I conclude that it is not.

Instead, I recommend that Maine establish the Maine Electric Generation Authority or "MEGA". This new authority would be authorized to issue revenue bonds for the sole purpose of developing and owning renewable generating plants. MEGA would enable Maine's municipalities to participate in syndicated electric generation projects. Initially, participation would be on a voluntary basis. MEGA would be authorized to impose assessments on all electric consumers within each participating municipality to cover its debt service and administrative costs associated with each syndication. The assessments would be in the form of a surcharge on each customer's electric bill, collected by the local electric utility and remitted to the MEGA. In addition, to the extent this voluntary activity fails to result in sufficient new renewable generation development to put Maine on a pathway to zero-carbon by 2050, the MEGA would be authorized to develop additional renewable generation projects for its own account and to impose renewable generation surcharges on all ratepayers in the state to cover its costs.

In this chapter, I discuss the advantages of the MEGA organization and structure as a vehicle for raising large amounts of capital compared to using the electric utility for the same purpose. I show that the MEGA is a more efficient structure for raising capital, as it provides a significantly lower cost of capital with little, if any, unmanageable increase in risks to ratepayers. This chapter also describes the organization and structure of a MEGA, including its purpose, permitted activities, financing arrangements and operations. But first, I look more closely at the capital requirements and the mechanisms currently being used to support deep decarbonization.

4.1 Deep Decarbonization
Scope of the Effort Required

Deep decarbonization of the United States economy requires nothing short of a retooling of our country's entire energy infrastructure. The retooling extends to the technologies we use to generate electricity, the vehicles we rely upon for transportation, the sources of heat for our industrial processes and the fuels we use to provide space heating and hot water to our homes and buildings.

There are no generally accepted blueprints for how deep decarbonization of the U.S. economy could be accomplished, and therefore no consensus estimates of how much this would cost. One point estimate by Mark Jacobson of Stanford University and his colleagues suggests that just the total new investments in electricity generation resources in 2017 dollars to achieve total decarbonization of the continental United States by 2050 will be between $12 and $16 trillion.[61] When additional costs of transmission and distribution investments required to support the increased electricification of our economy are included, the costs are significantly higher.

The generation resources identified by Jacobson to accomplish this objective are shown in **Table 4-1**. The scale, scope and penetration are noteworthy. Assuming an average size unit by generation type shown in the first column, the Jacobson "solution" requires more than 75 million residential solar PV roofs, 335,000 land-based wind turbines and another 150,000 off-shore, almost 3 million commercial building solar PV roofs, and 35,000 wave turbines and the list goes on to include generation technologies that are not yet being deployed in this country or anywhere in the world at commercial scale.

It is not surprising that this reconfigured generation fleet would require trillions of dollars of new investment. And, as discussed in the prior two chapters, this is only part of the picture – there will need to be further investments in electric transmission and distribution grids.

The scale and scope of the changes and investments necessary to achieve deep decarbonization of the U.S. economy are enormous. But, change on this scale is not unprecedented. Over our 200-plus year history, the United States has seen similar transformative activities relative to the then size of our country. These have included the development of canals in the early 1800s, railroads through the middle and late 1800s, telephone and electricity during the first half of the 1900s and the road and later interstate highway systems to support the automobile throughout the 20th century. In addition, we have constructed major infrastructure systems to provide clean water and the collection and treatment of sewerage.

[61] Mark Z. Jacobson, et.al., "A Low-Cost Solution to the Grid Reliability Problem with 100% Penetration of Intermittent Wind, Water and Solar for all Purposes (Supporting Information)," Proceedings of the National Academy of Sciences, 112, doi:10.1073/pnas.1510028112, 2015, Table S2, page 14. Jacobson's work is not without its critics, most of whom agree that he underestimates the resources required to actually "run" an electric grid to provide relable electricity. To the extent these criticisms are valid, they would increase the costs in the Jacobson work further.

TABLE 4-1 | Generation Necessary for Full Decarbonization

Generation Type	Capacity Per Unit (MW)	# Of Generating Plants		
		Existing	New	Total
Onshore Wind	5	12,160	323,240	335,422
Offshore Wind	5	0	154,380	154,387
Residential PV	0.005	692,000	74,668,000	75,360,000
Commercial/government PV	0.1	17,300	2,731,700	2,750,000
Utility Scale PV	50	35	46,285	46,329
CSP w/ some storage	100	0	3,629	3,629
Geothermal	100	24	184	207
Hydropower	1,300	67	0	67
Wave	0.75	0	34,933	34,926
Tidal	1	0	8,250	8,082
Solar Thermal for UTES	50	0	9,338	9,380

Each of these prior examples share some similarities with deep decarbonization, but also an important fundamental difference. With respect to the similarities, they all involved the development of complex network systems featuring infrastructure assets that were long-lived and where the value of the network increases with its size, breadth and scope. Each of these instances also involved the raising of enormous amounts of capital. The ability to raise such capital, in turn, required the creation of new organizations, institutions, rules and regulations. These included the establishment of charter corporations, the granting of franchises, the extension of eminent domain authority, the establishment of public utilities, the provision of government guarantees and the creation of governmental and quasi-governmental entities such as municipal authorities and cooperatives.

These new structures had one thing in common. They were designed to create conditions favorable to the raising of vast sums of capital to support transformative technologies. They did this in large measure by reducing the risks and the transaction costs of such investments. Without these new structures, it is doubtful that investors would have found such investments attractive without requiring returns that would have made the costs of developing such technologies and infrastructure systems prohibitive.[62]

The fundamental difference between deep decarbonization and these examples is that each of these prior examples resulted in the deployment of capital assets and technologies that significantly enhanced our nation's productivity and contributed to the growing wealth and economic well-being of the country. The return from these investments was measured in rising personal incomes, improved economic well-being and growing national wealth, thereby creating the economic imperative to initiate and then expand their development. In contrast, deep decarbonization does not create the same economic gains. There are no immediate productivity gains that result from replacing electricity generated in a coal plant with electricity generated by the sun or from replacing the internal combustion engine in a passenger car with lithium ion batteries

[62] A notable example of one such condition is the Price-Anderson Nuclear Industries Indemnity Act of 1957 limiting liability of companies that develop nuclear power plants, without which it is generally acknowledged no commercial nuclear power plants could have been financed. More recently, we have seen in New England how the lack of a structure to raise capital has made it impossible to financially support any significant expansion of natural gas pipelines into New England.

and electric drivetrains. Further, any longer-term productivity gains are speculative at best. Rather, the primary benefits of deep decarbonization lie in the avoidance of long-term costs associated with economic and social dislocations and adverse health consequences that are predicted to result from global climate change caused by increasing concentrations of CO_2 in earth's atmosphere. While Americans often reference Benjamin Franklin's adage that an ounce of prevention is worth a pound of cure, we have never been very successful at mobilizing resources in support of prevention policies, especially when what is being prevented lies a generation or more in the future, is not itself well-defined, and requires the collective actions of all of the world's nations.

Accordingly, as we look to accomplish deep decarbonization whether nationally or in Maine, we must solve two problems. First, we must develop the legal, regulatory and financial structures that will facilitate raising the trillions of dollars of investments necessary to support deep decarbonization. Second, we must ensure that those structures can be used by people and communities that have the desire to act today to prevent the catastrophic consequences of global warming rather than the need to respond in the future to cure the devastation caused.

4.2 | Current Decarbonization Activity

To date, most of the CO_2 reductions in the U.S. have been supported by government tax preferences or advantages (e.g., the PTC, ITC, ZEV tax credits and accelerated depreciation), state-level renewable portfolio requirements (RPS) and targeted state grant programs. However, these measures in and of themselves have not been sufficient for most large-scale renewable energy projects. Large scale investments have also required additional revenue streams to make them economically viable. These revenue streams have taken the form of long-term power purchase agreements (PPAs). For the vast majority of such projects, the counterparties in these long-term PPAs have been regulated electric utilities. Importantly, the cost calculations rarely include costs of externalities such as CO_2 emissions.

Regulated utilities have for the most part evaluated large scale renewable projects in the context of the need for new generation resources to meet loads. The decisionmaking processes have been driven by least-cost planning criteria. The generation projects selected are those that are determined to deliver the lowest cost energy to utility ratepayers over their life-cycles, while meeting overall system reliability and stability requirements.

There have been exceptions to the lowest cost decision criterion. In some instances, state policy has explicitly directed regulated utilities to seek PPAs from specific sets of generating resources that meet legislative criteria. The so-called "Tri-State RFP" (involving utilities in MA, CT and RI), the Massachusetts' hydro/wind and offshore wind RFPs and the most recent initiatives in New York, New Jersey and Rhode Island to procure off-shore wind generation are examples of this type of exception. In other instances, where states have set certain medium or long-term goals for CO_2 emission reductions from power generation, their regulated utilities have incorporated these goals into their decision making with respect to which generation resources to undertake. Finally, there are instances in which regulated utilities have developed or entered into PPAs with renewable projects to broaden their generation base and learn more about the characteristics of such resources. These latter instances have generally tended to be small scale – usually well below 100 MW of total capacity across all such instances.

The fundamental problem with this model is that it is inadequate to accomplish the goal of deep decarbonization. Despite astonishing improvements in the performances and costs of renewable energy resources, especially solar and onshore wind, renewable energy resources are still not cost-competitive with natural gas generation technologies in most of the country, including New England, in the absence of tax incentives and preferential subsidies. To compete financially, they still require some form of financial assistance. This is in part because real prices for fossil fuels (and especially natural gas) have fallen sharply over the past decade, while the long-term trajectories of fossil fuel prices have become much less bullish and, in some cases, have actually turned bearish as fossil fuels are replaced by renewable energy. For example, one study estimates that if EVs grow to a third of the automobile market worldwide, the demand for oil will be reduced worldwide by 9 million barrels a day, an amount that is just below the total production of Saudi Arabia.[63] The loss of such a large portion of demand can be expected to result in significant suppression of oil prices in world markets.

A consequence of low fossil fuel prices is that using a lowest cost standard for utility generation expansion planning and decisions to determine which generation technologies and projects will receive utility support will likely result in the development of renewable generation at levels far below those necessary to achieve deep decarbonization. For example, Ohio recently approved two new natural gas-fired generating plants with capacities of 1,100 and 900 MW to take advantage of cheap shale-based natural gas in the Utica field. While these plants may reduce CO_2 emissions in Ohio and the PJM Power Pool as a result of the displacement of coal-fired generation with natural gas, the reduction will be at the margin and relatively small in light of what is required to achieve deep decarbonization. In the final analysis, these plants are still fossil-fuel plants.

In addition to utilities as off-takers, we have seen a recent increase in renewable energy projects supported through "virtual" Power Purchase Agreements (VPPAs), where the counterparties have been some of the largest, most prestigious, most financially secure and highest rated private companies in the country. These VPPAs are being used to meet corporate goals for CO_2 reduction. **Figure 4-1** shows major purchases by large corporations through VPPAs from 2014 through the first quarter of 2019. These purchases total 15.5 GW of capacity, primarily for wind generation. Interestingly, these purchases have increased even as the average wholesale price of energy in the U.S. has fallen. The sharp increase in 2018 levels is the result of companies wishing to finalize VPPAs prior to when the reduction in federal tax incentives begins to phase-in.

Table 4-2 shows that it is not just large corporations that have entered this market. U.S. colleges and universities have begun to take advantage of PPA and VPPA opportunities to meet their greenhouse gas emission reductions commitments. Here, too, the volumes are still relatively small. In fact, the combined total of renewable generating capacity across both **Figure 4-1** and **Table 4-2** represent about two-tenths of one percent of the total 6.4 TW of renewable generating capacity identified in **Table 4-1** as required for deep decarbonization.

In the non-utility space, I believe that we can expect to see more examples of private companies, higher education institutions and even government entities entering VPPAs to support new renewable generation. However, the energy consumption of such entities with credit ratings high enough to underwrite financeable VPPAs is limited. And, of course, not all such entities will voluntarily enter into such long-term contracts.[64]

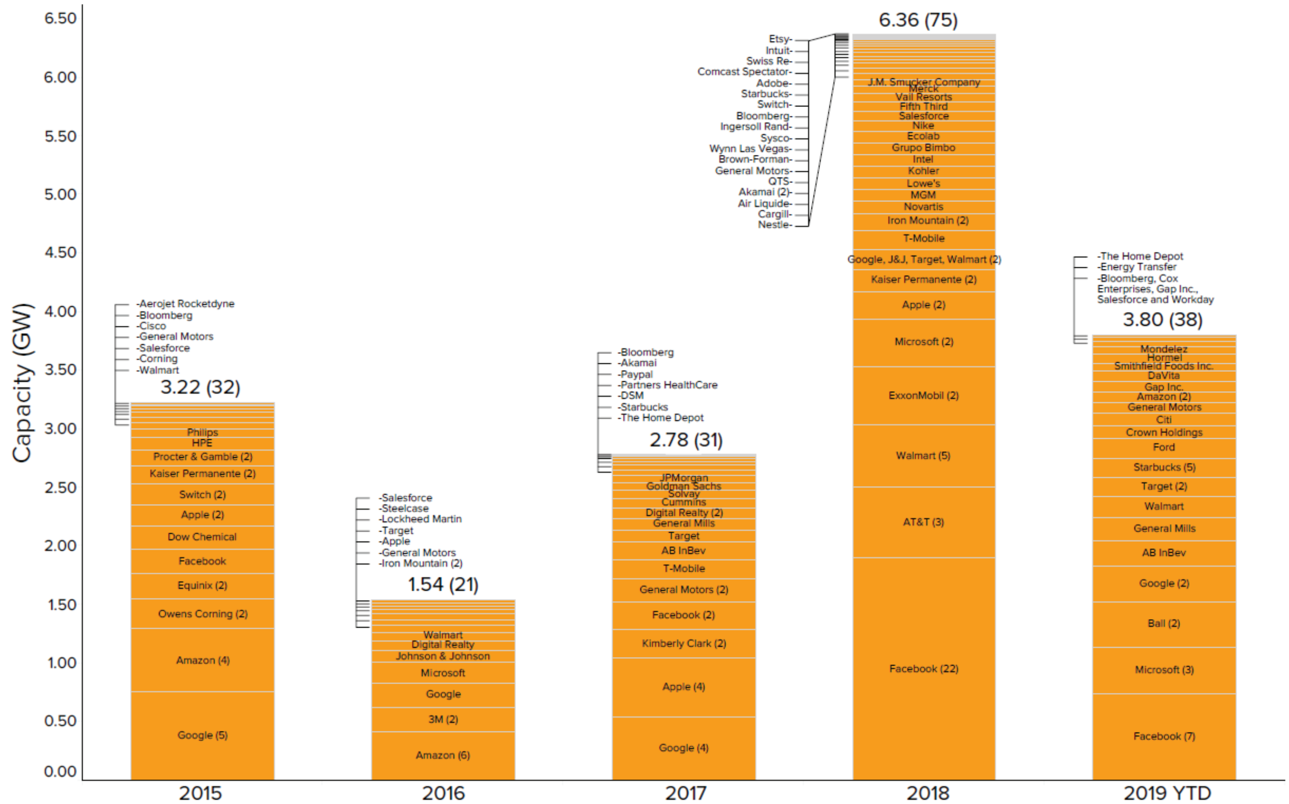
In addition to the above two sources of financial support for increased renewable generation, I expect to see increases in community aggregation efforts designed to support renewable energy projects. These may be undertaken in combination with municipal utilities,[65] or they may be through

[63] This is based on a recent study by Barclays. See https://www.cnbc.com/2017/10/05/electric-cars-could-cut-oil-demand-roughly-equal-to-irans-output.html.

[64] The Climate Group, which operates the RE100 initiative to which many of the country's largest companies belong, reported recently that the total electricity usage created of this group is now over 161 TWh a year. Assuming an average capacity factor of 45%, this equates to roughly 41 GW of capacity. While this is impressive, as we note in the next section, even if it is all met by renewable generation, it is about 20% of the amount of capacity that will need to be installed each year for the next three decades to achieve deep decarbonization. https://nawindpower.com/t-mobile-source-electricity-wind-power

[65] See, for example, https://sepapower.org/knowledge/nebraska-community-solar/

FIGURE 4-1 | Corporate VPPAs with Renewable Generation Projects



SOURCE: Renewable Energy Buyers Alliance. https://rebuyers.org/wp-content/uploads/2019/03/reba-deal-tracker.pdf

TABLE 4-2 | University VPPAs with Renewable Energy Projects

University	MW	Location
Michigan State University	10	Onsite
Cornell University	12	Offsite
American University**	12	Offsite
Harvard University	12	Offsite
University of Illinois 15	15	On/Offsite
UC Davis	16	Offsite
Mt. St. Mary's & Univ. of Maryland System	17	Onsite
Arizona State University	25	Onsite
George Washington University**	36	Offsite
MIT**	44	Offsite
Ohio State University	50	Offsite
University of Maryland	55	Offsite
Oklahoma State University	60	Offsite
Stanford	78	Offsite
UC System	80	Offsite
University of Oklahoma	101	Offsite

** Part of an Aggregated Purchase

SOURCE: Customer First Renewables, presentation to New York Campus Renewable Energy Solution (NYCARES)", October 13, 2017 aggregated purchasing arrangements, such as the "Community Choice Aggregation" option in California.[66] While these efforts are contributing to lowering greenhouse gas emissions, I do not believe that they will contribute much to meeting the full scope of renewable generation that is required to achieve deep decarbonization. The scale is very limited in large part because the transaction costs to achieve a developed project are very large.

In summary, I do not believe that the vehicles through which renewable energy projects are financed and developed today in the U.S. are adequate to meet the scale necessary to achieve deep decarbonization of the U.S. economy. The results to date bear this out. As shown in **Table 4-1**, across all of the renewable generation technologies included in the Jacobson "solution", only hydropower has met its target development levels. None of the other technologies come close. In fact, across all the technologies including hydropower, the total installed capacity today of 157 GW represents only 2.5% of the 6.4 TW of generation required.

4.3 Organizational Options for Raising the Required Capital

By any standard of comparison, the 6.4 TW of generating capacity required per the Jacobson study is a lot of generation, and $12 to $16 trillion is a lot of money. If deep decarbonization is to occur by 2050 and if the pathway to this result is generally linear between now and 2050, the annual renewable generation capacity additions required in the United States would be approximately 200 GW representing an annual investment of $375 billion. This $375 billion would represent one of out every eight dollars of the total $3.1 trillion of gross private domestic investment in the United States in 2016.[67] Further, this level of investment would have to continue for 30 years through 2050, a period during which much of our country's existing water, sewer and road networks will require replacement, and the demands for capital investments in the health care, technology, information, communications and manufacturing sectors will continue to grow.

An alternative way to put the 200 GW of generation and $375 billion of new investment in perspective is to compare each to the amount of all new generating capacity (including fossil-fueled and nuclear generation) brought on line across the entire United States during each of the past 10 years and the dollar amount of that investment. **Figure 4-2** presents annual generation by type commissioned in each of the ten years from 2006 through 2016.[68] The average amount of all new generation capacity, not just renewable generating capacity, brought on-line each year over this period was only 16 GW, with a high of 28 GW in 2016.

Figure 4-3 shows new capacity additions for only renewable generation, compared to the average annual amount of such generation that needs to be brought on line to reach the 6.4 TW level by 2050. Clearly, we are still falling far short of the investments required.

Figure 4-4 shows new investments in clean energy in the U.S. by generation type over the last 13 years. The figures are reported by quarter. They show quarterly investments ranging from $5 billion to $15 billion, or around $40 billion per year. This is just over 10% of the $375 billion required each year between now and 2050 to achieve deep decarbonization of the U.S. economy, based on the Jacobson study, or any of the other studies that have looked at this issue.

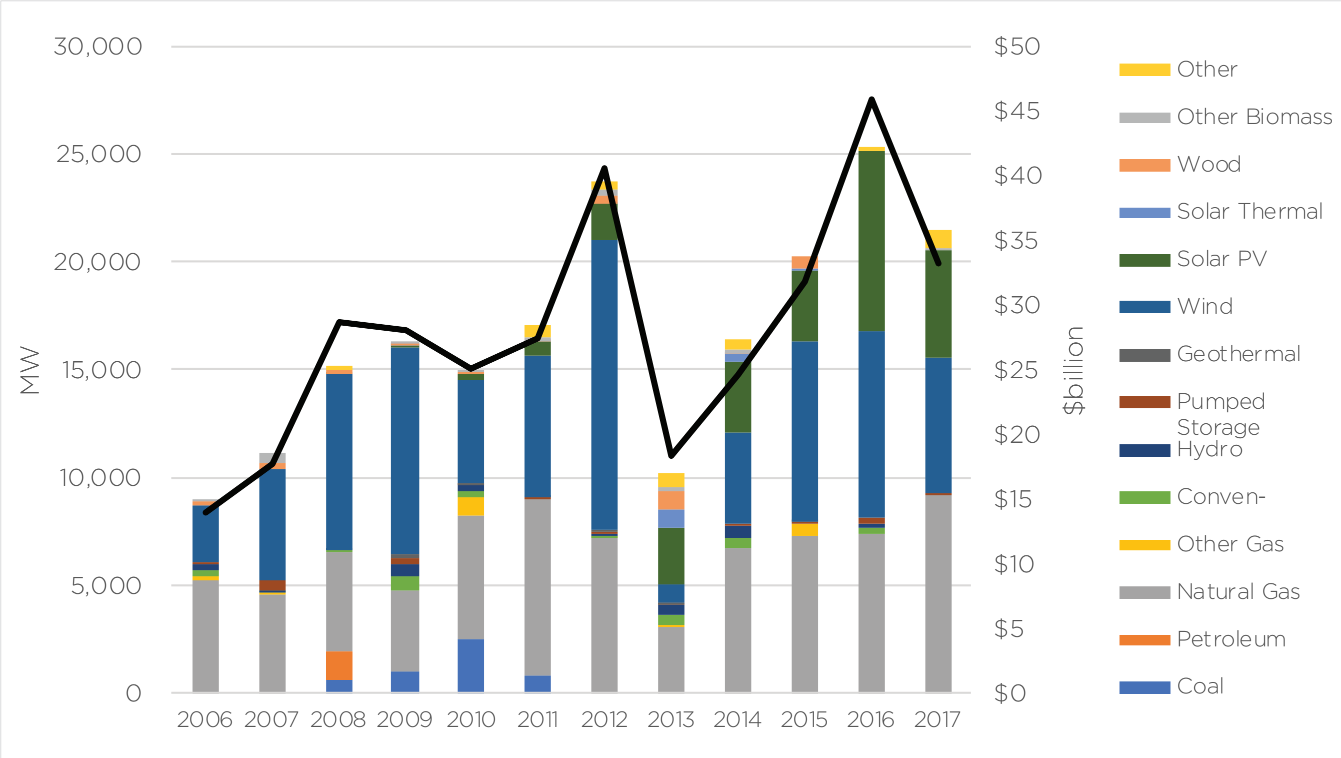
Absent new organizational structures, new investment vehicles or major changes in the electric utility industry, I expect that the means of raising the amounts of money required will

66 See, for example, https://geothermal.org/PDFs/Articles/16JulyAug.pdf

67 https://fred.stlouisfed.org/series/GPDI

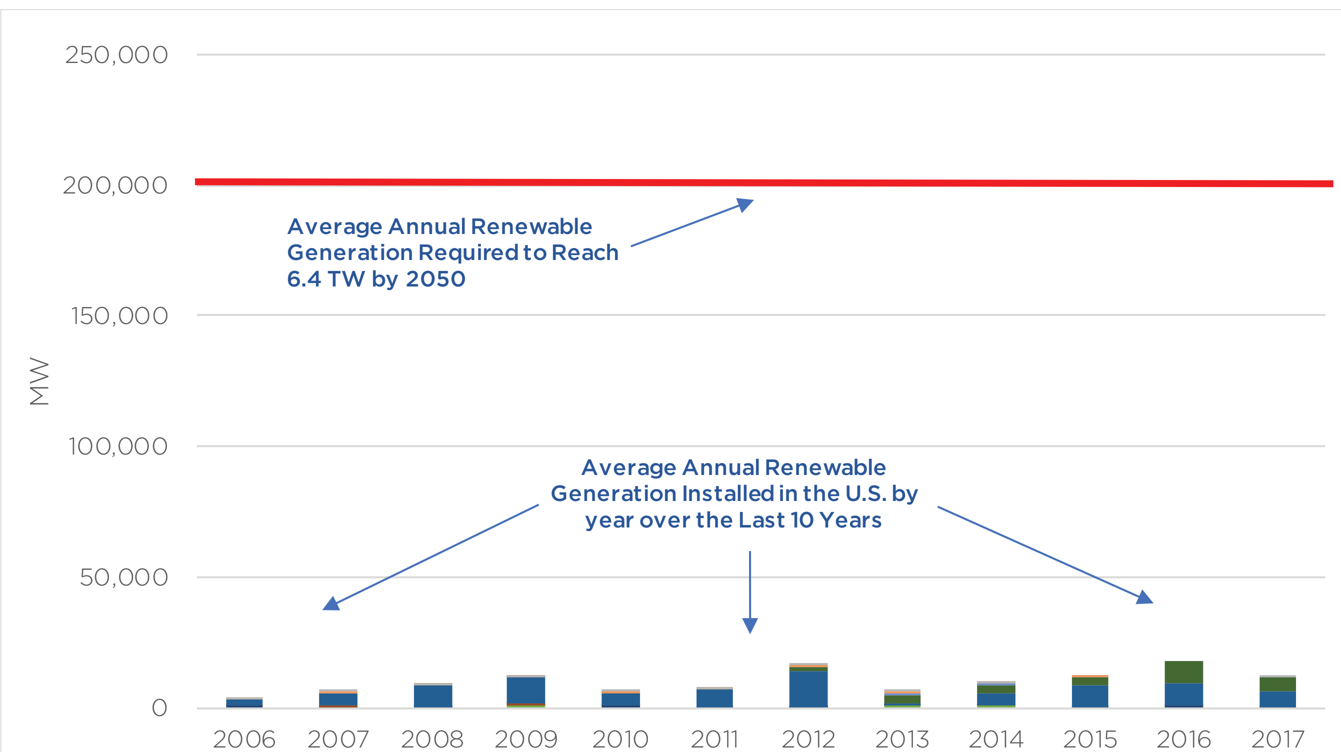
68 These figures are for all new generation and are not net of unit retirements.

FIGURE 4-2 | U.S. Generation Additions by Type from 2006 - 2017



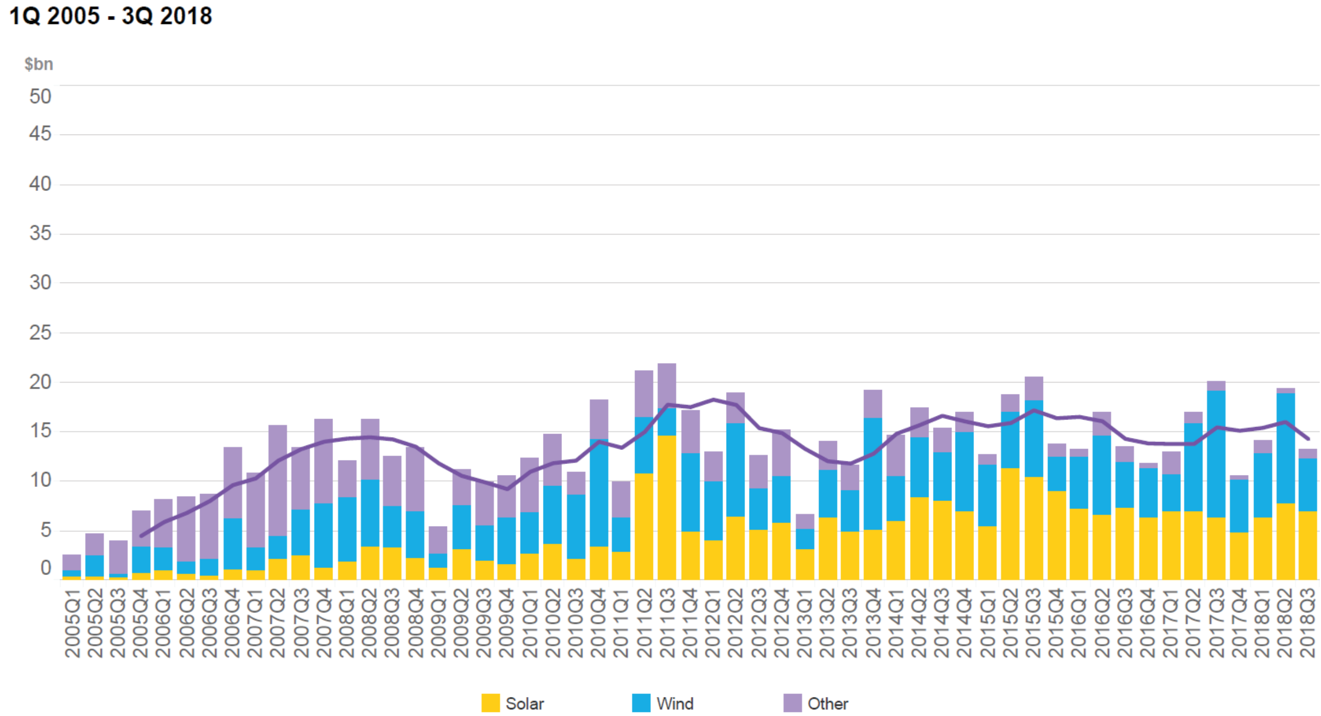
SOURCE: https://www.eia.gov/electricity/annual/html/epa_01_02.html

FIGURE 4-3 | Renewable Generation Requirement v. Actual Generation Installed over Last 12 years



SOURCE: https://www.eia.gov/electricity/annual/html/epa_01_02.html

FIGURE 4-4 | New Investment in Clean Energy – U.S. by Generation Technology



SOURCE: Bloomberg, ***"Clean Energy Investment Trends, 3Q 2018,"*** https://data.bloomberglp.com/bnef/sites/14/2018/10/BNEF-Clean-Energy-Investment-Trends-Q3-2018.pdf

be to follow the path begun in a few states such as Massachusetts. This path involves the conversion of investor-owned electric utilities (IOUs) into agents of social policy.

Our country's electric utilities have a long history of being used to affect social policies. Examples include low-income rate subsidies, rate designs to encourage economic development, administration and delivery of energy efficiency and conservation programs and the siting of energy infrastructure. These actions, however, have always represented only very small percentages of any utility's total costs of providing service, customers served or commitment of staff and operating budgets. To ask IOUs to raise $375 billion a year from their ratepayers to implement a societal decision to achieve deep decarbonization by the middle of this century is unlike any other action they have undertaken since the electrification of the country in the early 20th century.

This comparison with electrification that began in earnest over a century ago is an important one both for its similarities and its differences. Electrification for most of the population by World War II was enabled by the extraordinary capital raising capabilities of IOUs, made possible through a regulatory system that provided a legal right for shareholders of those utilities to earn a fair return on their invested capital. This has been referred to as the "regulatory bargain", an arrangement under which IOUs agreed to an obligation to provide electric service to all customers within their designated service territories on fair, equitable and non-discriminatory terms, and in return those customers assumed an obligation to compensate IOU shareholders by providing them a fair return on their invested capital. In essence, IOU shareholders (and by extension bond holders) secured access to the "wallets" of their customers as collateral for their investments. This collateral allowed for the lowering of the cost of invested capital to the IOU's ratepayers by reducing risks borne by shareholders. The captive ratepayers of the IOU provided the financial security that allowed

IOUs to raise the billions of dollars necessary to develop the generating plants and build out the electric grid to provide electric service to the vast majority of the country's businesses and residents.[69]

This experience has demonstrated that the regulatory bargain is capable of raising substantial amounts of capital. I believe that it could likely do the same today if called upon. There are two crucial differences, however, between the electricification of America in the early part of the 20th century and deep decarbonization. First, as noted earlier, electricification provided a significant improvement over prior technologies, thereby yielding positive economic returns to the beneficiaries. This created real advantages for people and businesses to interconnect to and remain customers of the electric grid. Second, electrification involved the build-out of an electric grid – a near ubiquitous network interconnecting virtually every home and business in the country. This network embodied many characteristics of a natural monopoly service essential to modern living and for which there are few effective substitutes. Combined, these differences enabled a very important concession - the utility's obligation to provide service was coupled with a grant of exclusivity under which it would be the only entity authorized to provide such service. This made ratepayers captive customers of the IOUs and made "exit" a very difficult and generally an uneconomic option for ratepayers, thereby enhancing the value of ratepayers as financial security for IOU shareholders and reducing overall capital requirements and costs.

In contrast, the generation investments necessary to achieve deep decarbonization have no similar productivity impacts or natural monopoly characteristics. In fact, with respect to the latter, most investments in renewable generation are being undertaken today by hundreds of entities that are not utilities, and that are not regulated. As a result, the natural monopoly argument provides no reason to use the utility as the vehicle for developing the required generation resources. Rather, there are two compelling reasons not to do so.

The first compelling reason not to use the utility as the vehicle for developing the renewable generation resources necessary to achieve deep decarbonization is that this option makes it much more difficult to take advantage of competitive market pressures to drive cost reductions and capture dynamic efficiencies. The advantages a utility possesses in terms of its access to captive ratepayers and its provision of transmission and distribution services are so dominant that there is a danger that these advantages will leave the utilities in sole possession of the entire electric industry much as they had been prior to the 1980s. This would effectively undo the gains achieved through competition over the past 40 years and could usher in an era of technological stagnation across the entire industry.

A second argument against using IOUs as agents for effecting social policy goals and objectives is that it places the IOU in a potential conflict situation. Management's fiduciary duties to IOU shareholders may not lead the IOU to outcomes consistent with the implementation of social policy. When IOUs are directed to pursue social policy goals and objectives, their shareholders become exposed to risks they would otherwise not have to bear. One would expect IOUs to seek to be compensated for these risks, either in the form of a higher allowed rate of return to equity or incentive payments to the IOUs. Not surprisingly, when IOUs have been asked to operate in this manner, they have done precisely that.[70]

69 As powerful as this model was as a means to raise capital, it could not overcome certain financial hurdles involved in providing electric service to very rural and/or very poor parts of the country. In these instances, community members formed municipal utilities or electric cooperatives and secured financing and concomitant guarantees from the federal government.

70 An interesting overview of this and the various approaches adopted by the California Public Utilities Commission can be found in "An Introduction to Debt Equivalency," California Public utilities Commission, Policy & Planning Division, August 4, 2017, http://www.cpuc.ca.gov/uploadedFiles/CPUC_Public_Website/Content/About_Us/Organization/Divisions/Policy_and_Planning/PPD_Work/PPD_Work_Products_(2014_forward)/PPD%20-%20Intro%20to%20Debt%20Equivalency(1).pdf

In effect, IOUs are positing that access through them to their captive ratepayers for the purposes of achieving social policy goals and objectives comes at a cost. This cost is the IOUs' assessments of the degrees and extents to which their shareholders are back-stopping the risks that (i) societal policies are changed leaving those assets acquired by the IOUs stranded and not capable of recovery through market-based prices from their ratepayers; (ii) the IOUs' implementations of social policies are done in a manner that is determined to be imprudent and therefore not qualified for cost recovery from ratepayers; or (iii) the IOUs incur administrative costs in implementing social policies for which they are denied recovery from ratepayers.

Each of these risks is a real one. Over the course of more than a century of electric utility regulation, each of these risks has been borne at one time or another and to one degree or another by many IOUs in this country. While utility shareholders, regulators and ratepayers may differ in their estimates of the likelihoods and magnitudes of these risks and therefore the amount of compensation due to IOU shareholders, the risks exist. Having IOU shareholders positioned to bear these risks provides value to society that must be taken into consideration, and for which they must be compensated.

The issue of risk does not disappear when utilities act as counterparties to long-term contracts with private developers compared to when they act as developers and owners of renewable generation projects. The PPA structure simply substitutes one group of shareholders (those who hold equity positions in the project) for the utility's shareholders. There is little reason to expect that these shareholders will view risks any differently or require less compensation to bear them compared to utility shareholders.

In addition, utility shareholders have indicated that the PPA itself exposes them to increase risks. This is not a new argument. Three decades ago, utilities made the same argument when they were being directed by state regulators to enter into long-term PURPA contracts with independent power producers. Their proposed remedy was to be allowed to charge an "adder" to the value of such contracts to cover administrative costs and as compensation for the increased risks to utility shareholders from the structure of long-term power contracts. Therefore, it is not a surprise to see that Massachusetts utilities (Eversource, National Grid and Unitil) sought and were awarded a 2.75% adder to the recently approved Avangrid off-shore wind PPAs in filings at the Massachusetts Department of Public Utilities.[71]

In summary, the use of IOUs as the implementing agents of a social policy designed to achieve deep decarbonization of the U.S. economy has both advantages and disadvantages. The key advantages are (i) access to captive ratepayers to support investments in long-lived assets, either directly through utility ownership of these assets or through PPAs with third-party owners, (ii) the presence of a management structure that can implement social policy directives and (iii) the role of IOU shareholders as back-stoppers of risks associated with changes in policy, technologies and economics or errors in implementation. The key disadvantages are the loss of competitive market pressures where IOUs develop and own renewable generation within their franchise territories and the risk exposure of IOU shareholders and/or the project owners, both of which add to the costs of achieving social policy objectives.

We know from experience that IOU shareholders can be coaxed into bearing risks that will come from financially supporting $375 billion a year in new generation plant alone, plus the additional billions in grid enhancements required to accommodate this generation and the growth in electricity usage from beneficial electrification. The question is whether they can be so coaxed at a reasonable price. For the management and shareholders of an IOU, the decision to act as

[71] See the Order of the Massachusetts Department of Public Utilities in D.P.U. 18-76, 18-77 and 18-78, respectively, Section 83C Long-term Contracts for Offshore Wind Energy Generation.

the implementing agent for a social policy of achieving deep decarbonization is nothing short of a "bet the farm" decision. We should not kid ourselves – IOUs will never make this type of commitment without a complete insulation of its shareholders from all risks that management can imagine and then some. If this occurs, it is fair to ask whether IOUs and their shareholders provide any incremental value in the effort to achieve deep decarbonization, and if they do not, whether there is another organizational structure or investment vehicle that provides the same access to captive ratepayers and an effective management structure but at a lower cost. I do not believe that IOUs provide any incremental value in the effort to achieve deep decarbonization, and that there is a viable alternative.

4.4 Electricity Generation Authorities

The key challenge of deep decarbonization is the creation of an organizational structure in lieu of existing IOUs that can serve as an investment vehicle for raising the trillions of dollars nationally and the $56 billion in Maine over the next three decades for investments in electric generating, transmission and distribution plant to achieve deep decarbonization of the U.S. and Maine economies. This new structure must provide for the creation of an entity with the following characteristics:

- An entity that is authorized to raise the capital necessary to develop the renewable generating assets required to achieve deep decarbonization on the most favorable and efficient terms.
- An entity that is empowered to make decisions regarding what renewable generating plants should be built and to develop those generating plants through the issuance of competitively bid design-build contracts to third-party developers to ensure the lowest possible costs.
- An entity that has access to existing electric ratepayers and the ability to commit those ratepayers as collateral to provide financial support for long-lived generating assets to reduce the cost of capital.
- An entity that has the ability to hold those electric ratepayers captive once such a commitment has been made on their behalf to reduce risks and therefore the cost of capital.

These characteristics follow from the nature of the investments required. The generation plant types shown in **Table 4-1** as well as the solar, on-shore and off-shore wind and battery storage units that are specified in the Maine pathway laid out in Chapters Two and Three possess a common attribute relative to fossil fuel generating plants operating today. They all involve a tradeoff of higher initial capital costs for very low ongoing operating costs. As a result, anything that can lower the cost of capital will have significant impacts on the total costs necessary to achieve deep decarbonization. Of all the potential options for raising capital today, one of the least expensive options is the use of states' and/or municipal governments' abilities to achieve 100% leverage through the issuance of debt. The cost of capital may be reduced further if it is possible to issue such debt on a tax-exempt basis or to secure federal government loan guarantees. I refer to entities capable of accomplishing this as Electricity Generation Authorities or EGAs.

While EGAs have some of the characteristics of municipal electric utilities, they are different from such utilities in terms of their scope and functions. They are authorized solely to raise the dollars necessary for the development of renewable generation over the next three decades. They have no responsibility in or involvement with the delivery of electricity. They exist independently from the transmission and distribution functions of today's municipal electric utilities, IOUs and RTOs, who remain responsible for ensuring that the electric grid meets all reliability and stability standards. Instead, EGAs operate to procure energy with expanded authority to develop and own renewable generation plants and to commit ratepayers to meeting the financial investments required to fulfill this task.

The value of an EGA derives from its ability to maximize leverage and to issue debt on tax advantaged terms for the sole purpose of financing the development of renewable generation plants. By using the full leveraging capability provided by their captive ratepayers and their tax advantaged status (with support of federal guarantees where applicable), EGAs are able to finance renewable generation development through the issuance of long-term bonds for 100% of the project cost at rates in the 3% range, given current capital market conditions. This compares to the weighted costs of capital sought by IOUs in excess of 7% and even higher returns sought by private project developers and reflected in long-term PPA prices. This roughly 400 basis point differential on a single year's worth of required investments of $375 billion, if financed over 30 years, results in a reduction in annual debt service costs of $11 billion and over $330 billion over the life of the financing for just this one year of investment. Compared with an IOU, an EGA offers the opportunity to cut in half the revenues that must be raised from ratepayers to achieve deep decarbonization. This is no small matter. For Maine alone, the difference between a 3% and 7% cost of capital, all other things being equal, is $12 billion over the thirty-year transition period, and approximately $1.2 billion a year thereafter.

The lower effective cost of capital is not cost-free. It is achieved through two important means. The first and the smaller of the two in terms of impact is the tax preference accorded interest income derived from debt issued by state authorities. Since this interest income is exempt from all income taxes, the market will support the issuance of such debt at lower rates, all other factors being equal.[72]

The more significant source of cost savings is achieved through the elimination of shareholder equity that comes with the ability to achieve 100% leverage for EGA supported investments. The elimination of shareholder equity means that all risk is borne by the purchasers of EGA debt.[73] This, in turn, requires that the debt is backstopped by ratepayers in the first instance and possibly state governments, to the extent that these government entities pledge their full faith and credit to support interest payments over the term of the debt to achieve even lower interest rates. Whether this represents an attractive option for ratepayers (and by extension state and local governments) depends on the nature of the risks assumed, and the probabilities that worse-case outcomes will occur with respect to these risks. Therefore, it is important to give careful consideration to the nature of the risks captive ratepayers will shoulder under the EGA structure. I will return to this issue of risk following a discussion of the organizational structure and operations of EGAs.

4.4.1 | Organizational Structure

The discussion thus far has been general enough to encompass Energy Generation Authorities at any level of government, including state, regional, county or municipal. My belief, however, is that the scale of investments required, the need to coordinate these investments to ensure grid reliability and stability and the level of expertise necessary to carry out the functions of an EGA point strongly to the establishment of a single EGA at the state level in Maine. At the same time, I recognize that support for the establishment of an EGA in Maine will vary considerably across the state. The evidence to date indicates that support for aggressive actions designed to reduce CO_2 emissions will tend to be strongest

72 It could be argued that this tax preference simply shifts income tax burdens onto other income sources, and therefore the tax preference represents a reshuffling of the government revenue deck of cards and not real savings to electric ratepayers. This is a fair point; however, given the full scope of all tax preferences embedded in the federal IRS codes as well as those in state and local income tax laws and regulations, it is very difficult to isolate one such preference and attach costs to that item.

73 This is not unprecedented. Many electric utilities that underwent restructuring were left with billions of dollars of uneconomic assets ("stranded costs"). The portion of stranded costs that were determined to be the obligation of ratepayers were often isolated and securitized through the issuance of bonds to cover 100% of the amount of such stranded costs. This was the lowest cost option for ratepayers, who achieved this outcome by guaranteeing to pay unconditionally the full amount of the debt service over the life of the bonds.

in those communities that have adopted or are planning to adopt sustainability plans that include significant emission reduction targets. Given the enormous efforts required to achieve deep decarbonization and the pressing need to begin these efforts sooner rather than later, I believe that a state EGA can provide those communities where the demand for clear and strong collective actions to address global warming exists with a vehicle for implementing those demands.[74]

4.4.2 | Purpose

The purpose of a Maine EGA ("MEGA") is to finance and own (a) energy generation plants that generate electricity using renewable fuels (including, but not limited to solar, wind, hydro, wave, tidal, and biomass), that produce zero greenhouse gas emissions and that are capable of delivering all electricity generated into Maine in amounts sufficient to meet residential and business energy requirements, and (b) electricity storage systems that can store sufficient quantities of electricity generated by renewable generation projects to enable Maine's electricity grid to meet total Maine demands for electricity at all times of the year.

For the first ten-years of its life, the MEGA will carry out this purpose through two parallel sets of activities. One track – its "municipal program" – will act to syndicate the development of renewable generation on behalf of municipalities that wish to provide their residents and businesses with renewable electricity generation. Participation of a municipality will be on a voluntary basis through acquiring subscription shares of renewable generation projects. These shares will entitle the municipality to its proportionate share of the environmental attributes of the project. In return, the municipality will be responsible for that same proportionate share of the financing costs incurred by the MEGA as well as an allocated share of MEGA's net administrative costs. These costs will be paid by the residents and businesses of the municipality. There is no limit to the amount of such projects that the MEGA can undertake.

The second track – its "state program" – will develop renewable generation projects on behalf of all electric ratepayers in Maine. The net costs and environmental attributes of these projects will be assigned to all ratepayers in the state based on their electric energy use. This track is limited to no more than 200 MW of nameplate capacity each year during the first ten years.

The MEGA will evaluate the total amount of generation capacity under contract in year ten under both the municipal and state programs. If that total amount is below the amounts it determines are necessary to achieve full decarbonization by 2050, the MEGA will be authorized to increase its purchases under its state program in amounts sufficient to bring the state back on track to achieve zero-carbon by 2050. In any case, the MEGA will continue to offer municipalities the opportunity to acquire shares of syndicated generation projects on a voluntary basis under its municipal program after year ten.

4.4.3 | Permissible Activities

The MEGA should be permitted to undertake the following activities in fulfillment of its purpose, but shall not be permitted to engage in any activities that could reasonably be expected to expose Maine ratepayers to additional financial risks. Its permitted activities include:

- **Acquire fee simple ownership or easements in or enter long-term leases of real estate within as well as outside of Maine.** All land holdings and improvements to the same regardless of where located shall be treated as exempt from Maine local property taxes to the fullest extent permitted under the law.

- **Issue revenue bonds of various terms (but none longer than 30-years) for up to 100% of the costs of a renewable generation plant**, including capitalized interest during construction of the plant and working capital related to the operations and administration of the MEGA.

[74] "Municipal" is meant to include counties or consortia of cities and towns that choose to organize to form a single off-taker for purposes of participating through the MEGA.

- **Enter into contracts with third-parties** for (i) the construction of renewable generation plant, (ii) the operations and maintenance of renewable generation plants owned by the MEGA and (iii) the provision of support services to the MEGA, including energy planning, energy market sales, energy contract review, accounting, legal and other types of administrative services.
- **Establish renewable energy surcharges that are imposed on Maine electricity ratepayers to support the revenue bonds issued by the MEGA and the other costs of the MEGA.** The surcharges are to be billed and collected by the local electric transmission and distribution utilities and remitted to the MEGA. For municipal track projects and related expenses, the surcharges shall apply only to ratepayers located in those municipalities participating in each syndicated project. For state track projects and their related expenses, the surcharges shall apply to all ratepayers in Maine.

The MEGA shall be explicitly prohibited from engaging in any of the following activities:

- Energy trading except to the extent necessary to sell the electricity generated by those renewable generation plants owned by the MEGA;
- Entering into any short-term or long-term energy contracts for speculation or hedging purposes;
- Acting in any manner as a retail electricity supplier for any ratepayers located in any utility service territory in the state;
- Selling or otherwise disposing of any environmental attribute in any form derived from electricity generated by a renewable generation plant owned by the MEGA, except through the retirement of such environmental attribute for the MEGA's account;[75] and
- Hiring persons to provide operations and maintenance services for any renewable generation plant owned by the MEGA.[76]

4.4.4 | Financing

All of the renewable generation plants owned by the MEGA will be financed through the issuance of revenue bonds.[77] These will be issued through the same channels that are available to similar authorities in the state, e.g., Maine Turnpike Authority, State Housing Authority. The intent is to create a structure that ensures the interest on all revenue bonds will be exempt from federal taxes to the maximum extent possible. All bonds issued by a MEGA must be approved by MEGA's Board of Directors.

4.4.5 | On Bill Cost Recovery

The primary source of revenue to the MEGA are renewable generation plant charges that are established by the MEGA and collected and remitted by the transmission and distribution utilities in Maine. MEGA's Board of Directors shall establish a revenue requirement for each fiscal year to support the operations and obligations of the MEGA. Using billing determinants for electric utility accounts in those municipalities participating in each syndicate and for the state as a whole that are provided by the local transmission and distribution utilities, the Board of Directors shall establish renewable generation plant charges for the recovery of the MEGA revenue requirement and submit those charges to local transmission and distribution utilities for the utilities to bill such charges.

The renewable generation plant charges shall be treated by transmission and distribution utilities for purposes of accounting as if they

[75] While the ability to sell RECs may offset a portion of the costs of MEGA-owned renewable generation facilities to the ratepayers or citizens in the municipality, such sales have no impact on overall CO_2 emission reductions, and arguably could lead to the purchasing entity taking fewer steps to reduce its own CO_2 emissions from energy use.

[76] The intent of this prohibition is to limit government's role in the MEGA to only ownership and financing. I believe that operations and maintenance of all renewable energy developed is best handled through contracts with specialized private sector entities that can provide more efficient scale and therefore lower costs.

[77] An outstanding issue is whether the state or a municipality should be permitted to extend to the MEGA its authority to issue general obligation bonds, either directly or through a loan guaranty arrangement.

were charges levied by the utility to recover its own costs. All payments received by transmission and distribution utilities shall be allocated pari parssu between the utility and the MEGA.[78] Those payments allocated to the MEGA shall be remitted to the MEGA within thirty days of the end of the calendar month in which the payments are received. Periodically, the transmission and distribution utilities and the MEGA shall true-up renewable plant generation charges to account for differences between expected and actual kWh usage levels in each municipality participating in a project syndication and for the state.

4.4.6 | Energy Market Settlements

Each MEGA shall sell 100% of the electricity (including energy, capacity and ancillary services, as may be applicable, but not including any environmental attributes) generated by each renewable generation plant it owns into the relevant wholesale market administered by ISO-NE or its counterpart for any plants located outside the New England Control Area. All sales shall be at the spot market price or its equivalent for those components of electricity for which a spot market does not exist. The MEGA shall contract with a third-party to enable all such sales to be made and to settle financially all such sales through the ISO-NE settlement process.[79] In no instance shall the beneficial title to the electricity generated by any renewable generation plant owned by the MEGA be held by any entity other than the MEGA prior to the point of its sale.

All revenue from the sale of electricity shall be remitted by the third-party in its entirety to the MEGA. These revenues will be allocated against the MEGA's revenue requirement and used to reduce renewable generation plant charges that would otherwise be required to cover MEGA issued debt and administration costs.

[78] The MEGA should apply the same bad debt/charity/uncollectibles factors to its revenue requirements as are applied by the transmission and distribution utilities.

[79] This could be done by the Efficiency Maine Trust.

4.4.7 | MEGA Risk Profile

A key consideration regarding whether a MEGA offers financial benefits to ratepayers is its risk profile and the amount of risk that is being borne by those ratepayers. I have identified four broad categories of risks that would be assumed by ratepayers under the MEGA structure. These are:

- **Technology Risk** - The risk that the technologies and generating plants invested in by the MEGA will become outdated or otherwise rendered uneconomic over the course of the life of the debt.
- **Construction Risk** - The risk that any renewable generation projects undertaken by the MEGA will experience cost-overruns and end up costing ratepayers more money than projected.
- **Performance Risk** – The risk that any generation technology or individual generation plant owned by the MEGA will not perform as expected once in operation.
- **Management Risk** – The risk that the management of any individual generation project by MEGA will be ineffective and lead to higher costs over the term of the debt than initially projected.

I discuss each of these risks below. On balance, I believe that these risks can be mitigated and in any case, that the monetary value of these incremental risks assumed by ratepayers represents a very small fraction of the savings afforded ratepayers through the MEGA structure.

4.4.7.1 | Technology Risk

Any technology, no matter how useful or cost effective when developed, is exposed to risks that technological change might render the technology obsolete or otherwise uneconomic during the term of its expected useful life. For example, new combined cycle generation technologies have resulted in the shut-down of many steam generating plants long before those plants exceeded their useful physical lives. In other cases, where electricity generation is tethered to a particular geographic feature such as river head for hydroelectric plants or wind corridors for wind turbines, upgrades to generating plants may be installed before the end of the useful physical life of the original equipment. In these and similar instances, economic considerations drive plant shut-down or modernization decisions. In shut-down scenarios, the expected incremental costs of continued operations exceed the expected incremental revenues the plant can produce, so it makes economic sense to shut-down rather than hemorrhage cash. In the modernization scenario, it may be cost-effective to maximize the economic value of a specific, scarce natural resource by replacing old technology with new technologies that convert the physical resource into electricity more cost-effectively at the same location.

The renewable generation technologies identified in **Table 4-1** and in the Maine pathway analysis in the previous chapters are unlikely to be subject to the first of the situations described above. These resources have essentially zero marginal costs, since they have no fuel costs or other variable operating costs. As long as it is possible to obtain even very small amounts of revenues from generating electricity, they will continue to operate. There is little to no risk to ratepayers that the marginal operating costs of these renewable resources will exceed the value of the electricity generated.[80]

The second instance of risk exposure, however, is more nuanced. Here, the risk depends on the technology and upon the scarcity of the geo-spatial locations of the natural resource that is being captured to generate electricity. As long as there is no scarcity of that natural resource, the very large amounts of new generation resources required for deep decarbonization means there is very little risk that there will be economic pressure to replace any original technology deployed prior to the end of its expected useful life. This is the case, for example, for solar PV, and given the relative amounts of generation called for, most likely for off-shore wind, wave and tidal technologies. It may be less true for on-shore wind, where, for example, we are now beginning to see repowering of some of the nation's oldest wind turbine projects 20-30 years after these first came on-line. That said, the very significant increase in the number of turbines required over the next three decades will require so much of a demand for new projects that it is not likely to make economic sense to repower generating plants before the end of their economic lives. To achieve Maine's target level of generation for on-shore wind under the pathway of 2,500 GW by 2050 will require the installation of more than 80 MW of new turbines each year. Given the imperative to construct new projects to achieve deep decarbonization, I see little risk that projects once constructed will pull financial resources away from new projects so that they can be upgraded.[81]

A different form of technology risk is that technological changes lead to lowering the cost of a generating technology over time. This could result in higher per unit costs for projects developed during the first ten-years of the transition period compared to projects done over the last ten-years, for example. Given the experiences of unit cost declines in solar PV and onshore wind over the past decade, I expect that this scenario is virtually certain. There is a good chance that late adopters of most renewable generation types will pay a lower per unit cost (in real terms) than early adopters.

While I believe that the risk of technology driven cost decreases is likely, I also believe that this risk is not one that has been or would be borne by IOU shareholders under the alternative structure in which IOUs are relied upon to finance the required generation. I am not aware of any case in which the timing of an investment decision by an IOU has been

80 As noted in the prior chapter, it is possible under certain market rules for prices to fall below zero. In such instances, the generator would choose not to operate.

81 We are seeing some repowering of wind projects across the country. I believe most of these are being driven by the financial benefits associated with bringing these repowerings on-line before the phase-out of federal tax credits, and not the economic imperative of capturing any incremental benefits from upgrading wind turbines at the site.

determined to be reasonable, yet where an IOU has not been able to recover fully both its investment and a return on that investment over the investment's useful life based solely on future declines in the unit cost of the technology. Accordingly, to the extent that an IOU is directed to take on investments in any generation technology at any time over the next three decades to achieve the societal imperative of deep decarbonization, I do not believe it likely that utility shareholders would ever be subjected to risk of non-recovery due to technology driven reductions in the unit costs of that technology in the future. All such risks would be borne by the ratepayers of the IOU. IOU shareholders provide no incremental risk protections to ratepayers.

Based on these considerations, I find that the potential costs to which ratepayers are exposed related to their assumption of technological risk through the MEGA structure are very small relative to the financial benefits such a structure offers these ratepayers.

4.4.7.2 | Construction Risk

Large-scale generation projects undertaken by IOUs have been plagued by cost overruns, many of which have been very substantial. The most egregious of these have involved construction of nuclear plants, although more recent examples of very large cost overruns have also included fossil-fuel generation plants that sought to achieve carbon sequestration and large hydroelectric projects.[82] In contrast, I am not aware of any recent projects undertaken by third-party developers using solar PV technologies, on-shore wind technologies or battery storage technologies that have experienced any significant cost overrun issues. Further, given the maturity of these technologies, I do not expect to see future projects plagued by cost overruns.

The last significant set of generating projects under the pathway are offshore wind projects. These projects represent about $20 billion of the more than $56 billion total investment. I do not expect to see any significant cost overruns from this technology for all shallow water projects that rest on the ocean floor. This technology has been deployed at scale in Europe successfully. This is not yet the case with deep water offshore wind that uses floating technologies, where the technologies remain largely in the experimental design phase. Deep water, off-shore wind does, however, represent a much larger share of renewable generation resources in the Maine pathway. To the extent these off-shore wind projects are undertaken at scale in the latter years of the 30-year transition as shown in Figure 3-3, I would expect their cost structures to be better known, their development less uncertain and construction risk more manageable.

4.4.7.3 | Performance Risk

With the exception of floating off-shore wind generation, the generating technologies in the pathway have performed under a wide range of operating conditions for a number of years. They have logged sufficient hours to demonstrate that they are not subject to any measurable systemic risk of non-performance. Even with floating offshore wind, the underlying physics and mechanics are well understood. The issues are how much the added installation costs will be and how well they will hold up in the ocean environment. Further, since one would not expect these technologies to be deployed at scale without first testing them under different operating conditions, I have postulated in the Maine pathway model in the previous chapter that they will not be constructed at scale until later in the three-decade window.

Project specific risk of non-performance or under-performance is also low across these technologies. Given the number of projects that will be constructed, it is virtually certain that some small number of them will not perform as expected over their useful lives. If expectations are set initially to something approximating average performance, then to

[82] The list of such projects is very long. Three of the most glaring recent examples of substantial cost overruns are the Santee-Cooper nuclear plant in South Carolina, the Kemper Project in Mississippi and the Muskrat Falls hydro project in Labrador, Newfoundland, Canada.

a significant degree, these under-performing projects will be offset by those projects that over-perform, so that on balance, one would expect that the portfolio of all projects to perform according to specifications. Nevertheless, there is some risk that any one project in the MEGA portfolio is not representative of the full spectrum of projects, especially if the number of individual projects within the portfolio is small. In this case, the MEGA subscribers to that generation project could be exposed to some small degree of performance risk; however, I believe that this risk is manageable through careful project selection and diversification by taking partial ownership of a large number of projects.

4.4.7.4 | Management Risk

The governance structure, decision-making processes and day-to-day management of a MEGA must be carefully considered to ensure that management risks are identified and mitigated to the fullest extent possible. In this sense, a MEGA is no different from any state electric utility, public authority, commission or board.

It is difficult to quantify management risk. Certainly, there are cases that can be cited of poor performance by public or quasi-public entities stemming from poor decision-making processes, inadequate systems of oversight and control and ineffective employment practices. These tend to be most conspicuous where the entity is charged with delivering an ongoing service; however, they have also occurred in the bidding, award and management of contracts for third-party work. It is this latter case that is especially relevant for MEGAs. I believe that this risk is best managed through subjecting all procurement decisions of a MEGA to the same administrative and review procedures used by similar state authorities for major capital purchases.

I do have some concerns that the governance structure of a MEGA may subject its planning decisions to political and related considerations that could expose ratepayers to higher costs and possibly delays in implementation. This risk, however, is not fundamentally different from what would be expected to occur under an IOU structure, especially if the IOU is specifically charged with carrying out a long-term public policy of deep decarbonization.[83]

On balance, I am not convinced that ratepayers would be exposed to measurably more risks when MEGAs are established to carry out the social policy of achieving deep decarbonization as compared to the case where IOUs are charged with that same function. While there may be some differences in governance and oversight structures, decision making processes and internal operations between a MEGA and an IOU, I do not believe that one provides inherently less risk exposure to ratepayers with respect to carrying out a social policy of achieving deep decarbonization by 2050. Further, to the extent that an IOU structure might provide a small degree of risk shifting from ratepayers to shareholders, I believe that any such incremental risk shifting is worth only a tiny fraction of the much higher (approximately double) revenue requirements resulting from the cost of capital differential between the two organizational structures.

4.5 | Summary

The essential aspect of transitioning the Maine or the U.S. economies away from fossil fuels to a zero-carbon state in 2050 is the ability to raise the vast amounts of capital necessary to support the investments in renewable generating resources and battery storage units to meet the electricity use requirements resulting from beneficial electrification of heating, industrial and commercial processes and transportation. In this regard, such a transition is no different from previous transitions – the development of railroads,

[83] There is an extensive literature regarding regulatory capture and rent-seeking behaviors of regulated companies, much of which focuses on IOUs. It is not necessary for the MEGA to be a perfect structure; it is only necessary for it to perform better than IOUs have historically performed. Unfortunately, this is not a very high bar.

the electrification of America, the expansion of the automobile and trucking industries and first the telephone and most recently the internet in the communications sector. In one very important respect, however, each of these was very different from the transition to a zero-carbon state. Each of these provided significant economic return in the form of improved productivity and living standards that could be captured by the users of the new technologies. In contrast, beneficial electrification and deep decarbonization provides little or no such opportunities. Its primary value is the creation of public goods – reducing global climate change and improving air quality. This makes the task of raising the capital to accomplish the transition more difficult.

I believe that the best means to raise capital to support the transition is through a state entity – the Maine Electric Generation Authority or MEGA. This entity brings two significant advantages to the effort to achieve deep decarbonization. First, it enables capital to be raised on a tax-advantaged basis while maximizing financing leverage. This results in a more than 50% reduction in the cost of capital. As we have seen in Chapters Two and Three, this reduction has a very significant impact on overall costs to residents and businesses. Second, by establishing two separate tracks one of which is a voluntary option for municipal participation in generation project syndication, those communities that place a stronger emphasis on the public good benefits of deep decarbonization are enabled to act as adoption leaders, thus avoiding the contention that often accompanies government mandates. While I do not expect voluntary efforts to be sufficient to achieve the zero-carbon goal by 2050, I do believe that this structure will provide for more rapid actions during the initial years of the transition period. I also believe that the successes of these early adopters will make it much easier to impose mandates later in the transition period should that be necessary.

The underlying concept and proposed structure of a MEGA is certainly not new. Many states have established such entities in one form or another to provide various utility-like services, including drinking water, sewer and waste water treatment, transportation infrastructure, affordable housing, telecommunications and electricity. We can learn from these experiences. Perhaps the most important lesson is to limit the functions of the entity to those areas with the least amount of exposure to risk, and in all cases to ensure that the actions of the entity are tightly controlled to minimize its exposure to politics. I believe that the principles I have set forth in this chapter accomplish both objectives.

Chapter 5

Energy Policies to Achieve Zero-Carbon By 2050

5.0 | Introduction

The ability to address global climate change and to slow down and ultimately reverse the warming of our planet depends on achieving the deep decarbonization of the world economies over the next three decades. This requires the complete transformation of major sectors of our economies to electrification, supported by an unprecedented expansion of zero-carbon renewable electric generation resources. In the U.S., researchers have estimated that this will require investments well in excess of $15 trillion over the next thirty years; for Maine, I have estimated that the required investment will be about $56 billion. These total investments are roughly equivalent to one year of U.S. GDP and Maine GDP, respectively.

I have demonstrated that the transformation of Maine's energy sector can be accomplished without increasing the total amount Maine spends on energy each year. Were Maine to establish a goal of near zero-carbon emissions by 2050, I have shown that there is a pathway that enables Maine to achieve that goal without imposing any additional costs on its residents and businesses over the thirty-year transition period from 2020 – 2050. Stated somewhat differently, if we impose the requirement that Maine's economy must be essentially carbon free by 2050, I have demonstrated that this can be accomplished without incurring any incremental energy costs over this transition period.

Demonstrating possibility is an important first step – a necessary condition, if you will, to achieving the objective of eliminating CO_2 emissions by 2050. Possibility, however, does not mean probability, which, itself, is still far short of the certain elimination of carbon emissions that scientists tell us is necessary if we are to avoid the most severe consequences of global warming.[84] One of the more comprehensive studies of world energy use through 2050 projects that CO_2 levels will fall globally from 32 Gt/year today to 18 Gt/year; that the world will reach the 2°C mark by the late 2030s; and that the world will not achieve a near zero-carbon outcome until 2090.[85] Clearly, this does not cut it.

The movement from possibility to probability to certainty by 2050 will require governments to take more aggressive actions than they have to date. In this chapter, I set out a wide range of state policies that I believe will need to be adopted in Maine to move from the

[84] Intergovernmental Panel on Climate Change, IPCC Press Release for the IPCC 5th Assessment states, "The report finds that limiting global warming to 1.5°C would require "rapid and far-reaching" transitions in land, energy, industry, buildings, transport, and cities. Global net human-caused emissions of carbon dioxide (CO_2) would need to fall by about 45 percent from 2010 levels by 2030, reaching 'net zero' around 2050. This means that any remaining emissions would need to be balanced by removing CO_2 from the air." October 8, 2018. http://www.ipcc.ch/pdf/session48/pr_181008_P48_spm_en.pdf

[85] Energy Transition Outlook – 2018: A Global and Regional Forecast to 2050, DNV GL, November 2018.

realm of possibility to the realm of probability. I have organized this discussion into four topic areas – beneficial electrification, renewable generation development, deep decarbonization financing and electric grid expansion. This is for convenience. As I discuss, policies in one area can have important impacts in other areas. For example, a policy that promotes residential roof-top solar that does not also address the expansion and modernization of the distribution grid will not yield the intended results. Similarly, an incentive to encourage conversion to passenger EVs can be enhanced by electric rate designs that provide for low cost charging of those vehicles during periods of maximum solar generation.

5.1 | Policies to Promote Beneficial Electrification

I focus on two of the three sectors that must undergo conversions from fossil fuels to electrification – transportation and heating. The pathway provides for more steady conversions in these two sectors, beginning slowly in 2020. The third sector – industrial and commercial processes – is assumed to undergo conversion later in the transition period when technologies are more mature. At this time, I have not seen evidence sufficient to make me believe that this sector is ripe for targeted policies in the early years of the transition period.[86]

I expect that much of the early adoption of passenger EVs will be as vehicles that are used primarily for commuting and other short-haul trips. These vehicles will be charged largely at home, consistent with the results of the California study discussed in Chapter Two. This adoption can be supported by electric rate designs that recognize the incremental nature of this end use of electricity, and the fact that over the next decade, charging EVs imposes no additional cost burdens on transmission and distribution networks when the vehicles are charged overnight. As the range of EVs increases and the technical capability of charging improves, I expect that EVs will displace all passenger vehicles. This displacement will need to be supported by expanded charging opportunities along transportation corridors within the State. Further, as distributed solar PV generation expands, it will be beneficial if EVs absorb some of this increased generation by charging during daylight hours at workplaces or other public parking facilities.

I have identified six policies that should be adopted by Maine to facilitate the electrification of Maine's transportation sector. These are:

- Delivery Service rates for Maine's electric utilities should be restructured as two-part tariffs consisting of a monthly flat customer charge that recovers the cost of interconnecting the customer to the grid and a usage-based demand charge that varies by time periods based on the stress and therefore additional costs such usage imposes on the electric grid. This rate structure should be capable of sending reasonably precise market signals to electricity consumers (and distributed energy resources) by taking full advantage of the Advanced Metering capabilities the utilities have deployed and the billing system enhancements that are being paid for by their ratepayers. All such tariffs will need to be dynamic and adaptable to what will be rapidly evolving electric grid and energy market conditions, as Maine undergoes beneficial electrification and deep decarbonization during the thirty-year transition period.
- Building permits for new commercial and industrial construction or retrofits of existing facilities that currently impose mandates with respect to parking facilities

[86] I do not specifically address policies that promote energy conservation and increased efficiency. To some extent they are considered in the modeling in the previous chapters. For example, we have assumed zero electricity load growth over the entire 30-year transition period as the net effect of increased conservation and efficiency, on the one hand, and population growth and increased energy use, on the other. Similarly, with respect to transportation, we have modeled in EV efficiency improvements by assuming performance levels above those achieved in today's EVs. Increases in efficiency and conservation beyond those included will reduce electric loads and therefore the amount of renewable generation resources required, with the result being lower total energy expenditures and a faster transition to a zero-carbon economy.

as a condition for the issuance of a permit should be further conditioned to require that 5% of such parking spaces be equipped with charging stations in the first year of operation, and that this percentage should increase to no less than 10% within the first 10 years of operation.

- Municipal ordinances should be amended to require that all parking garages or other public parking lots (including garages and lots owned and/or operated by government entities) have a minimum of 1 charging station for each 20 parking spaces by 2025, and that this number shall increase by 1 every five years until 2045, when 25% of all parking spaces shall be so-equipped.

- The Maine Department of Transportation ("MDOT") should provide grant money on a competitive basis to private, non-utility entities to provide EV charging stations along major arteries entering and leaving Maine. The location of those stations should be determined by MDOT with the purpose of encouraging and facilitating the use of passenger and commercial EVs for long-haul trips in and through Maine.[87]

- The Maine Department of Education, in coordination with MDOT, should require that a minimum of 150 school buses each year be converted from fossil fuel to electric, beginning in 2030, or earlier depending on the price and availabilities of qualified vehicles.

- The MDOT and the Maine Secretary of State should develop a proposal to tax EVs based on miles driven in lieu of gasoline consumed.[88] All monies collected would flow into the State's Highway Fund. The gasoline tax should remain in effect for gasoline and diesel vehicles until the percentage of each class of vehicles registered in the State that are EVs is so high as to make the continued collection of gas taxes a financial burden to the State. At that point the gasoline tax should be eliminated and all vehicles should be taxed for purposes of funding the State's Highway Fund based on miles driven.

I am reluctant to recommend aggressive state policies to promote the conversion of home and commercial heating systems from natural gas and distillate fuels to electric heat pumps at this time. Instead, I believe that the incremental advantages heat pumps have by providing summer air conditioning will be sufficient to encourage their adoption by many Mainers. Further, we are seeing these systems become the default option in much new construction, especially multi-family residential units. One exception I make is for low-income housing, where tenants are simply not able to support the increases in rents necessary to pay for the conversion. If conversion and adoption rates for heat pumps lag behind those levels in the pathway discussed in Chapter Three, I believe more aggressive steps should be taken. In the meantime, I recommend the following state policies:

- The Efficiency Maine Trust (EMT) should maintain its programs of education and promotion of heat pumps and its grant programs to support heat pump installation. With respect to the latter, monies should be targeted over the next 10 years to low income housing units that are currently heated with distillate fuels, combined with building envelop improvements.

- State, County and Municipal Governments should initiate long-term capital plans to convert a minimum of 10% (measured by square footage) of all government owned heated space (including schools) from distillate fuels to heat pumps by 2025. This should be expanded further to 30% by 2030, 60% by 2040 and 100% by 2050. Further, all newly constructed or renovated buildings should be required to be heated with ground-source or air-source heat pumps. As the saying goes, when one is in a hole and sinking, the best strategy is to stop digging.

[87] The Federal Highway Administration has designated eight major road corridors in Maine for alternative fuel vehicles as part of an effort to build out a statewide network of fast charges. April 29, 2019, https://www.mainebiz.biz/article/federal-government-designates-eight-alternative-fuel-corridors-in-maine

[88] The current state tax on gasoline is $0.3001 per gallon. Assuming an average passenger vehicle gets 25 mpg, the gas tax is equivalent to a mileage tax at the rate of $0.012 per mile.

Maine must be careful in implementing the above policies so as not to impose the costs of these policies on electricity ratepayers through such devices as system benefits charges and renewable portfolio standards. Doing so will result in increasing the price of electricity and exacerbating the price divergence between the price of electricity and the price of fossil fuels. As I noted in Chapter Three, this differential will slow the pace of beneficial electrification by increasing the costs of switching to electricity from fossil fuels in transportation, heating and process applications.

I am reticent to recommend at this time that Maine take any unilateral actions to adopt a carbon tax on fossil fuels, even though I believe that such a tax will ultimately be necessary if we are to achieve beneficial electrification through any means other than government mandates. I believe that a better political course is to allow the recommendations proposed in this Chapter to be implemented and to monitor energy use and CO_2 emissions over the next ten years. If at that time, Maine is lagging behind the path of beneficial electrification set forth herein and the economic value of conversion in the transportation and space heating sectors to electricity is being impacted by the relatively low cost of fossil fuels, a carbon tax should be adopted.

5.2 | Policies to Promote Renewable Generation Development

The pathway to a zero-carbon economy by 2050 I have identified in Chapter Three requires the development of 7,500 MW of solar PV, 2,500 MW of on-shore wind and 5,000 MW of off-shore wind and roughly 250,000 MWhs of battery storage. A small part of this development will be supported by investment decisions of individual homeowners or businesses who see value in self-generation and, for some, moving more rapidly to reduce CO_2 emissions. I expect these investments to consist largely of rooftop solar PV systems and perhaps some limited battery storage units. The lion's share of the required renewable energy development, however, will need the support of the Maine Energy Generation Authority described in Chapter Four. MEGA is intended to rapidly accelerate the demand for these new generation capacities and provide the financial capability to support their development. I identify below a number of areas in which targeted state policies can facilitate the development of these renewable generation resources.

The first area that requires policy attention relates to the interconnection of renewable generation projects to the electric grid. While some progress has been made in streamlining interconnection studies and standards, especially for smaller-scale projects, the interconnection process continues to present problems for project developers, especially in those instances in which the utility identifies necessary upstream grid improvements. Under current rules, any available capacity on the grid to support generator interconnection (capacity that has been paid for by ratepayers) is allocated at no charge to interconnecting generators on a first-come, first-served basis until such capacity is exhausted. At this point, the next generator in the interconnection queue must pay the full cost of all upstream improvements and upgrades to the grid that are required to interconnect its project. For small projects, the costs of this upgrade can amount to multiple times the cost of the project itself. Adding insult to injury, the next and succeeding generators in the queue are able to utilize any spare capacity created as a result of the upgrades paid for by the previous generator in the queue. Not surprisingly, this policy acts as a serious drag on the development of renewable generation projects, and in some states such as Hawaii and California that are further ahead of Maine, has resulted in generation interconnection moratoria.

This current structure is intended to ensure that large-scale generators bear the interconnection costs for their location decisions to discourage uneconomic location decisions, the cost of which would otherwise be borne by ratepayers. This policy has merit for large-scale generation projects. However, today, the vast majority of interconnection requests are not from large nuclear, gas or coal plants, or even wind farms, but rather are from small-scale distributed generation resources, many of which are interconnected behind the customer's meter. The current interconnection process has outlived its usefulness. The interconnection queue and the allocation of interconnection costs need fundamental change.

One proposal for addressing this issue is the so-called "clustering approach". This approach allows multiple generators to pool together to pay for grid related upgrades necessary for their interconnections. While there may be some cases involving a small number of very large-scale projects located in the same region of the electric grid where clustering could work, I am very skeptical that clustering will be effective in the majority of cases, especially those involving thousands of distributed solar PV installations and battery storage generation resources.

I believe that a better approach is one that facilitates the interconnection of small-scale projects, while preserving the price signaling feature of the current process for large utility-scale developments. This can be accomplished by allocating to electric loads in Maine the first $5 million of any upstream grid costs required to interconnect a generator. This compromise relieves distributed generation resources of the need to upgrade the immediately upstream substation as well as any feeders, reclosers, switches or other equipment located on the circuit serving the interconnecting generator, since these costs are almost always less than $5 million. On the other hand, those large-scale generators whose interconnection may impose significantly more costs on the utility in the form of new substation construction, new transformation capacity transmission line upgrades and other electronic equipment, will bear all costs in excess of the $5 million.

A second critical factor is property tax. The development of sufficient renewable generation resources to support beneficial electrification involves the substitution of capital investment in plant and equipment for the use of fossil fuels throughout the economy. The property tax incidence of this conversion, absent any change in state tax policies and assuming MEGA property would otherwise be subject to property taxes in the jurisdiction in which it is located, is to increase property tax receipts at the municipal level.[89] This will impose a significant cost burden on the MEGA.[90] It will also represent a revenue windfall to the municipalities in which generation resources are located, since this is revenue that they would not have received but for state policy. Finally, the renewable generation developments that MEGA will own will impose essentially no incremental demands on municipal services and thus no increase in municipal costs. Unlike housing developments, the MEGA projects bring no children to be educated; unlike commercial buildings, they bring virtually no traffic to be accommodated beyond the short-term construction period; and unlike industrial plants, they bring no obligations for sewerage or other waste treatments. Accordingly, I recommend the state exempt from municipal property taxes 100% of all MEGA owned real estate and business or personal property that is used directly or indirectly in the generation of electricity from zero-carbon, renewable energy generation resources. In lieu of property taxes, renewable generation projects should make reasonable contributions to the host communities related to the costs of providing police and fire protection services.[91]

89 I do not believe that investments in offshore wind projects will be subject to municipal property taxes, since it is unlikely that any of this investment will occur within the jurisdictional boundaries of any Maine cities or towns.

90 If we assume that the average property tax rate in Maine is $15 per thousand dollars of valuation, annual property taxes will amount to 1.5% of the original investment amount. Assuming a 3% cost of capital for MEGAs, the cost to the developer of property taxes is equal to 50% of the total debt service costs.

91 I have not gone so far as to require the exemption of all solar PV or wind generation from municipal property taxes; however, I believe that consideration should be given to this position in the context of business equipment property tax exemptions. I also do not believe it is appropriate for municipalities to levy property taxes on behind-the-meter solar PV systems installed on residences or businesses. To the extent that such installations increase the value of the property, they will be captured through overall assessments. If they do not increase property values, then they should

I believe that solar PV, on-shore wind or shallow water off-shore wind generation should not require further subsidies or incentives from the state other than those noted here and in other sections of this chapter. Additionally, once the reforms advocated herein are fully implemented, I recommend that all net metering in any form be phased out over a period no longer than 10 years. While various net metering structures may be important during the early stages of distributed generation development, the opponents of net metering are correct in one respect – over the longer-term net metering is an unsustainable policy and will have to be abolished when the costs of solar rooftops impose too great a burden on those without such facilities. Instead, I believe that with the correct rate design for delivery service and the restructuring of key aspects of wholesale energy markets, the layered values that distributed solar PV systems provide to the grid can be monetized and captured by these systems.

Deep water, floating off-shore wind is a different matter. Since this technology remains in its early development stages, I believe there is a limited role for the state to play in contributing to its further development. I have identified the following policy initiatives to accomplish this:

- The State should provide continued support for the University of Maine to Aqua Ventus project. This support should include a new negotiated long-term contract to purchase the generation output from the project as well as support for the University's ongoing efforts to secure research and development funding from the Department of Energy.

- In anticipation of significant development of Maine's deep water off-shore wind resource, Maine should initiate a five-year planning process to interface with the federal government regarding the issuance of long-term leases to generation developers and with the utilities and ISO-NE regarding the development of an off-shore transmission grid to interconnect this generation to the regional transmission grid.

In addition to the above policies, I believe that municipal ordinances need to be reexamined in the context of widespread development of distributed solar PV systems. Among the items that I believe warrant further consideration are the following:

- To free up roof space on commercial and industrial buildings to facilitate solar PV development, building set back requirements for buildings located in non-residential zones should be relaxed to allow for the placement of HVAC systems and other equipment, that would otherwise have been located on the roof, in the space in those setbacks. This modification should only apply where rooftop solar is installed.

- Property rights to solar irradiance need to be incorporated into zoning ordinances to protect investments in solar PV systems from actions of abutters that would impact generation output.

- Municipal ordinances should not be permitted to prohibit the development of solar PV systems in any manner consistent with the zoning for the property. This includes prohibitions designed to protect open space or related in any way to the visual impacts of installed systems.

Finally, municipalities should consider imposing mandatory rooftop solar PV systems on all new construction. This will add costs to new homes and commercial buildings, but these costs will fall as the cost of solar falls. Even at today's installation costs, a 2,000 sq.ft. home with a 7 kW solar PV installation costing $17,000 net of the 30% investment tax credit will add less than $10/sq.ft. to construction costs. With low-end construction costs in the $100 to $150 per sq.ft. range, this is less than a 10% increase, much or all of which is offset over time by savings in electricity costs.

not be separately assessed – any more than an upgrade to architectural roofing shingles, for example, would result in a separate assessment.

5.3 | Policies to Enable the Raising of Necessary Capital Investments

The transformation of Maine's economy from one heavily reliant on fossil fuels to a state of near zero carbon emissions by 2050 requires very large capital investments. The ability to raise and deploy capital to support beneficial electrification, renewable energy development and deep decarbonization is the *sine qua non* for addressing global climate change. I argue that this is best accomplished through the creation of the Maine Energy Generation Authority. The MEGA represents an aggregation of the demand for the electricity generated by renewable resource generators and is a source of highly rated and inexpensive investment capital.

The first step in creating the MEGA is the enactment of legislation that defines its purpose, establishes legislative authority for its existence, sets forth its governance structure and outlines the set of activities it can engage in and the actions it can take.

The legislation should be structured as enabling; it should impose no mandatory obligations on Maine's municipalities. This allows those municipalities that have adopted aspirational goals of reaching zero-carbon by dates certain to take unilateral actions that will move them toward the timely achievement of such goals by participating in renewable generation project syndications opportunities through MEGA. These municipalities will serve as examples to others that follow about how best to accomplish the transformation of their energy sectors.

I recommend that the Efficiency Maine Trust be directed to set aside $250,000 a year in each of the next four years to provide planning/implementation grants of no more than $25,000 on a competitive basis to municipalities that wish to participate in syndicated renewable generation projects through MEGA. To assist municipalities and to guide future state policy, I recommend that the Governor's Energy Office or its successor serves as a data repository for all activities undertaken by MEGA, and that it provides comprehensive reports every two-years to the legislature on MEGA's activities and performance.

5.4 | Policies to Support the Expansion of the Electric Grid

The existing transmission and distribution electric grid has only a fraction of the physical capacity and internal intelligence to handle the flows of electricity that will occur by 2050. Very large investments will be required by both CMP and Emera Maine to accommodate the nearly 5-fold increase in peak loads that will result from beneficial electrification and the hundreds of thousands of new distributed generation resources and utility-scale renewable energy projects that will deliver electricity. I believe that it is critical to the achievement of a zero-carbon economy by 2050 that the electric grid not act as an impediment to any electric consumer's or renewable energy resource developer's efforts to move Maine in that direction. To ensure that this does not occur, I propose the following policy recommendations:

- Distribution planning must transition from a process that remediates current grid conditions to one that is forward looking and accommodates rather than reacts to expected loads and distributed generation.
- Utilities must develop to the fullest extent the capabilities of technologies, systems and information already built into the smart grid and make further investments in technologies to enable the grid to function as an integrated network that interconnects millions of end uses and distributed generation locations on the grid.
- Utilities must develop the full capabilities of smart electric grids and their new billing systems to accommodate alternative rate designs described earlier and to enable the accounting and billing arrangements to support the renewable energy surcharges

that will be established by MEGA.

- Immediately, utilities should shift their investment focus away from building redundant transmission and toward building out the distribution grid to accommodate increased electrification and distributed generation. During this period, Maine should reevaluate the definition of reliability of an electric system that is fully networked and 100% renewable and revise transmission and distribution planning standards accordingly.[92]

In addition to these policy recommendations, I make one overarching recommendation based on the experiences of the telecommunications industry. I strongly recommend that Maine adopt the electric sector equivalence of "net neutrality" from the outset. This means that the electric grid must be defined and operated as a common carrier, and further that the owners of these grids must be prohibited from using their grids to deliver electricity generated from any entity in which they have financial interests. This strict form of "grid neutrality" was the basis of Maine's Restructuring Act almost 20 years ago; it should be the guiding principle for the future

[92] This policy will likely require the cooperation of ISO-NE and various regional and national reliability organizations.

Chapter 6

Concluding Thoughts

of Maine's electricity sector.

I set out to understand what actions are required to achieve the aspirational goals being adopted by communities and interest groups in Maine today of a carbon-free Maine economy by 2050 and how much these actions would cost Maine residents and businesses. My initial expectations were that Maine would face a "Hobson's Choice" of having to choose between a healthy economy and jobs, on the one hand, or a clean energy future, on the other. Instead, I have identified a pathway to a zero-carbon economy in 2050 that does not jeopardize Maine's economic health by imposing rising energy costs on Maine businesses and residents. This pathway results in the achievement of deep decarbonization through beneficial electrification and renewable generation resource development, while keeping the annual amount of money Mainers spend on energy at a level consistent with the average annual amount spent over the period 2000 – 2016.

I am the first to acknowledge that this pathway is defined by my assumptions. Any prediction of Maine's economy thirty-years into the future must be – my predictions can be no different. This means that the plausibility of the pathway depends on the reasonableness of those assumptions. I have thought at great length about each of my assumptions; I have described how each is reasonable on its own, and taken together, they are internally consistent. This means that my defined pathway is possible – the technologies are feasible; the cost structures are attainable; and the investment and energy use decisions of Maine residents and businesses are plausible. It does not mean, however, that this pathway represents a certain future or even a likely one. There are many serious impediments to its realization. In Chapter Five, I identify a broad range of state policies and actions that can address some of the more critical of these impediments. If they are all adopted, I believe that Maine will be heading in the right direction.

Direction matters, but it is not the sole indicator of successful performance. The speed with which Maine can transform its economy to be carbon-free is critical. As the recently released IPCC report stresses, time is of the essence. I have defined that time frame to be 2050, consistent with current science. I believe this represents an acceptable balancing of the imperative to act with all deliberate speed to prevent the worst effects of global warming with the need to manage the impacts of transformational change on the economy and society, more generally. Allowing for a thirty-year transformation reduces dislocation costs by allowing residents and businesses to adjust their capital stock and operating practices to shift from fossil fuels to electricity. I believe that this is sufficient time to enable the conversion of virtually all passenger vehicles, buses and trucks to electricity. During this period, Maine's entire fleet will undergo between two and three complete change-outs as existing vehicles age and are replaced. These replacements can be electric vehicles.

The transition period is also long enough to facilitate the replacement of many of the fossil fuel heating systems in homes and businesses with electricity. Nevertheless, I expect this transition to be more difficult than for transportation, given the longer life of heating equipment and the cost of its replacement, especially where major retrofitting is required. I anticipate that government may have to step in by modifying building codes to require conversion, if the conversion process is not moving as rapidly as necessary.

I am less certain of the time it will take to convert industrial and commercial processes from fossil fuels to electricity. The types of such processes are highly varied, and for most processes I am not aware of any off-the-shelf conversion equipment. This means that each case may require an engineered solution. This could increase costs and slow conversion times. In addition, I do not believe that this conversion will be able to capture the significant energy efficiencies that are available through electricification in the transportation and heating sectors. As a result, I have delayed the conversion of this end use in the model to the last third of the transition period and expect that full conversion will require some form of government mandate.

As long as there is sufficient capital available at a reasonable cost, the thirty-year transition period should easily accommodate the amounts of solar PV, on-shore wind and shallow water off-shore wind generation specified in the pathway. I believe that it will also accommodate the development of deep water off-shore wind generation in the Gulf of Maine in the latter third of the transition period and the proposed deployment of battery storage systems, although each will depend on continuous advancements in technology and the falling unit costs such advances will bring.

The state policies I have proposed to move Maine along the pathway represent a blend of incentives and enabling legislation and contain only a few narrowly focused mandates. I am optimistic that the combination of these and a well-spring of support in selected communities across Maine will result in voluntary actions by residents, businesses and these communities to get us started. For example, I believe that the cities of Portland and South Portland are poised to take actions to support their municipal carbon reduction goals, as are other towns that have adopted as town policy a zero-carbon goal by the middle of this century. I also believe that Maine's Yankee culture of "common-wealth" will lead other communities to follow.

The most serious impediment to broad-scale and rapid movement along the pathway will be our ability to overcome two fundamental but related problems in economics – the commons problem and the free rider problem. The commons problem posits that people will act in their private self-interest to use as much of a common resource as possible before that resource is fully depleted by the actions of others. The free rider problem states that people will not contribute to the provision or protection of a common resource or good, but instead will seek to rely on the actions of others to provide or protect that good. Examples of the commons problem and the free-rider problem that are well-known in Maine involve the management of Maine's fisheries and the support of public broadcasting, respectively. Unfortunately, climate induced global warming combines both of these problems, along with two other factors – an uncertainty as to the exact relationship between fossil fuel use and global warming and the fact that the direct impacts of a warming planet may be perceived to be very different depending on location. This has made it more difficult to achieve consensus around the imperative to act and to act quickly. If even a few of the world's major countries pursue policies that result in their continued exploitation of the atmosphere's CO_2 carrying capacity or lead to their failure to invest in technologies to achieve deep decarbonization of their economies, no actions that Maine takes will have the desired effect of preventing the consequences of global warming.

There is another consequence of the failure to act collectively, this one closer to home. My finding that Maine can achieve a zero-carbon economy by 2050 at no incremental energy costs to its residents and businesses depends on all states in New England undertaking similar efforts with respect to electricity generation. They also must convert their electric generation to zero-carbon emission renewable generation resources by 2050. Since all states are part of the same integrated electricity grid and wholesale market, it is only through collective actions across the six New England states, that Maine will receive price suppression benefits to offset the capital costs required to support its conversion to 100% renewable generation (inclusive of battery storage). As a small actor, Maine's ability to internalize the beneficial consequences of its actions is impossible. It will pay 100% of the costs of those beneficial actions yet receive only a very small share of the benefits from those actions. This could put Maine in a most uncomfortable position.

Fortunately for Maine, there is very strong indication that other New England states are pursuing deep decarbonization of their economies by expanding significantly the percent of renewable electricity generation resources they rely on for energy. All the New England states are members of the Regional Greenhouse Gas Initiative or RGGI, which calls for a reduction in carbon emissions of 80% by 2050. Individually, Massachusetts, Connecticut and Rhode Island have each enacted legislation requiring a reduction of CO_2 emissions in the state of 80% by 2050. Vermont has pursued a similar course and is in many respects further along the path than the other New England states. It has an aspirational goal of 80%-95% by 2050. New Hampshire also has an aspirational goal of 80% by 2050. The pathway I have identified will move Maine largely in parallel with these other states, thus enabling Maine to realize the full economic and environmental benefits of its actions through the New England electric market.

There is no mechanism, however, through which Maine's actions can be guaranteed to reverse global warming and result in clean air for its citizens. For better or worse, Maine is dependent on the collective actions of close to 200 countries and 7 billion people to achieve this outcome. What I have shown by identifying a pathway through which Maine can achieve zero-carbon emissions by 2050 without incurring any additional energy costs is that Maine can act as a responsible global citizen without damaging the economic well-being of its citizens. This is a very important finding. When there is no cost to taking the moral position, there is no excuse for not taking it.

Dr. Richard Silkman is a Yale University Ph.D. economist and a nationally recognized expert in the regulation of public utilities, the development of competitive energy markets and the development, licensing and operation of power plants, including hydroelectric generating stations. Dr. Silkman has extensive experience in a wide range of settings, including education, government, consulting and the private sector. He has served as an expert witness before a number of state public utilities regulatory commissions, as well as advised state legislatures on matters related to electric utility regulation and deregulation.

Dr. Silkman is the founding partner and CEO of Competitive Energy Services, an energy consulting company based in Portland, Maine, that provides energy procurement and consulting services to companies, institutions and governments across the country. He is also the founder of GridSolar, a company established to develop non-wires alternatives to transmission lines to provide reliability to electric grids. In addition, he founded the Kennebec Valley Gas Company to develop a natural gas pipeline that is providing natural gas service to businesses and homes along the Kennebec River from Gardiner to Madison and Beaver Ridge Wind, which developed the second large commercial wind project in Maine.

Previously, Dr. Silkman was appointed by Governor John R. McKernan, Jr. to direct the Maine State Planning Office, a cabinet-level office. Dr. Silkman served as the chief policy advisor to the Governor on matters related to economic policy, energy, hydropower and river management policy, telecommunications regulation, state tax policy, health care regulation and cost-containment and land-use and natural resources policy.

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