White Paper:

Analysis of Estimated Emission Benefits of Maine Wind Farm Generation

Prepared for:

MREA Maine Renewable Energy Association

by:

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March 11, 2015

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Executive Summary

Conflicting information in circulation on the emission impacts of increasing wind generation in Maine inhibits a broader understanding of the costs and benefits of wind power by Maine's legislators and policy-makers, members of the media, and the general public. To contribute to a clearer understanding of these impacts, the Maine Renewable Energy Association ("MREA") sought a rigorous, credible and relevant estimate of actual and projected emission impacts of wind generation in Maine.

In pursuit of this goal, MREA commissioned Sustainable Energy Advantage, LLC ("SEA") to develop a white paper estimating the emission impacts resulting from current and projected levels of wind power in Maine. To accomplish this task, SEA estimated the impact of wind in Maine on reducing emissions from key pollutants.

SEA first estimated the annual and temporal production of the existing wind fleet, as well as that of a projected Maine wind generation fleet expanded to 1,782 MW by 2020. SEA considered the production of these wind generators under a range of future transmission constraint scenarios and associated levels of curtailment.

Next, SEA estimated the direct emissions reductions from the regional power supply mix as a result of Maine wind power's displacement of fossil fuel generators which would otherwise need to operate.

As a final step, SEA estimated the indirect, increased emissions associated with the increase in fossil fuel power plant 'cycling' required to integrate an increased quantity of variable generation to yield the net emission reductions attributable to wind power.

Even before the introduction of significant wind power in Maine, Maine's generation mix – due to its existing renewable energy fleet - is considerably less carbon-intensive than most of areas of the nation. Nonetheless, the past and future additions of wind power in Maine, in addition to making central contributions towards recent progress toward meeting the regional clean energy goals, are important, necessary and effective contributors to furthering progress towards meeting the state's and the region's greenhouse gas reduction and other clean energy goals. As further described in this paper, SEA estimates that, in 2013, wind energy in Maine reduced CO_2 emissions by 490,000 tons,[1] SO_x emissions by 201 tons, and NO_x emissions by 123 tons. SEA forecasts that, in 2020, wind energy in Maine will reduce CO_2 emission by between 2.05 and 2.21 million tons, SO_x emissions by between 90 and 97 tons, and NO_x emissions by between 355-380 tons.

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[1] Where used in this paper, Tons is intended to mean Short Tons (i.e., 2000 lbs.)

Table 1: Net Emission Reductions, - Annually (Tons)

	2013-Actual	2020 - High Production Scenario	2020 - Low Production Scenario
MW Capacity	431	1782	1782
GWh Production	1,052	5,198	4,828
CO_2	490,000	2,215,000	2,057,000
SO_x	201	97	90
NO_x	123	382	355

With respect to CO_2 emission reductions, these reductions are equivalent to the emission reductions that could be realized by avoiding emissions from the activities shown in Table 2.

Table 2: Emissions Reductions Equivalences, CO_2[2]

Metric	2013-Actual	2020-High Production Scenario	2020-Low Production Scenario
Miles/year driven by an average passenger vehicle	1.1 Billion	4.8 Billion	4.4 Billion
Passenger vehicles taken off the Road	94,000	423,000	393,000
# of Homes' electricity use for one year	61,000	276,000	257,000

Additional findings of this paper include:

- Regardless of the level of transmission expansion carried out by 2020, this paper estimates that 1,782 MW of wind generation in Maine will lead to significant greenhouse gas reductions through net emission reductions of greater than 2 million tons of CO_2 in 2020.
- ISO-NE is implementing a range of ongoing planning and operations initiatives designed to alleviate material operating reserve issues and transmission congestion. If ISO successfully implements such initiatives, they would likely further increase emission benefits towards the higher end of the results projected herein (i.e. closer to the High Production Scenario results).

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[2] Equivalences determined using the EPA Greenhouse Gas Equivalency Calculator, found at: http://www.epa.gov/cleanenergy/energy-resources/calculator.html

- Maine, and the rest of New England, already has a relatively clean mix of generation compared to the national average. The New England system mix is becoming progressively cleaner over time due to a combination of switching away from dirtier fuels, increases in fossil fuel generator efficiency, and increased renewable energy penetration. Introduction of additional wind power is one contributor to making the region's supply mix cleaner.

- In 2013, wind generation in Maine displaced primarily natural gas, as well as a very small quantity of coal and oil.[3] Following the announced retirement of two large coal plants in 2014 and 2017, respectively, introduction of additional wind generation to the ISO-NE system in Maine in the future is expected to displace primarily natural gas generation, and a small amount of oil[4]. Due to the retirement of these dirtier plants, the avoided emission *rate* of CO_2 is projected to decrease by approximately 8.6% by 2020. Similarly, wind generation is expected to reduce less SO_x in 2020 than in 2013 - even with four times the amount of wind generation - because fossil fuel generators operating in 2020 will produce significantly less SO_x as a result of the retirement of coal plants.

- As increasing levels of wind generation outstrip the natural variability of electrical demand, ramping and cycling by operating reserves will increase as they respond to the variability of wind generation. This increased ramping and cycling (sometimes referred to as 'wind integration impacts') leads to indirect emission increases, although these increases are estimated to represent a minor erosion of the overall CO_2 emissions benefit (approximately 5%) from increasing levels of wind power in 2020. All recent studies of actual U.S. power systems point to this same conclusion: that cycling impacts are a fraction of the direct emission impacts of wind power. The Net Emission Reductions in this report account for these indirect emission increases.

- In 2013, wind power production in Maine was being curtailed to a moderate degree because of local transmission constraints and transmission lines being temporarily taken out of service during the year as part of construction related to the Maine Power Reliability Program (a transmission system upgrade that will ultimately relieve some transmission constraints). In 2013, such curtailment reduced MWh production and Net Emission Reductions by approximately 5.4-8.2%,[5] relative to uncurtailed quantities. Market incentives have been put in place going forward to encourage wind developers to locate future wind facilities in places that are not transmission constrained; therefore, in 2020, depending on the level of transmission expansion between now and 2020, this paper estimates curtailment could reduce MWh production, and corresponding Net Emission Reductions, by as little as 1.15% (High Production-Transmission Unconstrained Scenario) to a high of 8.2% (Low Production-Transmission Constrained Scenario) from uncurtailed quantities.

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[3] As well as a *de-minimis* amount of biomass fueled generation.

[4] We note that the use of oil will continue to ebb and flow depending upon the relative availability and pricing of both natural gas and oil supplies.

[5] This range takes into account an abnormal level of curtailment levels in 2013 due to the construction of the Maine Power Reliability Project, which resulted in some turbines being curtailed in January and February at triple their normal levels. While the actual production was curtailed by 8.18%, if the abnormal outages are normalized, energy production would have been curtailed by about 5.4%. *See* Section 3.4.1.

1. Introduction

1.1. Overview, Context, and Objective of this Paper

Wind energy in Maine has grown substantially since the first wind farm was built in the state in 2007 to a current fleet of 431 MW. A substantial expansion of the fleet has been proposed by a number of wind power developers to meet the region's needs for a low-emission and diversified power supply portfolio. In the context of permitting deliberations on individual wind power projects, or legislative consideration of renewable energy policy, issues of wind power's costs, impacts and benefits are frequently raised.

When it comes to emission impacts or benefits, a range of assertions have been made, with varying degrees of supporting analysis, claiming to characterize the emissions benefits (or lack thereof) of wind power in Maine and elsewhere. In the authors' assessment, these varying positions reflect several factors:

- The variable nature of wind combined with the lack of understanding of: (1) the relationship of fuel consumption and emissions to power production; (2) the sharing of reserves[6] in integrated power systems like ISO-New England ("ISO-NE"); and (3) the actual resource mix used to follow load variations within a particular power pool. Together, these lead to a common misconception that wind power needs to be 'backed up" one-to-one with an equivalent amount of fossil-fueled generation running on idle, whose increased emissions fully offset the avoided fossil fuel generation;[7] and

- Information – sometimes selective or misleading - publicized by either wind project proponents or opponents with intent to influence opinion.[8]

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[6] The authors find an analogy helpful in understanding the concept of shared reserves: Consider that a fleet of idling taxis can serve a city at a ratio of about 1-4 taxis per 100,000 people (Schaller, 2005, p. 5). If 100,000 more people (variable loads) move into a city, the number of taxis required does not increase by 100,000.

[7] As summarized on the National Renewable Energy Laboratory's Transmission Grid Integration web site, "Electric power systems must maintain continuous balance between electricity production and electricity consumption. If a generation source on the system fails, the power system must be prepared to react. But it doesn't use one-to-one backup generation to respond. To create balance between electricity production and consumption, electric power system operators call on a stable of controllable generators to "follow," or respond to, changes in total system demand, or load. They don't follow a single generator or a load source. Therefore, when variable generation such as solar and wind energy is added to a system, the variability in overall load is still the operating target for the system operator." (National Renewable Energy Laboratory, 2014).

[8] For example, because wind power's impacts are particular to the power system in which wind generation is introduced, studies applicable to systems with substantially different characteristics (such as islands or baseload coal-heavy systems) have limited applicability to, or are likely to overstate, impacts expected for Maine. The ISO New England power system is a particularly flexible system, with high penetration of hydroelectric generation with storage, pumped storage generation, and natural gas combined cycle generators capable of efficiently providing operating reserves.

Whatever their genesis, the presence of potentially conflicting information on emission impacts of wind power serves to confuse stakeholders, the public and lay decision-makers, and can interfere with fact-based decision-making.

Ideally, ISO-NE, the region's independent system operator, would be the source of estimates of past and projected net emission impacts of wind power in Maine. ISO-NE has access to all the relevant data, much of which is proprietary and not publically available. In addition, ISO-NE is by definition independent and not subject to critique that its study was subject to influence by its funders. In 2010, ISO-NE published its 2010 New England Wind Integration Study ("NEWIS") (General Electric, 2010). The NEWIS specifically modeled emissions impacts from varying penetrations of wind power in New England, making major strides in estimating and quantifying emissions reductions. Although this detailed study intended to answer this and many related questions[9] - the NEWIS has some limitations for the purposes of this paper:

1. NEWIS' relied on fuel mix and emissions rate data reflecting conditions that existed in 2008 or that were anticipated at that time. Although the NEWIS is instructive, the data used predates the recent phasing-out of coal fired plants in ISO-NE in favor of natural gas generation.[10] Because the NEWIS reflects a system that is no longer appropriate given changes experienced and expected in the ISO-NE system, exclusive use of NEWIS data as a basis for this paper would likely overstate the expected emissions benefits of wind generation in New England.

2. NEWIS' does not *separately* study or report the impacts of plant cycling on emissions. As discussed in section 4.3, wind generation, due to its variability, can induce increased cycling among marginal generators; increased emissions from cycling units can offset some fraction of the emissions directly avoided by wind generation as a result of a reduced production of energy from fossil-fueled generators. Although NEWIS did *implicitly* study this issue (by modeling the behavior of the ISO-NE supply mix as a whole), it does not directly discuss the distinct effects of cycling. In contrast, the more recent Western Wind and Solar Integration Study Phase 2 ("WWSIS") (NREL, 2013) and PJM Renewable Integration Study ("PRIS") (General Electric, 2014), have explicitly examined in detail, and report results on, the effect of cycling on emissions. The absence of such an explicit New England-specific analysis of integration impacts limits the ability to adjust and apply the NEWIS's projected emission impacts to reflect a changing New England supply mix.

There are no current plans for ISO-NE to update the NEWIS study. In the absence of such a single, definitive study which can be used to provide reliable information on the emission impacts of wind power in Maine, the Maine Renewable Energy Association ("MREA") commissioned Sustainable Energy

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[9] In addition to projecting emission impacts, which are sensitive to changes in the marginal generators in the supply mix, the NEWIS also addressed the increase in operating reserves required to integrate increasing wind penetrations in New England. The NEWIS projected an increase in the regional power system's operating reserve requirements of between about 2% to 5% of the MW of added wind across all categories of operating reserves. For instance, the NEWIS estimated that for 1140 MW of additional wind, an increase of 20 MW of average required Total Operating Reserves would be needed (1.8%); for a wind penetration of 4170 MW of additional wind, the same study projected an increase of 229 MW of average required Total Operating Reserves would be required (5.5%).

[10] A study conducted in 2014 – The *2012 ISO New England Electric Generator Air Emissions Report* (ISO-NE, 2014) - captures a portion of the evolution.

Advantage, LLC ("SEA") to develop a white paper estimating the emission impacts resulting from current and projected levels of wind power in Maine. SEA was asked to estimate and anticipate - based on readily available information - what such an updated ISO-NE study would conclude were it to be performed today. This paper is intended to help legislators, members of the media, and the general public understand and interpret what emission impacts may reasonably be expected, taking into account all the relevant factors.

This study provides an estimate of the total reduction in CO_2, NO_x and SO_x emissions that resulted, and will result, from the operation of wind energy facilities in Maine in 2013 and 2020, respectively. In doing so, SEA uses existing publically available studies on emissions rates, marginal generation and wind integration, as well as actual production and operational data from five (5) operational wind energy facilities in Maine. The goal of this study is to quantify the net emissions reductions attributable to Maine wind energy production due to reductions in fossil fuel consumption.

The methodology used by previous studies to estimate net impacts of renewable generation is complex and costly, and each study advances the state-of-the-art. This analysis does not include any new production simulation modeling or transmission modeling (which are the core of many of those previous studies), but leverages and stands on the shoulders of those previous studies. This paper attempts to use and coalesce the relevant findings from previous studies to bound the estimates of net adjusted avoided emissions from Maine wind power.

Specifically, this paper commences with a literature review of prior relevant analysis that can be used to quantify the avoided emissions resulting from Maine's wind power industry. It relies on the best publically available data on emission impacts, including studies of the emissions impacts of possible system operational impacts that can result in increased emissions from certain generators (e.g., cycling, spinning reserve) in the presence of increasing variable generation (e.g., wind).

The paper estimates the net expected CO_2, NO_X and SO_X reductions attributable to 431 MW of wind generation in Maine during 2013, and estimates the net expected reductions in these same pollutant emissions from an assumed 1,782 MW fleet of Maine wind generation in 2020 under two scenarios intended to bound the results. These two scenarios account for different electric transmission futures (Transmission Constrained and Transmission Unconstrained) and their associated wind production estimates.

In estimating the net emission reductions, this paper considers both direct emission displacement by wind, as well as the secondary impact that increasing quantities of variable wind generation may have on the operation (and associated emissions) of fossil fuel fired generators required to accommodate wind power's variability.

1.2. About Maine Renewable Energy Association

MREA is a not-for-profit association of renewable power producers, suppliers, and supporters of the renewable power industry in Maine. MREA leads the local and statewide policy debate on renewable energy generation in Maine, and works to ensure its efforts are united with those of its member companies.

1.3. About the Authors

SEA, a consulting firm located in Massachusetts, specializes in analysis of renewable energy markets and policies for a wide range of government, private sector market participant, utility, end-user and non-profit sector clients. SEA is committed to supporting well-informed decision-making through its independent analysis efforts, which seek to take into account a diverse and comprehensive set of perspectives. Among SEA's specialties is producing independent, free-standing, expert analysis in multi-stakeholder settings where being seen as credible by a wide range of stakeholders with competing/ conflicting interests is essential. Through its subscription-based New England Renewable Energy Market Outlook and New England Renewable Energy Eyes & Ears services, SEA provides its independent, free-standing and ongoing analysis of renewable energy markets and policies to any interested stakeholder.

SEA is engaged in encouraging good decision-making on wind power issues by bringing forth credible, salient and reliable information. SEA was the creator and manager of several past Federally-funded projects in New England as part of the Department of Energy's Wind Powering America program: the New England Wind Forum, and the New England Wind Energy Education Project (NEWEEP). Through NEWEEP, SEA conducted a series of well-attended conferences and webinars encouraging dialog among diverse stakeholders on issues impacting wind power public acceptance.[11] Currently, SEA is managing the land-based wind program of the nascent Northeast Wind Resource Center[12] under DOE's renamed WINDExchange program,[13] through which SEA will coordinate development of an information resource and other activities to support all participants in wind power decision-making.

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[11] See: http://www.northeastwindcenter.org/land-based-wind/helpful-links/

[12] See: http://www.northeastwindcenter.org/

[13] WINDExchange is the U.S. Department of Energy (DOE) Wind Program's hub of stakeholder engagement and outreach activities. The purpose of WINDExchange is to help communities weigh the benefits and costs of wind energy, understand the deployment process, and make wind development decisions supported by the best available science and other fact-based information. See: http://energy.gov/eere/wind/windexchange.

2. Methodology

2.1. Context

It is clear that for a large regional transmission system like ISO-NE, that integration of zero-emission wind power generation displaces energy production from the marginal plants (generally natural gas fired plants in ISO-NE), and the resulting reduction in fuel usage at these plants provides a significant reduction of emissions. One key question addressed here and in other studies is: what is the *net* adjusted emissions avoided by wind power after taking into account the impacts that increasing quantities of intermittent wind generation place on the system. Other recent studies conducted in the United States show that wind power-driven emission reductions remain significant even after accounting for the following factors:

- Additional operating reserve requirements caused by increased variability;
- Emission impact resulting from increased cycling from fossil fuel plants running at part load and providing additional ramping capability; and
- At very small penetration, the impact of wind generation on operations of other plants is negligible and generally within the noise of load fluctuations that have much larger variability. However, as wind generation penetration grows, the variability imposed by larger amounts of wind generation increases demand on operating reserves (including increased cycling of fossil fuel plants used to follow load), which will in turn impact the emissions of the non-wind generation portion of the system.

Additional factors considered in establishing this paper's methodology include:

- At the remote locations on the radial edges of the electric system, where many wind projects are sited, voltage stability and other reliability concerns, or bottlenecks in the system, may lead to transmission constraints. Under certain conditions when constraints arise, curtailments of wind systems may result, which of course mean less overall wind energy produced to displace fossil fuel generation and reduce emissions. In some cases, these impacts can be amplified if the marginal plants in the area are less efficient than marginal plants elsewhere in the system.
- The impacts on an electric system from following variable load and variable generation are greater if the variation is unpredictable than if it is predictable. ISO-NE has recently adopted and implemented a sophisticated wind forecasting function which is designed to partially mitigate the impacts inherent in the variability of the wind. (ISO-NEwswire, Staff, 2014)
- The regional power grid in which wind power plants operates matters to the calculation of avoided emissions and the impact of integration (cycling) impacts. The western United States grid and the PJM power market (the focus of two recent studies from other systems included in our literature review) are much more heavily baseload systems, dominated by nuclear and coal-steam plants. They have 'lumpy' supply and are relatively inflexible. A big issue for these regions is that coal plants which are designed for base load operation and are inefficient when

cycling up and down are becoming and/or modeled to become cycling plants. Thus the Western region and PJM are limited in their ability to smoothly integrate wind, and will experience higher costs, more substantial emission impacts in integrating large quantities of wind power than some other systems.

- In comparison, electric systems run in an integrated manner with efficient markets to price services, and that have a high degree of dispatchable hydroelectric, pumped storage, and/or natural gas plants capable of rapid cycling (e.g., natural gas combined cycle and natural gas combustion turbines), are better able to manage wind variability. ISO-NE is just such a system. ISO-NE is generally capable of managing fluctuations in generation, like fluctuations in load, with less cycling plant impacts than many other regions. Where this study incorporates estimates from other regions (because of the lack of system-specific studies using the latest methodology), we are being conservative with the estimation of system impacts that would be imposed in ISO-NE and Maine, and thus conservative in final net adjusted emission reductions.

It is appropriate to take these factors into account, and we do so wherever possible.

2.2. Data Sources

In order to develop emission reduction estimates, SEA first conducted a literature review of the best and most recent studies, as well as current publically available information. Specifically, SEA focused on studies and other sources which provide data regarding: 1.) emission rates from marginal units in ISO-NE, 2.) proposed Maine and ISO-NE transmission infrastructure expansions, 3.) wind turbine curtailment, and 4.) emission impacts due to increased cycling from marginal fossil plants.

Where possible, this paper uses data from sources that were prepared by independent experts and professionals in the field who had limited or no interest in the outcome. All sources, aside from proprietary information concerning the MWh production and curtailment of certain facilities, can be accessed by the reader. Many of these sources use scenario analysis or provide multiple report methodologies. When applying the results of these scenarios, the goal of this paper was to use the scenario or methodology that best fits the analysis at hand.

The following key sources were reviewed as part of this study:

- New England Wind Integration Study (2010)
- Eastern Wind Integration and Transmission Study (2011)
- The Western Wind and Solar Integration Study Phase 2 (2013)
- PJM – Renewable Integration Study (2014)
- 2012 ISO New England Electric Generator Air Emissions Report (2014)
- Maine Wind Assessment 2012, A Report (2012)
- U.S. Renewable Electricity: How Does Wind Generation Impact Competitive Power Markets? (2012)
- Avoided Energy Supply Costs in New England: 2013 Report
- New Wind Power Forecast Integrated into ISO-NE Processes and Control Room Operations (April, 2014)
- Public Meeting Draft 2014 Regional System Plan (August 2014)
- How Less Became More...Wind Power and Unintended Consequences in the Colorado Energy Market (2010)
- Air Emissions Due to Wind and Solar Power (2009)

- ISO New England 2014 Capacity, Energy, Load and Transmission Report (2014)
- Interviews conducted by SEA with ISO-NE System Planning Staff
- ISO New England Strategic Transmission Analysis: Wind integration Study 1- Maine Regional Constraints (2014)
- Wind Power's Impact on Grid Reliability, Backup Supply, and Fossil Fuel Use in New England: A New England Wind Energy Education Project Webinar (2010)
- IEA Task 26: The Past and Future Cost of Wind Energy (2012)
- U.S. DOE 2013 Wind Technologies Market Report (2014)
- Avoided Emissions from the Antrim Wind Project (2011)
- Wind Energy for a Cleaner America II: Wind Energy's Growing Benefits for our Environment and Health (2013)

Appendix A describes these sources in more detail, and hyperlinks to those sources available on the internet.

2.3. Methodology Overview

This paper estimates net emissions reductions, as a result of wind generation in Maine, in 2013. The paper also provides high and low estimates for net emission reductions in 2020, modeled by assuming two different transmission constraint scenarios. The methodology is outlined as follows, with the details provided in subsequent sections of the paper.

Net Emission Reductions due to wind generation in Maine were first calculated for the 2013 calendar year.

U.S. Energy Information Agency (EIA) reports[14] provide information on total MW of wind energy capacity installed in Maine in 2013, as well as total annual MWh production from these facilities; this data serves as the foundation for estimates of wind energy production in Maine in 2013. Additionally, owners of five operating wind farms in Maine (together totaling 239 MW of capacity, provided SEA with: (1) actual 2013 hourly energy production statistics , and (2) data showing the energy production lost due to ISO-NE required curtailment.[15]

From these data sources, annual and seasonal capacity factors[16] and curtailment levels were calculated. In the absence of detailed historical hourly performance data from all operating wind farms, the production data provided by the wind farm owners was assumed to be sufficiently representative for the purposes of this analysis. The aggregate data from the five wind farms was applied as a proxy to estimate the total amount of curtailment, and the relative proportions of seasonal production, for the 431 MW of

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[14] EIA Form 923 available at: http://www.eia.gov/electricity/data/eia923/

[15] This curtailment data allowed estimation (or reconstitution) of total expected production in the absence of such curtailments. Production information was reconstituted to provide baseline data, without curtailment, necessary to project production in 2020.

[16] Capacity factor is a measure of energy production per unit of installed capacity. See glossary for full definition.

wind energy capacity operational in Maine in 2013.[17] The estimated curtailment is used later in the report to compare existing curtailment levels with two possible future curtailment scenarios.[18]

The total MWh of production, calculated above, was then multiplied by the Locational Marginal Unit ("LMU") emission rates (lbs/MWh) contained in *ISO-NE's 2012 ISO New England Electric Generator Air Emissions Report* (2014) for NO_X, SO_X and CO_2 in order to estimate the total emissions that wind generation directly avoids by displacing marginal fossil-fuel generators. The LMU emission rates were adjusted to take into account changes in heat rate (i.e., generator efficiency) between 2012 and 2013, as described in Section 4.1.1.

These Direct Avoided Emissions were then reduced to take into account an estimate of emissions resulting from increased cycling of fossil-fuel generators used to balance short-term fluctuations in wind production, to derive a final Net Emissions Reduction estimate in 2013.

Net Emissions Reductions in 2020 were then estimated for a hypothetical 2020 wind generation fleet of 1782 MW installed capacity in Maine. This quantity of 2020 wind installed capacity was derived using information contained in the ISO-NE Interconnection Queue and other publicly available sources, and applying a 50% success rate for projects not yet under construction or permitted. Of this quantity, 1351 MW were assumed to be installed in 2015 or later.

Annual energy production from this fleet was projected taking into account: (i) production degradation at currently operating wind projects due to normal wear and tear applicable to all power plants; (ii) increased capacity factors for wind projects that become operational post-2014 reflecting industry trends towards use of taller towers (to access higher winds), longer blades (to increase wind capture) and other recent technology advances[19]; and (iii) changes to curtailment, as a result of changes in transmission infrastructure. Projected energy production in 2020 was derived for two scenarios:

- **High Production (Transmission Unconstrained) Scenario**: This scenario assumes that there will be a material expansion of transmission infrastructure between 2013 and 2020.
- **Low Production (Transmission Constrained) Scenario**: This scenario assumes that there will be limited expansion of transmission infrastructure between 2013 and 2020. Under this scenario, the effects of curtailment, and indirect emissions from cycling, are greater than under the High Production Scenario, leading to comparatively lower Net Emission Reductions.

These 2020 MWh production estimates were then used to calculate Net Emissions Reductions for the above scenarios. The MWh production estimates were multiplied by the 2012 ISO-NE emission rates,

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[17] Wind generation fluctuates, sometimes by as much as 20%, year to year. Given the dearth of historical operating data, a statistically –valid conclusion on whether 2013 is a typical year, or an outlier (either in terms of below average or above average generation), cannot be drawn.

[18] Note that current curtailment levels may be higher than otherwise anticipated due to a multi-year transmission system improvement project in Maine. Certain sections of the Maine transmission system have been de-energized during this period while upgrade work is being done. We would expect lower levels of curtailment at a subset of operating projects after this work is completed in 2015.

[19] For an extensive discussion of technology advances and their impacts on wind power production, see: (U.S. DOE, 2013 Wind Tech Report, 2014) and (IEA, 2012).

which were adjusted to take into account a continued trend of estimated heat rate reductions (efficiency improvements) between 2012 and 2020 for the generators whose production would be displaced, to derive Direct Avoided Emissions for both scenarios.

These Direct Avoided Emissions estimates were then adjusted to take into account the effects of increased cycling. The cases examined are summarized in Table 3 below.

Table 3: Cases Examined

Case	2013 (Actual)	2020 Low Production Scenario	2020 High Production Scenario
MWh Production	Actual	High Transmission Constraints	Low Transmission Constraints
Direct Emissions Avoided	ISO-NE emitting locational marginal unit, extrapolated to 2013	ISO-NE oil & natural gas locational marginal unit, extrapolated to 2020	ISO-NE oil & natural gas locational marginal unit, extrapolated to 2020
Indirect Emissions Impacts (due to increased cycling)	**5.3%** of Directly Avoided Emissions	**5.3%** of Directly Avoided Emissions	**5.3%** of Directly Avoided Emissions

The individual assumptions associated with each scenario are discussed in greater detail in later sections of this paper.

2.4. Inputs and Sources

SEA created an MS Excel spreadsheet model to conduct the analysis described above. Listed below in Figure 1 are the primary data inputs used in this model, for both MWh production and emissions estimates, and the sources of these data inputs. Bold lines indicate data was directly taken from these sources and used in the model; dashed lines indicate that the source informed analysis, but that input values were not directly taken from the source and used in the model.

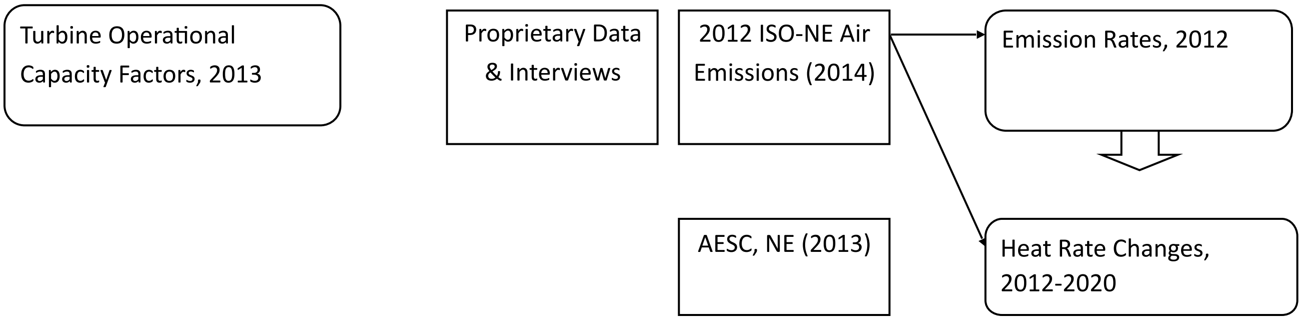
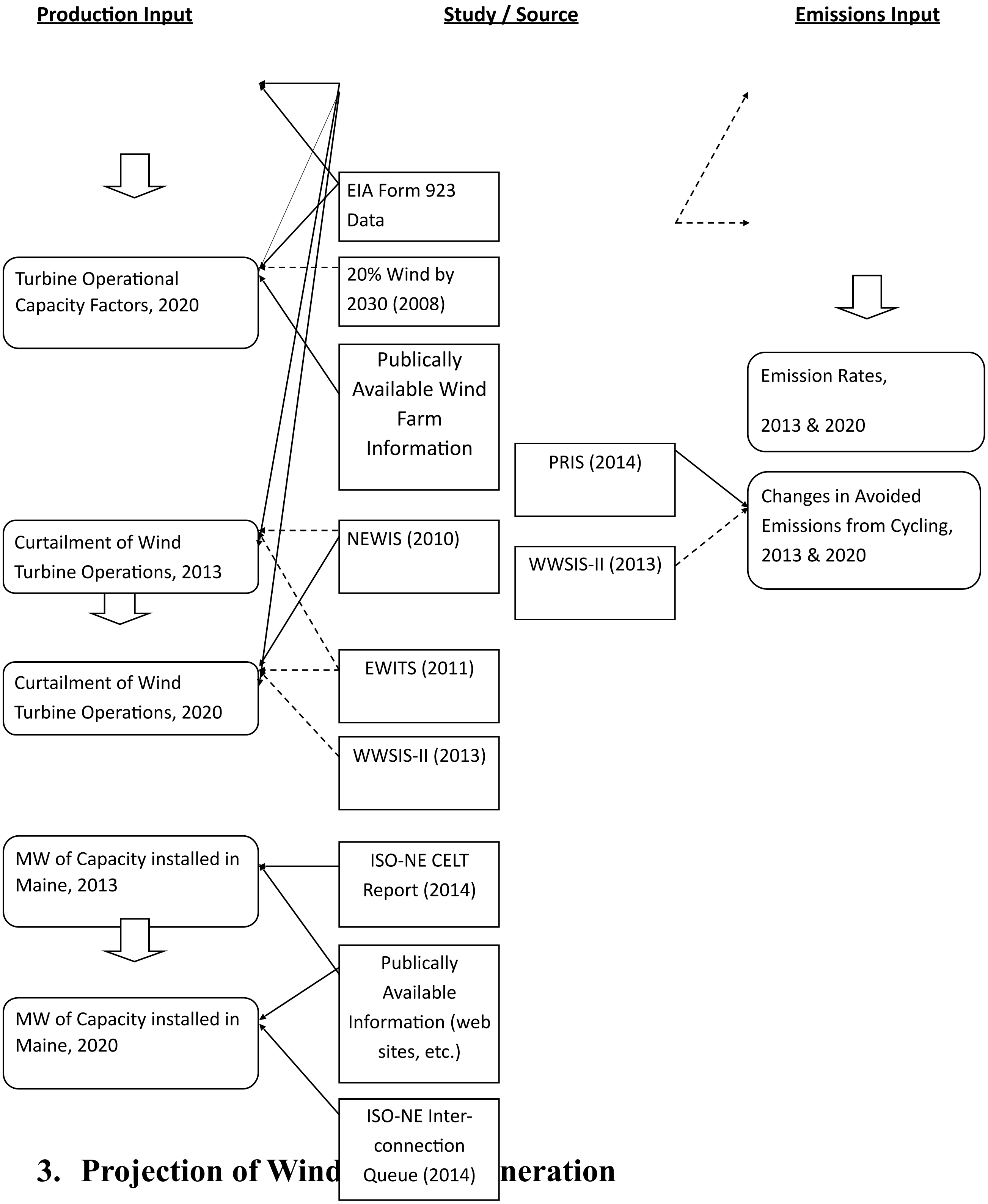


Figure 1: Primary Data Inputs Used in Modeling



3. Projection of Wind neration

Projection of wind energy generation in 2013 and 2020 requires several steps, including determination of the amount of nameplate capacity of wind generation in operation in each case and the energy production from those generators, which is dictated by capacity factor as well as equipment degradation and curtailment due to transmission system constraints. Estimation of each of these factors is discussed below.

3.1. Estimation of MW Capacity, 2013 and 2020

Maine had 431.4 MW of wind energy capacity during 2013, from ten wind projects of various sizes as well as a handful of distributed sources, as shown in Table 4.

Table 4: Wind Energy Capacity installed in Maine as of 1/1/2013, with Est. Fleet Capacity Factor

Project	MW
KIBBY WIND POWER	132
RECORD HILL WIND	50.6
MARS HILL WIND	42
STETSON WIND FARM	57
BEAVER RIDGE WIND	4.5
STETSON II WIND FARM	25.5
FOX ISLAND WIND	4.5
SPRUCE MOUNTAIN WIND	20
ROLLINS WIND PLANT	60
BULL HILL WIND	34.2
Other Small Projects	1.1
TOTAL MW Capacity (2013):	431.4
Weighted Average Capacity Factor	27.8%

A projection of wind power capacity for the purposes of this paper in 2020 was developed by summing the following:

1. The capacity of all currently operating wind farms in the 2013 fleet;
2. The capacity of future wind farms that are either under construction or permitted and likely to be operating in the next few years; and
3. 50% of the capacity of all wind energy projects in the ISO-NE Interconnection Queue (as of August 1, 2014), which are not currently operating, under construction or permitted. 50% was

used to reflect the expectation that not all projects will be successfully permitted or built.[20] In arriving at the true total quantity of wind power in the interconnection queue, SEA attempted to remove likely duplicates from the gross total of projects represented in the queue.[21]

The capacities of future wind farms that are either under construction or permitted are presented in Table 5. The projection of additional projects in the ISO-NE Interconnection Queue, derated by a factor of 50%, is shown in Table 6.

Table 5: MW Capacity of Permitted, But Not Yet Operational Wind Farms[22]

Project	MW
Hancock Wind	54
Oakfield Wind	147.6
Saddleback Mountain Wind	34.2
Passadumkeag Windpark	42
Bingham Wind	186
Total Near-Term MW Capacity (as of 9/26/2014)	464

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[20] The ISO New England interconnection queue is perhaps the most visible indicator of the quantity of wind power generation under development, but it is imperfect in several respects. The total quantity of wind in the queue certainly understates the amount of wind development that could be brought online by 2020, as there are projects under development but not yet in the queue, because either (i) it is too early for the developer to start incurring interconnection study costs, or (ii) a project has temporarily withdrawn from the queue to avoid incurring study costs before project permitting is deemed sufficiently likely to merit the investment. The queue figures can also overstate the ultimate wind development volume. The queue contains duplicates i.e. projects examining multiple interconnection alternatives, which we have attempted to remove. And of course, not all projects in the interconnection queue will ultimately be permitted. A factor of 50% was applied to projects not fully committed to reflect an assumption that less than 50% of projects in the queue will ultimately get built, but that more projects are under development than are currently visible in the queue. The actual volume installed by 2020 could be somewhat higher or lower than this estimate.

[21] The interconnection queue represents a useful, though incomplete, picture of the wind development pipeline. Projects whose development progress has reached a sufficiently advanced stage that its developers are ready to invest in various studies (with associated payment deadlines), request interconnection studies from ISO-NE through the queue. Projects that are abandoned remove themselves from the queue, but projects often drop out of the queue for other reasons, including avoiding incurring payment obligations for projects that are not sufficiently advanced to merit the investment in further interconnection study; these projects may reenter the queue at a later time. Many projects study alternative interconnection routes in parallel, and thus may appear in the interconnection queue multiple times. Projects in the interconnection queue are usually not identified by name. SEA follows the wind development pipeline and applied its industry knowledge and judgment to remove likely duplicates.

[22] The permit for Canton Mountain Wind, a 22.8 MW project located in Oxford Maine, was under appeal at the time the analysis for this paper was conducted; as a result Canton Mountain Wind is not included in this table.

Table 6: Capacity of Maine Wind Energy in ISO-NE Interconnection Queue (MW)

Interconnection Queue (as of 7/1/2014)	
Total as of 7/1/2014 Non-Operating Wind Projects in Maine Interconnection Queue (MW)	3,147
Estimated Duplicates	913
Total Permitted But Not Yet Operational within above	461
Est. Incremental MW in queue	1,773
Estimate of percentage ultimately developed	50%
Total (MW):	887

Summing these three groups of projects results in 1,782 MW of wind energy capacity operating in Maine in 2020, as summarized in Table 7.

Table 7: Estimated MW of Wind Energy Capacity in Maine in 2020 (MW)

Category	MW
Operating Projects:	431
Under Construction and Permitted Projects:	464
Additional Projects Completed by 2020:	887
Total Operational Wind Energy Capacity, 2020	1,782

3.2. Capacity Factors

3.2.1. Capacity Factors, 2013

First, SEA determined annual capacity factors for Maine's wind generation fleet during 2013 using generation data which is publically available in EIA Form 923.[23] Because (at the time of this analysis) the Form 923 data for 2013 did not enumerate data for three wind facilities known to be operating in 2013, 2012 Form 923 generation data or proprietary production data (where more recent than 2012) was used as a proxy. In 2013, it is estimated that Maine wind facilities had an aggregate annual capacity factor of **27.83%,** net of curtailment.

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[23] EIA form 923 available at: http://www.eia.gov/electricity/data/eia923/

Table 8: 2013 Annual Capacity Factor

Category	#
MW of Capacity, with data contained in EIA Form 923 (2013)	401.3
MW of Capacity, with data drawn from EIA Form 923 (2012) and Proprietary Information	29
Total MW Capacity (for which a 2013 Capacity Factor was determined):	430.3
Total Generation from the above 430.3 MW of Capacity (MWh)	1,049,179
2013, Full Year Capacity Factor	**27.83%**

ISO-NE Locational Marginal Unit (LMU) emission rates, discussed in Section 4.1, are presented for four time periods during the year (the "Analysis Periods"):

- **Ozone Season; On-Peak** (where the Ozone Season is defined as occurring from May 1 to September 30) consisting of all weekdays between 8 A.M. and 10 P.M. from May 1 to September 30

- **Ozone Season; Off-Peak** consisting of all weekdays between 10 P.M. and 8 A.M. and all weekends from May 1 to September 30

- **Non-Ozone Season; On-Peak** consisting of all weekdays between 8 A.M. and 10 P.M. from January 1 to April 30 and from October 1 to December 31

- **Non-Ozone Season; Off-Peak** consisting of all weekdays between 10 P.M. and 8 A.M. (ISO-NE, 2014, p. 12)

In order to utilize the seasonal LMU emission rates to more granularly and accurately estimate emission reductions, it was also necessary to determine capacity factors during each of the Analysis Periods. In order to do this, SEA obtained actual 2013 hourly production data for five operating wind projects in Maine, together totaling 239 MW of nameplate capacity.[24] Using the weighted average of the actual 2013 production for these five operating wind farms, the ratio of the capacity factor during the Analysis Period to the annual capacity factors was calculated for each Analysis Period.

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[24] In exchange for SEA's request for this proprietary wind production data, SEA committed to only reveal the data in aggregate form, so that individual wind plant production could not be discerned.

Table 9: Production by Analysis Period, Relative to 2013 Annual Capacity Factor Achieved by Analysis Period

Period	On/Off Peak	Ratio of Capacity Factor During Analysis Period to Annual Capacity Factor	Hrs/Period
Ozone	On-Peak	68.0%	1526
Ozone	Off-Peak	84.0%	2146
Non-Ozone	On-Peak	116.0%	2128
Non-Ozone	Off-Peak	116.6%	2960
Annual		N/A	8760

It was assumed that these Analysis Period results are a reasonable proxy for the entire 431 MW Maine fleet.[25] The annual capacity factor determined using EIA Form 923 Data (as discussed above) was then multiplied by the above percentages to estimate Analysis Period specific capacity factors.

Capacity factor results, by Analysis Period, are presented in Table 10 below. Actual individual facility capacity factors during the Analysis Periods range from 17.2% (Wind Farm #4, Ozone-Season, On-peak) to 47.4% (Wind Farm #2, Non-Ozone Season, Off-Peak).

Table 10: 2013 Capacity Factors by Analysis Period

Period	On/Off Peak	Capacity Factor	Hrs/Period
Ozone	On-Peak	18.92%	1526
Ozone	Off-Peak	23.38%	2146
Non-Ozone	On-Peak	32.29%	2128
Non-Ozone	Off-Peak	32.45%	2960
Annual		27.83%	8760

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[25] It should be noted that two of the five operating wind projects, whose hourly production data was used to determine the above capacity factors, suffered an atypical level of curtailment during January and February of 2013, significantly decreasing their production. This atypical curtailment was due to construction related to the Maine Power Reliability Project ("MPRP"); during these two months, curtailment levels rose to triple the monthly average (the effects of MPRP construction on curtailment are discussed in detail in Section 3.4). Had this atypical MPRP construction not taken place, actual 2013 annual capacity factors for these five turbines would likely have been closer to 30.94% in 2013; the actual capacity factor for these same 5 projects in 2013 (with MPRP curtailment) was 30.12%. This reconstituted capacity factor was determined by simply reconstituting what production in January and February would have been for the two MPRP constricted projects, had curtailment equal to the annual average occurred, and then calculating the capacity factor accordingly.

3.2.2. Capacity Factors, 2020

As discussed in Section 2.3, this paper models the effects of changes in curtailment between 2013 and 2020 (due to changes transmission constraints) on annual energy production. In order to effectively model these impacts, it is necessary to estimate a reconstituted projection of 2013 capacity factors had no curtailment occurred. This was done by summing the estimated MWh of curtailment wind projects experienced in 2013, adding this total to the actual 2013 energy production from these facilities, and then recalculating a revised 'no curtailment' weighted average capacity factor. In 2013, Maine wind farms would have had a capacity factor of 30.11%, had no curtailment occurred.

Between the currently operating fleet of wind turbines and those to be built in the years between now and 2020, more advanced technology yielding higher expected capacity factors, is expected. The installation of turbines on taller towers, using longer blades, often with improved systems to better capture energy from low-speed winds common in New England (as compared to the Midwest) will yield greater energy production.[26] This trend is evident in comparing the turbine technology used in currently operating wind farms, Table 11, with that used in the most recent of the operating wind farms and planned to be used in the next round of wind farms either under construction or recently permitted, as shown in Table 12; even in the near term, capacity factors will likely increase.

Table 11: Turbine Technology, Wind Farms Operational as of 1/1/2013

Project	MW	Tower Height	Blade Length	Low-Wind-Speed Technology
KIBBY WIND POWER	132	80m	90 m	No
RECORD HILL WIND	50.6	80m	93m	No
MARS HILL WIND	42	80m	77m	No
STETSON WIND FARM	57	80m	77m	No
BEAVER RIDGE WIND	4.5	80m	77m	No
STETSON II WIND FARM	25.5	80m	77m	No
FOX ISLAND WIND	4.5	80m	77m	No
SPRUCE MOUNTAIN WIND	20	78m	90m	No
ROLLINS WIND PLANT	60	80m	77m	No
BULL HILL WIND	34.2	95m	112m	Yes

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[26] See: US Department of Energy, 2013 Wind Technologies Market Report, which shows continual increases in tower height, blade length, and nameplate capacity, have resulted in increased capacity factors and individual wind turbine output (U.S. DOE, 2013 Wind Tech Report, 2014). The National Energy Modeling System: Renewable Fuels Module assumes continued improvement in wind turbines "*resulting from taller towers, more reliable equipment, and advanced technologies*" (EIA, 2014, p. 179). See also (IEA, 2012).

Table 12: Turbine Technology, Maine Wind Farms Operational in the Near Future

Project	MW	Tower Height	Blade Length	Low-Wind-Speed Technology
Hancock Wind	54	116m	117m	Yes
Oakfield Wind	147.6	84m	112m	Yes
Passadumkeag Windpark	42	80m	112m	Yes
Saddleback Mountain Wind	34.2	85m	103m	No
Bingham Wind	186	94m	112m	Yes

Similarly, turbine control algorithms, which allow wind turbines to more efficiently respond to changing environmental factors, are also expected to continue to improve (Chadbourne & Parke LLP, 2014).

For 2020, this paper assumes that wind farms that begin operating in Maine after 2014 will have a capacity factor of **35%,** not including losses from curtailment.[27] This is a ~16.3% increase over 2013 average energy production (assuming no curtailment). The 2013 distribution of production among the four Analysis Periods was applied to the increased capacity factors projected for post-2013 wind farms, with results summarized in Table 13.

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[27] This figure is consistent with recent information on technology advances as detailed in recent studies (IEA, 2012) (U.S. DOE, 2013 Wind Tech Report, 2014). It is also consistent with the capacity-weighted average of information on P(50) production estimates for the wind farms identified in Table 12 and other projects slated for development over the next few years, as reported to SEA in confidential interviews conducted for other projects. These increases are generally technology-related, including use of taller towers, longer blades and other technology often lumped under the category of 'low-wind-speed' technology. P(50) production estimates are levels of production expected to have a 50% probability of being exceeded.

Table 13: Capacity Factors, 2013 & 2020

Analysis Period	On/Off-Peak	% Of Annual Capacity Factor During Time Period	Capacity Factor, Projects Operating in 2013, w/ Curtailment (2013)	Capacity Factor, Projects Operating in 2013, w/o Curtailment (2013)	Capacity Factor, Projects that Began Operating Post 2013, w/o Curtailment (2020)
Ozone	On-Peak	68.0%	18.9%	20.5%	23.8%
Ozone	Off-Peak	84.0%	23.4%	25.3%	29.4%
Non-Ozone	On-Peak	116.0%	32.3%	34.9%	40.6%
Non-Ozone	Off-Peak	116.6%	32.5%	35.1%	40.8%
Annual		N/A	27.8%	30.1%	35.0%

3.3. Production Degradation 2013 and 2020

This paper assumes that annual energy production from the wind farms operating during 2013 will degrade by 0.25% annually due to blade soiling and normal wear-and-tear. This leads to a total reduction of 1.76% production due to degradation by 2020. The production from subsequent projects is not degraded, because most of this generation will be brought online shortly before 2020, and as virtually new equipment, it is assumed these projects will not yet be experiencing the degree of production degradation expected later in their lives.

3.4. Curtailment

3.4.1. Curtailment Levels, 2013

Operators of wind farms are sometimes required by system operators to decrease wind turbine operations due to transmission congestion, excess electricity supply relative to demand and must-run generation ("minimum generation" limits), limitations in ramping capability, or availability of adequate operating reserves. This decrease in operations is known as "curtailment" (Enernex Corporation, 2011, p. 47). The amount of curtailment a wind farm experiences affects the farm's annual energy production, and as a result, the emissions it reduces by displacing generation from fossil fuel plants.

As local transmission congestion increases, curtailment increases, and MWh production decreases (Enernex Corporation, 2011) (General Electric, 2010). The *Eastern Wind Integration and Transmission Study* ("EWITS", 2011) indicates that transmission constraints account for the vast majority of curtailment, as much as 99%, under high wind penetration scenarios. (Enernex Corporation, 2011, p. 47).

In order to estimate curtailment levels for 2013, this paper uses proprietary information from the same five wind projects that provided hourly actual energy production data. All five of these wind projects provided data on annual curtailment levels. Three of these five wind projects also provided data on monthly curtailment. Using the annual curtailment data from the five wind projects, the total MWh of production lost due to curtailment annually, as a percentage of the total annual potential production of these facilities (had no curtailment occurred), was estimated. Using the monthly data from the three farms, the percentage change in curtailment during ozone and non-ozone season versus the annual average was calculated. Table 14 presents curtailment levels during 2013, during ozone and non-ozone season and annually.

Table 14: Curtailment Levels, 2013

Time Period	MWh Curtailed, as % of Potential MWh Production (Had No Curtailment Occurred)
OZONE Season	9.56%
NON-OZONE Season	7.52%
ANNUAL	8.18%

Two of the five wind farms experienced significant curtailment during January and February of 2013, due to construction of the MPRP; curtailment during these months was 24-30% of potential production (i.e. production if no curtailment had occurred). Although curtailment during these months was likely a one-time non-repeating event, we did not normalize to control for this outlier in modeling the annual curtailment levels used in this paper. As there is significant ongoing transmission construction in Maine currently (discussed further below), these outliers may be representative of intermittent spikes in curtailment that are occurring throughout Maine. By retaining these likely anomalous curtailments in estimating annual curtailment levels, we have introduced an additional source of conservatism into this analysis.[28]

Had the data been normalized, annual curtailment levels would be reduced to 5.4% of potential annual energy production.

3.4.2. Projected Curtailment Levels, 2020

Projecting changes to curtailment levels between 2013 and 2020 depends entirely on future transmission investments as well as implementation of other initiatives and activities designed to mitigate causes of curtailment, the specifics and timing of which are subject to continued uncertainty. This situation makes projection of future curtailment levels difficult, and suggests an approach which considers the range of possibilities. In considering possible futures, three recent studies were examined. The studies, and the assumptions on which these studies are based, are summarized below:

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[28] Because the outlier curtailment events happened in January and February, and there is no reason to believe that similar events would happen then, as opposed to during the other 10 months of the year, data was normalized in determining the percentages changes versus annual curtailment during ozone and non-ozone season.

- The ***Western Wind and Solar Integration Study – Phase II*** ("WWSIS-II", 2013)[29] finds that, under a scenario where Wind energy penetrations exceed 25%, material transmission expansions occur[30] and curtailment levels are roughly 3%.[31] While this study may provide insight into the magnitude of wind curtailment that might be expected in the presence of deep wind penetration coupled with associated transmission planning, the WWSIS-II focuses on the Western United States, making direct application of these results to New England inappropriate.

- In contrast, the **Eastern Wind Integration and Transmission Study** ("EWITS") provides projections of curtailment data for the entire Eastern Region[32], under both transmission constrained and transmission expanded scenarios, for wind penetration levels of 20-30% (Enernex Corporation, 2011) – well beyond the approximately 4% energy penetration levels considered in this paper. The transmission constrained scenario, which assumes that *no new transmission infrastructure* will be built to accommodate new wind energy facilities shows curtailment across the entire Eastern Region of 18-47% (Enernex Corporation, 2011, p. 120). However, under scenarios in which major transmission expansions occur[33], wind energy curtailment in the ISO-NE zone is between 0.02%-9.06% of production. However, in cases in which significant development of offshore wind energy capacity[34] does not occur, curtailment levels are below 1.0% in ISO-NE (Enernex Corporation, 2011, pp. 120-125).

- The most recent detailed study of the impact of wind power in New England, the NEWIS (General Electric, 2010), concluded that curtailment levels will be less than 1.15% in 2020, at wind energy penetration[35] levels of 20% (General Electric, 2010, p. 257). NEWIS assumes that material expansions to transmission infrastructure, both in New England and Maine, will occur by 2020, largely mitigating the effects of congestion (General Electric, 2010, p. 110).[36]

Study details, parameters, assumptions and findings are summarized further in Appendix B.

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[29] Per the study's name, the WWSIS-II also analyzes the effects of both solar and wind integration, concurrently, also making extrapolation difficult.

[30] The WWSIS-II curtailment figures are based on the assumption that sufficient intra-zonal transmission capacity is built for each additional (modeled) plant, largely eliminating increased curtailment from local congestion (NREL, 2013, p. xiii).

[31] Under this scenario, solar penetrations are 8%; solar penetrations cause curtailment at different times than wind (due to solar being most productive during the day, wind at night) affecting results.

[32] The "Eastern Region" includes the following Regional Transmission Organizations: ISO-NE, MISO, NYISO, PJM, SERC, SPP, and TVA.

[33] The study scenarios build sufficient transmission infrastructure to most economically transfer power between potential future generation sites and load zones

[34] In the EWITS, increased offshore wind penetration correlates with higher curtailment.

[35] In this paper "penetration" refers to MWh of electricity produced by wind energy resources, as a percentage of the total MWh within the system.

[36] NEWIS assumes the build-out of the "Governors' 4 GW Overlay", a transmission upgrade plan identified in *New England 2030 Power System Study* (February 2010) and expanded on in the NEWIS Report. This overlay was specifically modeled in the NEWIS to be able "to robustly deliver a total additional generation nameplate capacity (of Wind Energy) of 4 GW" (General Electric, 2010, p. 119).

Since the NEWIS publication, the level of wind power curtailment in Maine has become apparent.[37] Without transmission upgrades – either socialized by the region of privately funded by merchant generation developers, the expected level of curtailment would be expected to increase with addition of more wind or other types of generation. Because of this, ISO-NE is addressing curtailment (and integration impacts, which are discussed in Section 4.3) from transmission congestion via a variety of initiatives, detailed in Appendix C. These initiatives are expected to help to reduce curtailment.

There are currently several competing or complementary transmission projects underway, planned, proposed or under consideration in ISO-NE and in Maine, that would relieve transmission bottlenecks constraining wind power (and other generators') access to market. An overview of these projects is presented in Appendix D.[38] Although it is unclear which projects will proceed, when they will be completed, precisely how these transmission upgrades will affect curtailment of wind turbine operations, or how to quantify these effects, it is clear that increased transmission relative to wind energy penetration levels will help reduce curtailment.

In view of the findings contained in the NEWIS, WWSIS-II and EWITS, and the numerous transmission expansion and ISO-NE initiatives, this paper applies the following curtailment level assumptions for the two scenarios which we believe bound the future level of curtailment and the associated energy production expected in 2020:

1. **High Production (Transmission Unconstrained) Scenario:** For this scenario, a curtailment level of **1.15%** was used in modeling MWh production. This number corresponds to the curtailment levels predicted by the NEWIS study in a transmission unconstrained scenario. As the NEWIS study specifically modeled the ISO-NE system, these findings were viewed as more applicable than those contained in other studies. This represents a more idealized outcome and is therefore treated as a lower-bound on curtailment and an upper-bound on wind energy production.

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[37] ISO-NE has presented several interim presentations discussing their analysis of this issue, which were reviewed by the authors but are not explicitly cited here (they are designated as Critical Energy Infrastructure Information (CEII) which is not available to the general public, and terms of access prohibit quoting or citing these materials). (ISO-NE, CEII, 2014)

[38] An incomplete list of current transmission upgrade projects (ongoing and proposed) which will or could relieve congestion otherwise affecting wind generation in Maine include:
The Maine Power Reliability Program: A $1.4 billion investment in Maine's bulk power transmission system started in 2009 and near completion. "When completed, [the MPRP] will provide basic infrastructure needed to increase the ability to move power from New Hampshire into Maine and will improve the ability of the transmission system within Maine to move power into the local load pockets as necessary." (ISO-NE, RSP, 2014, p. p. i).
The Northeast Energy Link: Two 660 MW DC cable circuits with DC converter stations. The line would be 250 miles long and transmit significant renewable energy into the New England market. The Northeast Energy Link would create a major corridor for transmission of Northern Maine and Canadian renewable energy sources. http://www.northeastenergylink.com/
The Green Line: A high-voltage direct current (HVDC) transmission system designed to transmit up to 1,000 megawatts (MW) of electricity from northern Maine to southern New England. http://greenlineproject.com/.

2. **Low Production (Transmission Constrained) Scenario:** For this scenario, the 2013 curtailment level **8.18%** was used. This percentage corresponds to the curtailment levels in 2013, when there were significant transmission constraints on production, due to MPRP construction. Since the unexpectedly high level of curtailments during this period served to trigger a range of initiatives to mitigate wind curtailment, we view this level as problematic for wind generators in this region, and representative of the high end of future curtailment conditions. Therefore, this level serves as a proxy for modeling a future scenario in which curtailment continue to be constrained and an upper-bound on the long-term average level of curtailment experienced by the Maine wind fleet (and a corresponding lower-bound on energy production).

Curtailment levels assumed for this study in each analysis period are summarized in Table 15.

Table 15: Curtailment Levels, 2013 & 2020

Analysis Period	On/ Off-Peak	Ratio of Curtailment During Analysis Period to Annual Curtailment %	% of MWh Production (vs. Potential) lost to Curtailment, 2013 (%)	Expected % of MWh Production (vs. Potential) lost to Curtailment, 2020 (%)	
				High Production (Transmission Unconstrained) Scenario	Low Production (Transmission Constrained) Scenario
Ozone	On-Peak	117.0%	9.6%	1.3%	9.6%
Ozone	Off-Peak	117.0%	9.6%	1.3%	9.6%
Non-Ozone	On-Peak	92.0%	7.5%	1.1%	7.5%
Non-Ozone	Off-Peak	92.0%	7.5%	1.1%	7.5%
ANNUAL		N/A	8.18%	1.15%	8.18%

3.5. Annual Energy Production, 2013 and 2020

Annual production estimates are presented in Table 16, below:

Table 16: Energy Produced by Maine Wind Energy, 2013 and 2020 (GWh/yr)

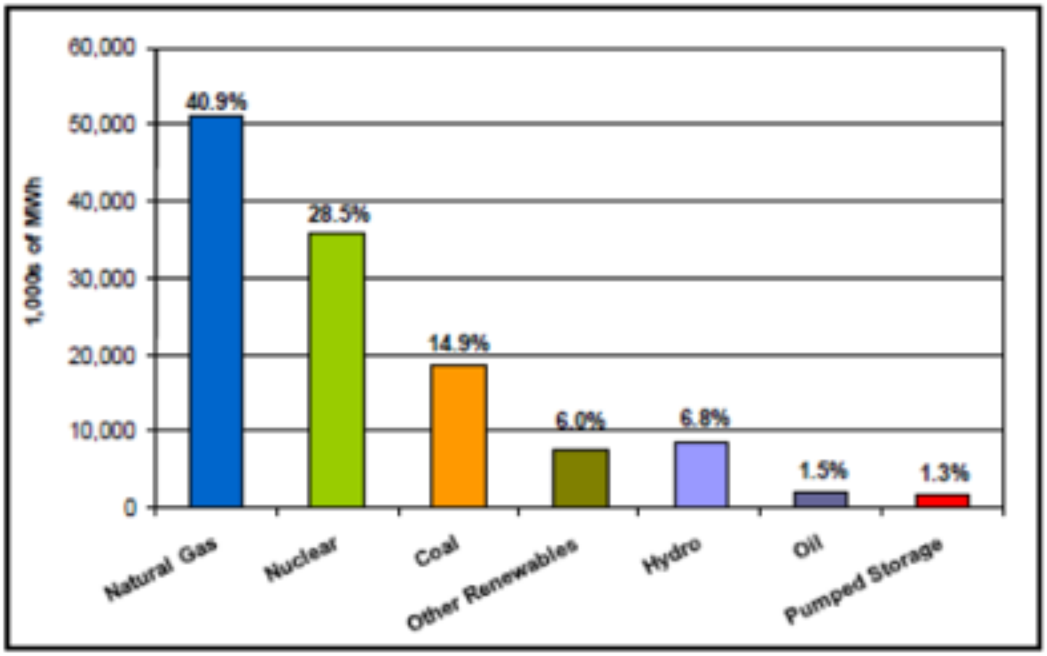
Analysis Period	On/Off-Peak	Estimated Production 2013, Actual (GWh)	Expected Production 2020, High Production (Transmission Unconstrained) Scenario (GWh)	Expected Production 2020, Low Production (Transmission Constrained) Scenario (GWh)
Ozone	On-Peak	125	615	570
Ozone	Off-Peak	216	1069	990
Non-Ozone	On-Peak	296	1465	1363
Non-Ozone	Off-Peak	414	2048	1905
Annual Production		1052	5198	4828

4. Estimate of Avoided Emissions

4.1. Estimation of Direct Avoided Emissions, 2013 and 2020

As alluded to in Section 2.1, the 2010 NEWIS estimated avoided emissions as a result of wind energy generation (General Electric, 2010). These estimates, however, were based on a fuel mix that has significantly changed since the study's publication. As shown in Figure 2, below, the NEWIS used data from 2008, a time when coal generation comprised nearly 15% of all generation in New England.

Figure 2: Fuel Mix Assumptions in NEWIS



Source: (General Electric, 2010, p. 78)

This fuel mix profile stands in contrast to that presented in the most recent *2012 ISO New England Generator Air Emissions Report* (ISO-NE, 2014), shown in Figure 3, below. As one can readily see, in 2012 coal fired plants generated less than 1/4th of the total electricity they produced in 2008, with natural gas conversely comprising a significantly increased share.

More importantly, coal has also declined as a marginal fuel source[39] over the same time period, as shown in Figure 4, below. Coal was the Locational Marginal Unit ("LMU")[40] 14% of the time in 2009; in contrast coal was the LMU 4% of the time in 2012 (a 71.5% decrease). This is especially important,

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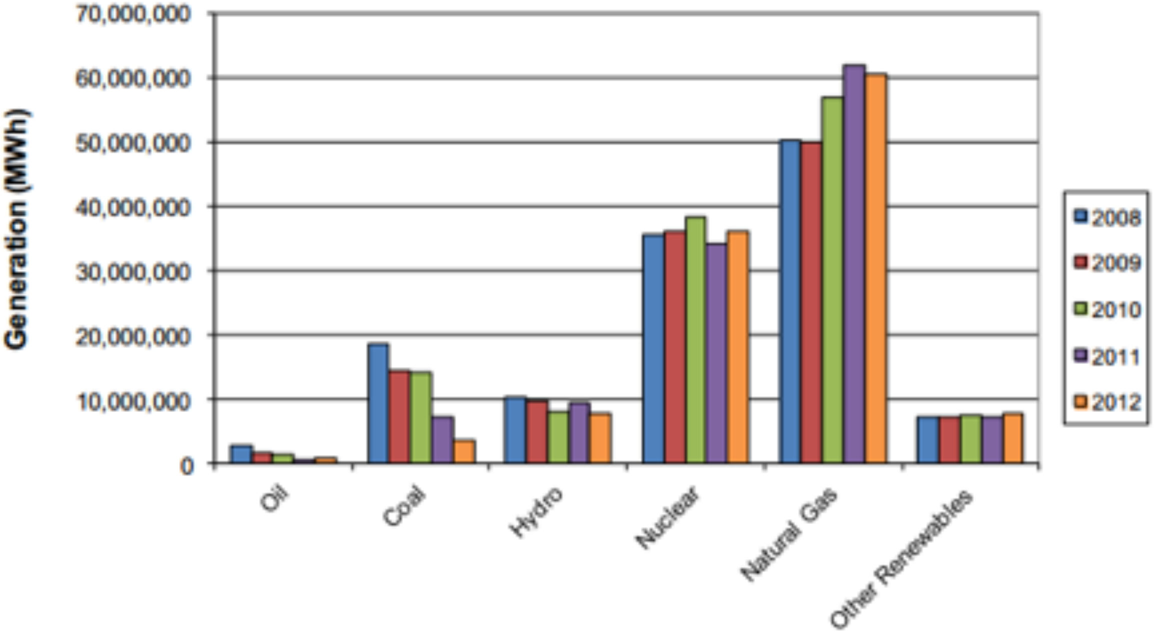
[39] The marginal generator is the next generator that would be dispatched to provide additional electricity production in the event that the electrical system requires such production, or that would be reduced in the event of less load or introduction of an incremental generation source. Changes in marginal generation dictate the emission impact of changes to the supply mix such as the introduction of more wind power.

[40] The LMU is the "ISO-NE identified marginal unit(s) that set the Energy Market hourly Locational Marginal Price(s) (LMP)." (ISO-NE, 2014, p. 6)

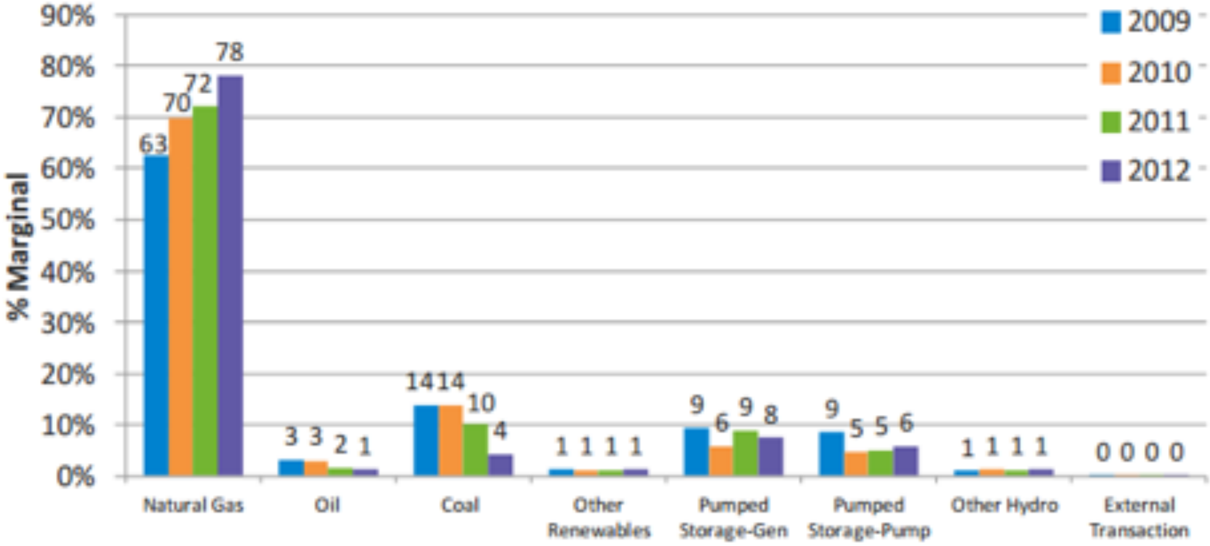
because wind generation or other resources (including energy efficiency) will displace the marginal fuels, rather than average generation mix.

Figure 3: ISO-NE Generation Fuel Mix, 2008-2012



Source: **(ISO-NE, 2014, p. 17)**

Figure 4: ISO-NE Percentage of Time Locational Marginal Unit, by Fuel Type, 2009-2012



Source: (ISO-NE, 2014, p. 18)

As discussed further below, additional coal-fired retirements have been announced, meaning that coal's contribution to marginal emissions is expected to be trivial after 2017. Because of this movement from "dirty" coal generation to comparatively cleaner natural gas generation, the results from the NEWIS, while informative, also likely materially overstate the emissions benefits of wind generation. As a result, avoided emissions must be determined using the most recent data which reflects the current fuel mix regime in New England.

The best (most recent, most applicable, and objective) source of information on avoided emissions in ISO-NE is the *2012 ISO New England Generator Air Emissions Report* (ISO-NE, 2014)*,* a report updated periodically by ISO-NE and last published in January of 2014 based on actual 2012 data. That report provides system and marginal emissions (kTons) and emission rates (lb/MWh & lb/MMBtu). The report (previously known as the Marginal Emission Rate Analysis) was originally developed to to determine the emission reductions that demand-side management programs had on ISO-NE's aggregate NO_X, SO_2, and CO_2 air emissions. The emission rates provided in the report have also been used to determine the benefits from energy efficiency programs, and from increased development of renewable energy resources (ISO-NE, 2014, p. 1).

The ISO New England Generator Air Emissions Report, however, is backward looking, limiting its direct use for application to estimating future emission reductions without further adjustment. Also, the report, while used to estimate the benefits of renewable energy (including wind), is not designed to, and does not adjust for the potential impacts on overall system operation caused by the integration of an increasing quantity of variable generation (wind & solar).

This ISO-NE study provides emissions rate information for three different groupings of LMUs[41]: All LMUs, Emitting LMUs, and Oil & Natural Gas-Fired ("O&NG") LMUs. Marginal generator[42] emission rates, rather than system-wide average emission rates, are used in this paper, and in all similar recent studies, because wind generation or other resources (including energy efficiency) will displace these units.

The first category, All LMUs, includes all identified marginal units in calculating the marginal emission rates. This calculation includes hours when non-emitting generators such as hydro-electric generation and pumped storage[43] (which together comprise 15% of marginal generation) were 'on the margin'. However, hydroelectric and pumped storage generation would not be avoided by wind generation, as the energy available would simply be used at other times. So this metric is not applicable to estimating the emission impacts of wind, and is not considered further in this paper. The second category, Emitting LMUs, captures the marginal energy, and associated emissions, that could be avoided from natural gas,

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[41] ISO-NE's LMU emission rates determination method "uses the emissions rates from the ISO-NE identified marginal unit(s) that set the Energy Market hourly Locational Marginal Price(s) (LMP). The LMP results from a process that minimizes total energy costs for the entire New England region, subject to a set of constraints reflecting physical limitations of the power system." The rates from all LMU's are then averaged, to determine rates for each Analysis Period. (ISO-NE, 2014, p. 6)

[42] The marginal generator is the next generator that would be dispatched to provide additional electricity production in the event that the electrical system requires such production, or that would be reduced in the event of less load or introduction of an incremental generation source.

[43] Pumped storage is an energy storage technology that uses energy from other sources to pump water to an uphill reservoir, to be released through a turbine to generate energy at a later time, operating like a huge battery.

coal, oil and a very small quantity of other renewables, as occurred in 2012. The last category, O&NG LMUs, calculates the emissions rate from just oil and natural gas units on the margin.

The LMU emission rates for each Analysis Period under the latter two calculations are presented in Table 17 and Table 18, below.

Table 17: All Emitting LMU Emission Rates, 2012 (lb/MWh)

Analysis Period	Time	NO_x	SO_x	CO_2
Ozone	on-peak	0.4	0.45	1019
Ozone	off-peak	0.26	0.39	1003
non-ozone	on-peak	0.23	0.45	1019
non-ozone	off-peak	0.19	0.39	1003

Source: (ISO-NE, 2014, pp. 26-27)

Table 18: O&NG LMU Emission Rates, 2012 (lb/MWh)

Analysis Period	Time	NO_x	SO_x	CO_2
Ozone	on-peak	0.32	0.07	933
Ozone	off-peak	0.11	0.02	902
non-ozone	on-peak	0.12	0.07	933
non-ozone	off-peak	0.14	0.02	902

Source: (ISO-NE, 2014, pp. 26-27)

This paper uses emission rates from marginal Emitting LMUs in modeling emission reductions in 2013, and marginal emission rates for O&NG LMU's in modeling 2020 emission reductions.

The 2012 Emitting LMU rate is used as the basis for modeling 2013 emission reductions because it represents the mix of avoidable resources that can be displaced from the region's power supply mix at that time.[44] This rate includes coal generation, which currently functions as the marginal generator 4% of the time.

The O&NG rate is used for modeling 2020 emission rates because, according to NEWIS, wind energy generation will predominately displace natural gas fired units in the future (General Electric, 2010), and perhaps more importantly, because coal power plants are being progressively decommissioned in New England, as discussed above. Further, additional coal generation is slated to be de-commissioned, which will further reduce coal's roles as a marginal fuel to a negligible amount.[45] Using this rate implicitly

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[44] There were limited changes to ISO-NE's resource mix between 2012 and 2013.

[45] By 2020, both the Massachusetts-based Salem Harbor power plant (2014) and Brayton Point power plant (2017) are committed to be closed. Together, these plants account for most of the remaining coal generation in New England.

assumes that coal fired generators will provide only a *de-minimis* amount of marginal generation in 2020.[46]

4.1.1. Adjustments to 2012 Emission Rates for 2013 and 2020:

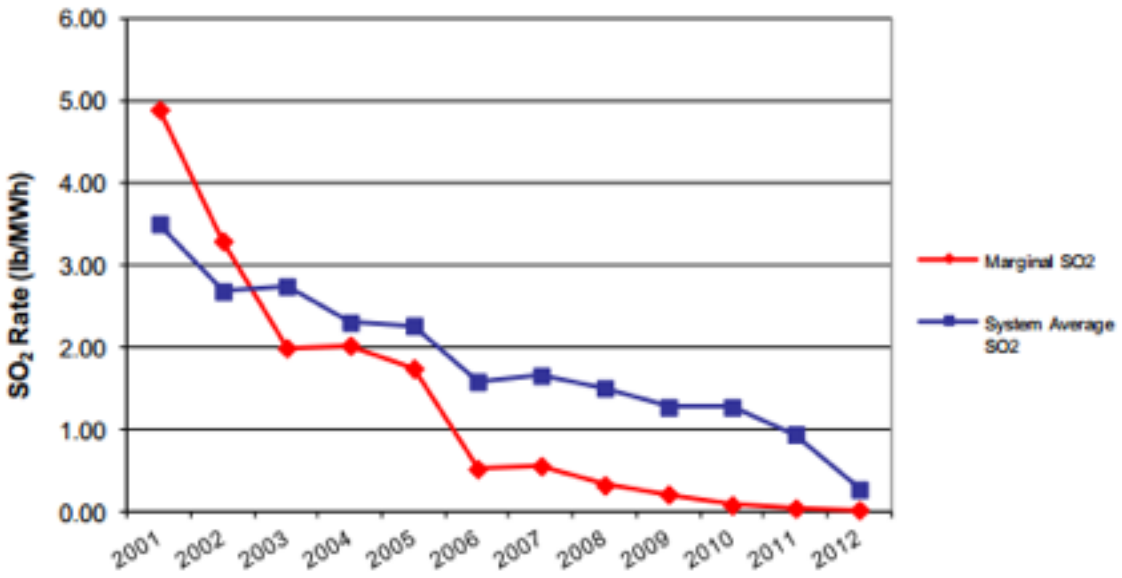
Because this paper models emission reductions in 2013 and 2020, 2012 emission rates must be forecasted to 2013 and 2020.

Marginal emission rates change over time due to a number of factors. These rates are impacted by:

1. Changes to the fuel mix among marginal generators (e.g. emission rates will decrease if a greater percentage of marginal units are gas, rather than oil or coal fueled);
2. Changes to regulations applicable to various emission control technologies or processes; and
3. The ISO-NE system's movement to more efficient technologies, which produce less emissions for each MWh of generation.

As can be seen in the *2012 ISO-NE New England Electric Generator Air Emissions Report,* aggregate emission rates have progressively fallen over the last decade. Similarly, marginal unit emission rates have also progressively declined. This trend is depicted in Figure 5, Figure 6 and Figure 7, below:

Figure 5: 2001–2012 Calculated New England Annual Average System SO_X Emission Rate vs. SO_X FTA (Fuel Type Assumed) Marginal Emission Rate (lb/MWh)



Source: (ISO-NE, 2014, p. 34)

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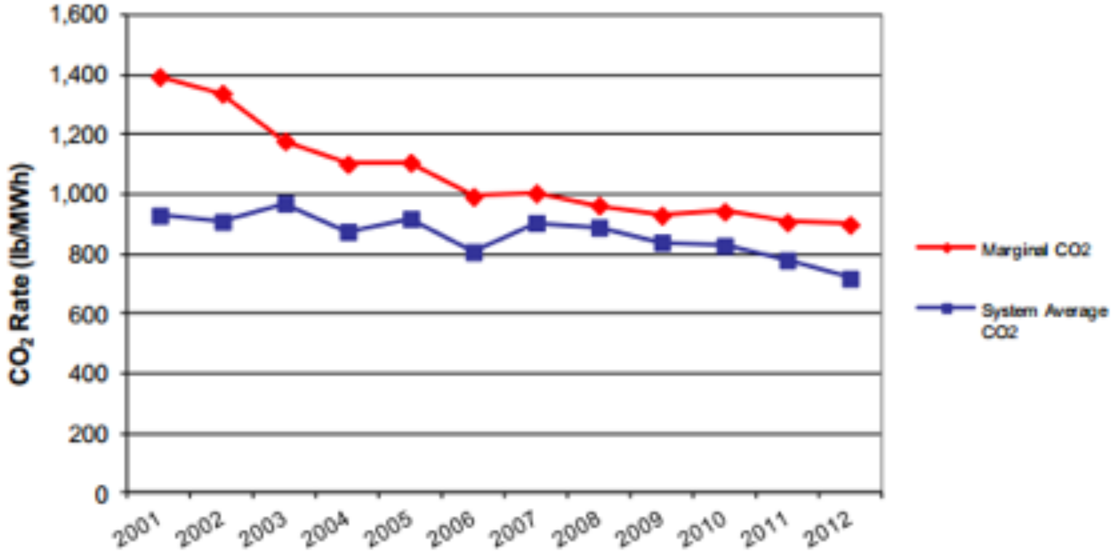
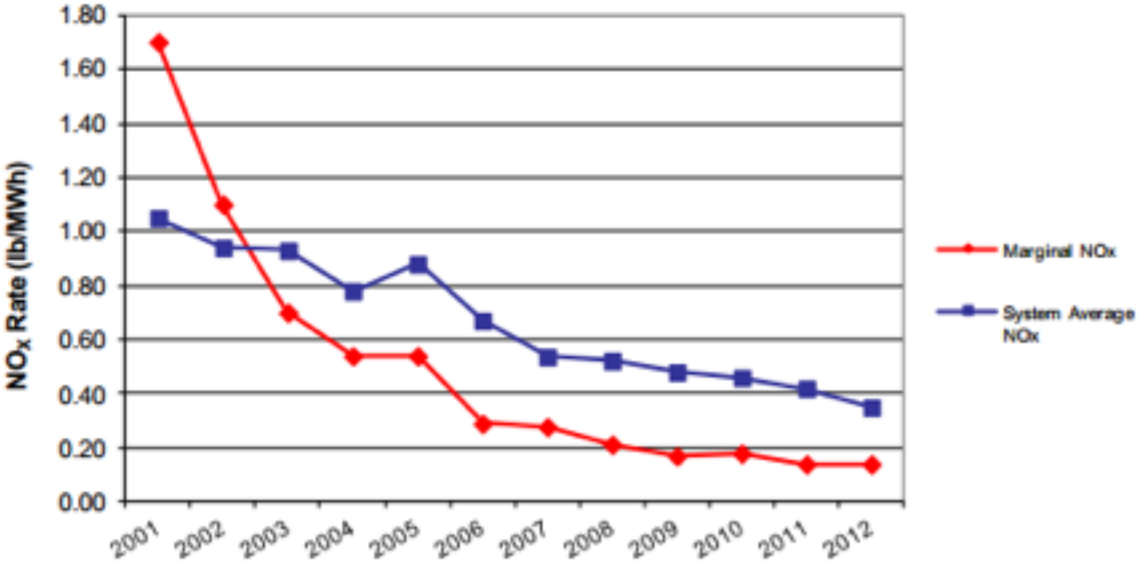
[46] If coal makes up a greater than a negligible percentage of marginal generation in 2020, the emission reduction results presented by this paper would be conservative, as coal fired generators generally have much higher emission rates than oil or natural gas fired generators.

Figure 6: Historically Calculated New England CO_2 FTA (Fuel Type Assumed) Marginal Emission Rates



Source: (ISO-NE, 2014, p. 34)

Figure 7: 2001–2012 Calculated New England Annual Average System NO_X Emission Rate vs. NO_X FTA Marginal Emission Rate (lb/MWh)



Source: (ISO-NE, 2014, p. 34)

Marginal emissions rate have dropped off materially in the last decade due to a number of factors, including the implementation of new regulation regarding emissions controls, fuel sulfur content, the increased penetration of zero-emission renewable generation, the increased role of natural gas in the region's supply mix, and most importantly, the shutdown of much of the ISO-NE region's coal generation (ISO-NE, 2014, pp. 17-28), as discussed above. The implication is that the incremental benefits of more wind (or solar or energy efficiency) are smaller on a per-MWh than they used to be, because wind is displacing generation from an increasingly less polluting system.

Changes to fuel mix from 2012-2020 are modeled by using the O&NG Emission Rate for 2020. By using this rate, the paper's methodology incorporates the phasing out of coal to *de minimis* levels by 2020. This paper does not expressly model fuel mix changes between 2012 and 2013. This assumption may be slightly conservative, as marginal coal generation declined by 60% between 2011 and 2012 (ISO-NE, 2014, p. 17). However, as coal comprised only 5% of marginal generation in 2014 (ISO-NE, 2014, p. 18), this conservatism will have, at most, a limited effect.

This paper also assumes that there will be no material changes to environmental regulations resulting in further decreased per-unit emissions from marginal generators in New England. The major changes to SO_x and NO_x regulations already have occurred and dramatic future reductions for these emissions are unlikely given that there is limited downward movement in SO_x and NO_x emissions available relative to efficient natural gas plants. Further, this paper assumes that EPA 111d will build on regional processes and utilize the Regional Greenhouse Gas Initiative (RGGI), rather than force direct emissions rate reductions.

Because changes in emission rates due to regulation are not modeled, this paper focuses primarily on changes to power plant efficiency in extrapolating the 2012 marginal emission rates to 2013 and 2020.

Fossil fuel generators have experienced an increase in conversion efficiency (i.e. the efficiency at converting chemical energy locked in the fuel into electric energy production) over the last decade. In industry parlance, efficiency among fossil fuel generators is referred to as the generators "heat rate". Heat rate and efficiency are inversely related to each other: as a generator's efficiency increases, its heat rate decreases.

Improvements in efficiency, or decreases in heat rate, correlate to decreased emissions for the same MWh production of electricity. This affects the emissions that can be directly avoided by wind generation; as generators become more efficient, the emissions wind reduces by displacing these generators is reduced. This paper assumes continued turnover of the generation fleet to more efficient generators (e.g., new generation will on average have lower heat rates than the installed fleet).

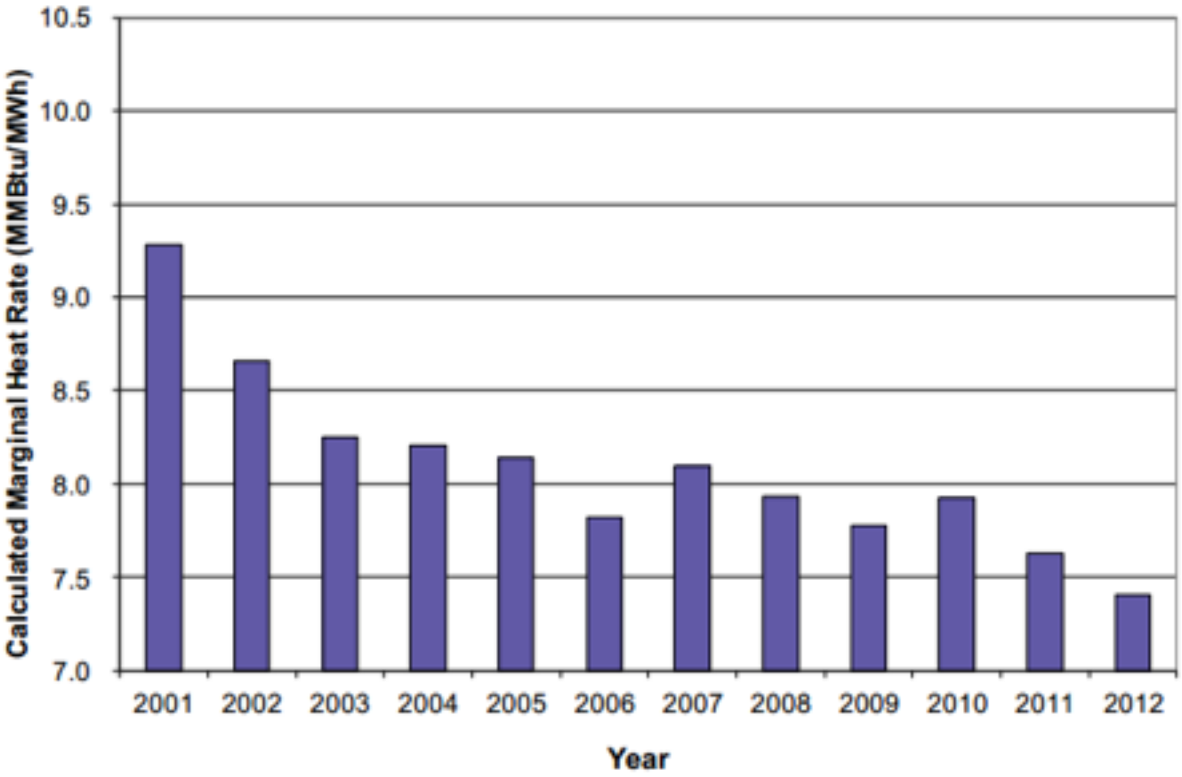
As shown in Table 19 and Figure 8 below, heat rates have declined in New England over the last decade. This paper expects heat rates to continue to decline following these trends as gas generation technology continues to improve.

Table 19: LMU Heat Rates, 2009-2012 (MMBtu/MWh)

	All LMUs	Emitting LMUs	O & NG LMUs
2009	8.591	8.507	7.881
2010	7.414	8.385	7.821
2011	6.907	8.19	7.758
2012	6.678	7.87	7.676

Source: (ISO-NE, 2014, p. 23)

Figure 8: Historical New England FTA Marginal Heat Rate (MMBtu/MWh)

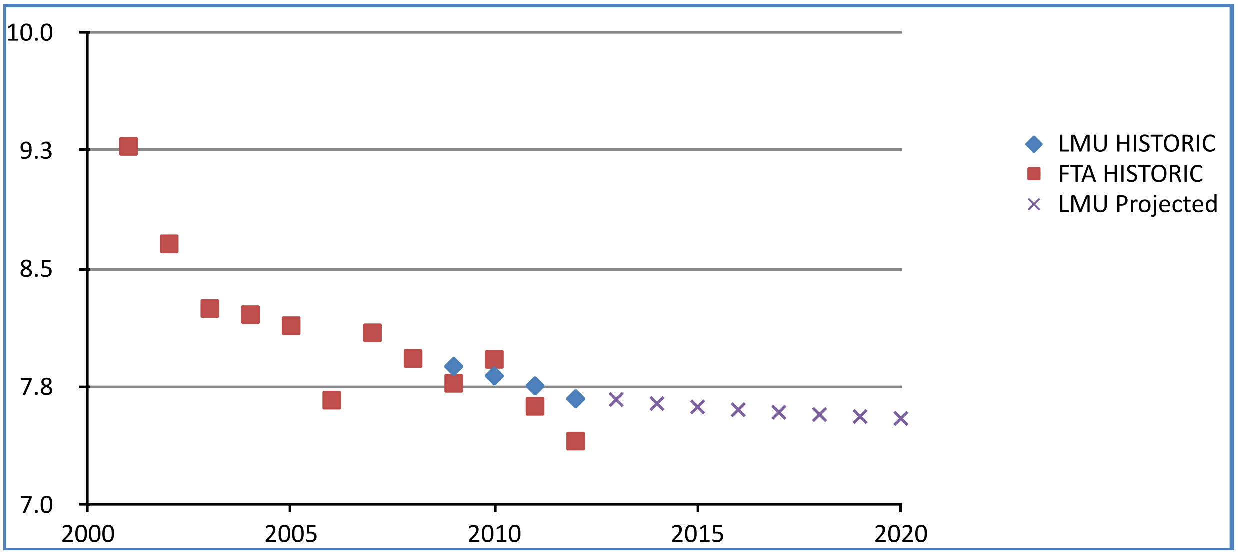


Source: (ISO-NE, 2014, p. 23)

Using historic heat rate data for Emitting LMU's, SEA projected future heat rate decreases into 2013 based on the average annual reduction over the prior 4 years. This approach results in an estimate that Emitting LMU heat rates will decrease by approximately 2.6% between 2012 and 2013. To account for this increase in efficiency, Emitting LMU emission rates were decreased from 2012 by this percentage to forecast a projected 2013 Emitting LMU emission rate.

Using the historic heat rate data for O&NG LMUs SEA projected an exponential best fit curve to forecast future heat rate decreases into 2020, as shown in Figure 9.[47] This approach results in an estimate that heat rates will decrease by roughly 1.7% between 2012 and 2020. To account for this increase to efficiency, O&NG LMU emission rates were decreased by this percentage to forecast a projected 2020 O&NG LMU emission rate.

Figure 9: Historic and Projected FTA and LMU O&NG Heat Rates, 2001-2020 (MMBtu/MWh)



Heat Rates, Historic and Projected, 2001-2020

4.2. Estimate of Direct Avoided Emissions

The 2013 and 2020 Emitting LMU and O&NG LMU emission rates, adjusted from the 2012 rates to take into account changes in heat rate as discussed above, were multiplied by the MWh of production in 2013 and 2020, forecasted in Section3, to estimate direct emission reductions as a result of wind generation.

These results are presented in Table 20, below.

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[47] Figure 8 also shows Historic FTA (Fuel Type Assumed) marginal emission rates; while this method is now largely disfavored, and the LMU methodology is favored (ISO-NE, 2014), this paper looked at the these rates comparatively.

Table 20: Annual Emissions Directly Reduced by Wind Generation (Tons)

	2013-Actual	2020 – High Production (Transmission Unconstrained) Scenario	2020 – Low Production (Transmission Constrained) Scenario
CO_2	517,309	2,337,740	2,171,510
SO_x	212	102	95
NO_x	123	382	355

4.3. Estimating Indirect Emissions Increases Due to Integration Efficiencies

4.3.1. Overview, Context of Indirect Emissions Methodology

The electrical grid is a highly complex, interconnected system. Altering electrical generation, or fluctuations in electrical generation, in one part of the grid can affect operations in other parts (NREL, 2013, p. vii). The variable nature of wind generation can cause an increase in cycling[48] of certain fossil fuel plants designed, and relied upon by system operators, to following fluctuations in demand. Plant cycling can affect emissions rates (NREL, 2013, p. 13). Generally, as wind penetration increases, cycling and emissions rates increase (General Electric, 2010) (NREL, 2013).

It is not surprising, given the difficulties of modeling and applicability, that there is a lack of understanding about the impact of increased cycling of fossil fuel plants, and increased operating reserve requirements, on emissions. As discussed in Section 1.1, the ideal source of information on integration inefficiency impacts on emission is the independent operator of a system. The 2010 NEWIS (General Electric, 2010) made major strides in estimating emissions reductions taking into account cycling (regulation and spinning reserve) demands on the system. However, the NEWIS did not separately report direct avoided emissions and indirect emissions, instead only reporting net combined avoided emissions. Unfortunately, this means that this paper cannot directly use the NEWIS results to estimate indirect emissions caused by wind generation.

ISO-NE has no plans to update the NEWIS at this time.[49] Short of commissioning a new detailed study, the next best available approach is to examine the best and most recently available analyses, and consider how they might guide expectations of emission impacts of wind in ISO-NE and Maine.

4.3.2. Overview, Studies Reviewed

As a result of increased focus on the impacts of integration inefficiencies recently, studies examining this issue have become more sophisticated, and their methodology has evolved and improved, over the last

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[48] In this study, the term “cycling” is defined to be consistent with the definition used in the Western Wind and Solar Integration Study, Phase 2, and means “shutting down and restarting, ramping up and down, and operating at part-load.” (NREL, 2013, p. vii)

[49] Nonetheless, ISO-NE is addressing recommendations from the NEWIS study to alleviate wind integration issues, as discussed in Section 3. These changes and others will likely result in better integration of wind installations in the future, thus mitigating increased emissions due to integration impacts to some degree.

several years. That said, an important caveat must be understood before these studies can be directly applied to the ISO-NE system.

The impacts of increased marginal power plant cycling will differ in different electric systems.[50] Systems that are comprised largely of inflexible base load coal plants, small systems, and island systems may experience much more substantial impacts from integrating wind power than more flexible systems. ISO-NE benefits from a particularly flexible mix of resources, including substantial volumes of hydroelectric with storage, pumped hydro storage, and natural gas combined cycle and combustion turbines designed to follow load fluctuations. The ISO-NE system also has comparatively little inflexible coal or other fossil generation on the margin (ISO-NE, 2014). Because of this, results from other systems generally cannot be readily applied to ISO-NE, although they can be useful for comparison and to bound expected results.

The major US studies reviewed for this paper that addressed wind integration and emission impacts include (in chronological order):

- The earliest relevant US studies posited that the impacts of cycling significantly reduced, or almost completely offset, emissions reductions from wind generation (Bentek Energy, 2010) (Katzenstein & Apt, 2009). There is little relevance of the Bentek study to the ISO-NE as much of its focus was on the Public Service of Colorado service territory which relied on coal as the marginal fuel much of the time. The Katzenstein & Apt academic paper modeled net increases in NO_x emissions under certain scenarios; however the results are not applicable to ISO-NE as NO_x emissions have continued to decrease even with increasing wind (and solar) penetration.

- The 2010 NEWIS (General Electric, 2010), discussed above.

- The Western Wind and Solar Integration Study ("WWSIS-II") (NREL, 2013) examined the cycling impacts of wind and provided separate estimates of direct and indirect emission impacts, the latter of which it projected to be a small fraction (a few percent) of direct emissions avoidance. WWIS assumed no significant transmission constraints. The system modeled in WWSIS-II is significantly different than the ISO-NE system, however, with substantially more coal and less natural gas.

- The PJM Renewable Integration Study ("PRIS") (General Electric, 2014) is the most recent and most sophisticated of all the state-of-the-art of integration studies reviewed. As with WWIS, PRIS projected indirect emission impacts to be a small fraction of Direct Avoided Emissions. PRIS scenarios included transmission constraints, but again applicability is somewhat hamstrung because of significantly more coal on the margin in the PJM interconnection than in ISO-NE.

The key findings of the two most recent studies, WWSIS-II and PRIS, are detailed in Table 21.

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[50] As used here, the concept of an electric system is one that is operated in a centralized control area to balance load and generation at all time. The power supply mix in New England, which is dispatched by the system operators at ISO-NE, represents such a system.

Table 21: Summary of Most Recent Integration Study Emission Impact Findings

Study Name	Definition of Cycling	Region Covered	Key Assumptions/Findings
PJM Renewable Integration Study (PRIS): Plant Cycling and Emissions (2014) (General Electric, 2014)	Cycling refers to the operation of electric generating units at varying load levels, including on/off, load following, and minimum load operation, in response to changes in system load requirements (p. 13)	PJM Interconnection	• Renewable Energy penetration modeled at 14%, 20%, and 30% (with wind comprising >$2/3^{rds}$ of penetration). • Under different scenarios models a significant penetration of offshore wind (6-10% of total renewable energy capacity) and Solar (15-50% of total renewable capacity). • Assumes economic development of transmission infrastructure, with some congestion, but most congestion mitigated. • Under scenario most similar to that used in this analysis, which models the smallest amount of offshore wind capacity, cycling reduces the direct avoided emissions by 5.3% for CO_2, 0% for NO_x, and 22.2% for SO_x (pp. 88-89).
Western Wind and Solar Integration Study (WWSIS) (2013) (NREL, 2013)	In this report, cycling is a broad term that means shutting down and restarting, ramping up and down, and operating at part-load. (p. viii)	States and Regional Transmission Organizations that comprise the Western Electricity Coordinating Council	• Wind Power is modeled at >25% penetration in the entire Western Interconnection; Solar at 7-10%. • Sufficient intra-zonal transmission capacity was assumed built for each additional (modeled) plant (NREL, 2013, p. xiii). • Cycling reduces avoided emissions of CO_2 by 0.0%, NO_x by 1.6%, and SO_x by 2.1% (p. 113).

Although the PRIS studies an electrical grid system that is significantly different than ISO-NE, of the available studies (and in the absence of an ISO-NE study explicitly quantifying cycling impacts of wind integration), its results were viewed by the authors as most useful to the analysis in this paper. This is because the PRIS is the most recent study commissioned by an independent system operator which comprehensively models system behavior in order to examine the effects of integration inefficiencies on emissions. However, because the PJM supply mix has a substantially larger proportion of inflexible coal generation on the margin compared to the ISO-NE system's flexible supply mix and lower-emitting marginal resources, there is good reason to believe that a similar study conducted for New England would yield results with a smaller cycling impact than projected by the PRIS.

4.3.3. Application of Percentage Impacts from PRIS to Estimate Indirect Emission Impacts

Background, CO_2, SO_x & NO_x: In order to understand the application of the PRIS results to the current analysis, the source of CO_2, NO_x and SO_x emissions from electrical generation must first be discussed.

- **CO_2 and SO_x:** Both CO_2 and SO_X emissions are produced from the carbon and sulphur contained in fuel when it is combusted to generate electricity. Carbon and sulfur in the fuel can only go two places when combusted: into air emissions, or into solid waste-product (ash for coal combustion; natural gas combustion produces no solid waste byproduct).

  The amount of CO_2 and SO_x emitted per MWh of generation is a direct function of: 1) the content of these elements in the combusted fuel; and 2) the generator's efficiency in converting the fuel to electricity. Other things constant, combusting one ton of fuel will produce the same emissions, regardless of a generator's efficiency. However, the electricity produced from combusting this one ton decreases with decreased efficiency. Thus, where cycling decreases the efficiency of a marginal generator, greater emissions are produced for the same quantity of electricity production. The relationship between decreased efficiency and increased emissions is proportional.

  Further, as natural gas has very limited sulphur content, emissions of SO_x from burning natural gas are negligible.[51]

- **NO_x:** In contrast, NO_x emissions from combusting fossil fuels comes from three sources:

  - Fuel NO_x: Created during the combustion process from nitrogen bound in the fuel. This is a material source of NO_x for coal, but negligible for natural gas.

  - Thermal NO_x: Results from the conversion of nitrogen in the atmosphere to NO_x during combustion. Thermal NO_x is created in the combustion of coal, oil and natural gas. The conversion of atmospheric nitrogen to NO_x increases exponentially with flame temperature in the generator.

  - Prompt NO_x: This source is formed when atmospheric nitrogen combines with fuel in fuel-rich conditions during combustion, and then oxidizes along with fuel to become NO_x. The contribution of prompt NO_x to overall NO_x is small and its causation can be ignored for our purposes.[52]

  Power plant NOx emissions are typically controlled through a combination of combustion controls (such as Low-NO_x burners or overfire air ports, steam or water injection, etc.) or post-combustion controls (Selective Catalytic Reduction or Selective Non-Catalytic Reduction). PRIS found that cycling, which decreases combustion temperatures for natural gas generators, will

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[51] For additional information, see (Enivronmental Protection Agency, 2013), hyperlinked at: http://www.epa.gov/cleanenergy/energy-and-you/affect/natural-gas.html

[52] See (EPA - Clean Air Technology Center, 1999), hyperlinked at: http://www.epa.gov/ttncatc1/dir1/fnoxdoc.pdf

not increase natural-gas-fired NO_x emissions rates, and in fact may actually decrease emission rates. Indeed, per the PRIS:

> *"NO_x and SO_x rates (lbs/MMBtu) … decrease for the gas turbine and combined cycle plants... For gas turbines low loads often have lower average flame temperatures leading to lower NO_x"* (General Electric, 2014, pp. 86-87).[53]

Cycling Impacts, CO_2, SOx & NOx: Based on the above, as well as information contained in the PRIS, this paper makes the following assumptions in estimating indirect emissions impacts.

- **CO_2:**. Under the PRIS's "20% Low-Offshore, Best-Sites Onshore" Scenario" (LOBO)[54] the PRIS study finds that integration inefficiencies reduce Directly Avoided Emissions by **5.3%** (or to phrase another way, integration inefficiencies result in additional emissions from fossil generators roughly equal to 5.3% of emissions directly avoided) (General Electric, 2014, p. 89). This percentage was determined by comparing the reduction in MWh output from fossil fuel generators to the reduction in CO_2 emissions from these same generators, presented in Table 22: PRIS Reductions MWh Output % CO_2 Emissions, Fossil Fuel GeneratorsTable 22, below:

Table 22: PRIS Reductions MWh Output % CO_2 Emissions, Fossil Fuel Generators

Scenario	Reduction in MWh Output	Reduction in CO2 Emissions
20% LOBO	19%	18%

Source: (General Electric, 2014, p. 89)

If cycling had no effect on efficiency, and therefore CO_2 emissions, the reduction in MWh output and CO_2 reductions would be exactly equal. Here, as CO_2 emissions decrease by 18% relative to a 19% reduction in MWh production, this signals an inefficiency caused by cycling of approximately 5.3%.

The PRIS result, 5.3%, likely overstates the impacts of cycling on emissions if applied to ISO-NE. In the PJM over the last 48 months, coal generators have comprised between 49%-58% of marginal generation, and natural gas generators have comprised 32-42% of marginal generation.[55] In contrast, in ISO-NE natural gas is the marginal generator 96% of the time, with coal providing marginal generation only 5% of the time, during 2012 (ISO-NE, 2014, p. 19). As natural gas combined cycle and combustion turbine generators are designed to cycle, and coal

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[53] Similarly, the WWSIS finds that NO_x emissions do not increase as a result of cycling, and actually decrease (NREL, 2013, p. 113).

[54] This scenario was viewed as most applicable to the ISO-NE system and to a study of wind emission impacts in Maine, among the scenarios studied in the PRIS, because it has the most similar proportion of land-based wind to solar and offshore wind to the expected New England mix.

[55] Marginal Fuel type in PJM has varied over the last 48 months; see various PJM State of the Market reports prepared by Monitoring Analytics, LLC, Independent Market Monitor, found at http://www.monitoringanalytics.com/reports/pjm_state_of_the_market/2014.shtml. In particular, see the most recent report: (Monitoring Analytics, LLC, 2014)

plants were designed as baseload generators, one would expect the impacts of cycling to be lower at comparable wind penetration levels, and use of the PRIS data is likely to be conservative.

Moreover, while the specific relationship of cycling impacts to wind penetration will be system-specific, it is generally understood that the higher the penetration, the bigger the cycling impact.[56] The PRIS scenario used assumes renewable energy penetrations of 20%. This is a far higher penetration than that experienced in New England in 2013, and what will be seen in New England in 2020. In 2012, 431 MW of wind energy, if one assumes average capacity factor of 30%, represents less than 1% (of energy) penetration. Similarly, 1782 MW of wind energy capacity in 2020, at a 35% capacity factor, represents less than 4% penetration. Indeed, one would need more than 9,000 MW of renewable energy capacity installed in the ISO-NE region by 2020 before penetrations of 20% were reached.[57,58] This observation again militates toward a 5.3% reduction being a conservative "upper bound" for the impacts of cycling.

- **SO_x**: As stated previously, like CO_2, the SO_x emissions produced per MWh generated is a direct function of fuel content and efficiency. We therefore use the percentage cycling impacts on CO_2 emissions, calculated above, as a directly relevant proxy for cycling impacts on SO_x emissions. As a result, this paper estimates that cycling will result in a **5.3%** reduction to the SO_x emissions wind directly avoids.[59]

- **NO_x:** As stated previously, NO_x emission are a function of combustion temperature, not fuel content or efficiency. Cycling generally lowers combustion temperature; as such NO_x would not increase (and potentially decrease) as a result of cycling. The PRIS and WWSIS results, discussed

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[56] For instance, while the NEWIS does not explicitly identify the cycling emission impacts, it does produce results showing a greater need for additional reserves with larger wind penetration. (General Electric, 2010)

[57] These calculations are based on 137,193 GWh annual energy needs of ISO-NE in 2013, and 147,551 GWh in 2020. (ISO-NE, CELT, 2014) http://www.iso-ne.com/trans/celt/fsct_detail/2014/pac_19feb2014_prelim_iso_energy_peak_forecast.pdf

[58] If one were to assume that the north-south interconnection transmission constraints within ISO-NE are so severe that wind energy generated in Maine does not ever leave the state – an unrealistic assumption, to be sure - penetration levels in Maine would be correspondingly higher. Using the same capacity factor assumptions as above, in 2013 431 MW of wind capacity corresponds to 7% penetration levels in Maine. Likewise, 1782 MW of capacity corresponds to roughly 37% energy penetration for Maine alone. Based on Maine annual electricity production of 14,428 GWh. EIA, State Electricity Profiles. http://www.eia.gov/electricity/state/maine/.

[59] It must be noted that the PRIS LOBO estimates that cycling will decrease Directly Avoided SO_x Emissions by 22.2%, in comparison to 5.3% for CO_2. With the New England marginal fuel mix being what it is (containing trivial sources of SO_x) there is no physical rationale for applying the PRIS value to New England. We must infer that the 22.2% estimated reduction in directly avoided SO_x emissions from the PRIS is the result of increasingly inefficient coal plants being forced to cycle. This situation is inapplicable in New England, where natural gas dominates the marginal fuel mix, and because natural gas contains a *de minimis* amount of SO_x. Predicting cycling impacts on SO_x in proportion to fuel conversion efficiency changes is, thus, a much more reliable method of predicting what a study comparable to PRIS performed for New England would conclude.

above, confirm this supposition. Therefore, this paper estimates that cycling will result in a **0.0%** reduction to the NO_x emissions wind directly avoids.[60]

Cycling Impact Results: The above reduction percentages were applied to both the 2013 Actual and the 2020 Low and High Production scenarios.

Because ISO-NE benefits from a particularly flexible mix of resources, and has almost no inflexible coal or other fossil generation on the margin (ISO-NE, 2014), in contrast to PJM and because we believe that the reduction percentages due to cycling impacts estimated above are conservative. A 5.3% reduction to Directly Avoided Emissions is likely greater than an updated ISO-NE study would conclude. We further conclude that this approach is more likely to overestimate the effects of cycling for the 2020 High Production (Low Transmission Constraint) scenario than for the 2020 Low Production scenario. This is because material transmission constraints can make pockets of a flexible system like ISO-NE function more comparably to an inflexible system like PJM.

Similarly, because integration inefficiencies increase with penetration, the reduction percentages likely overestimate the effects of cycling on emissions during 2013 (when wind penetration was less than 1%) to a greater degree than during 2020 (when penetration is projected to be roughly 4%).

The estimated annual Indirect Emission increases as a result of cycling are presented in Table 23 and **Error! Reference source not found.** below:

Table 23: Est. Annual Indirect Emission Increase due to Wind Integration Impacts (Tons)

	2013-Actual	2020 – High Production Scenario	2020 - Low Production Scenario	Percentage of Directly Avoided Emissions Estimated to be Lost
CO_2	27,227	123,039	114,290	5.3%
SO_x	11.2	5.4	5.0	5.3%
NO_x	0	0	0	0.0%

As one can see, this paper estimates that annual CO_2 and SO_x emission increases, as a result of integration inefficiencies, will be only a modest fraction of Directly Reduced Emissions shown in Table 20, and that NO_x emissions will not be materially affected by cycling.

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[60] Gas fired plants dominant fossil fuel generation in ISO-NE. A 0% increase in NO_x emissions as a result of cycling may actually be conservative, and wind induced cycling could actually increase emissions reductions in ISO-NE, per results in the PRIS and WWSIS discussed above.

5. Results, Sensitivity Analysis and Conclusions

5.1. Results, Net Emissions Reduced

Using the methodology and based on the assumptions detailed in Section 00, above, this study concludes that Maine wind farm capacities of 431 MW and 1782 MW in 2013 and 2020, respectively, will result in the following reductions of emissions:

Table 24: Net Emissions Reductions - Annually (Tons)

Pollutant	2013-Actual	2020 - High Scenario	2020 - Low Scenario
MW Capacity	431	1782	1782
GWh Production	1,052	5,198	4,828
CO_2	490,000	2,215,000	2,057,000
SO_x	201	97	90
NO_x	123	382	355

These estimates are dependent on the modeling assumptions used. As one can see, the quantity of CO_2 and NO_x emissions reduced grows substantially between 2013 and 2020, regardless of the scenario. While SO_x emission reductions actually decrease between 2013 and 2020, this is result of retirements of coal plants. Coal generators (which produce significantly more SO_x and NO_x than other emitting generators) will generally no longer be present to be displaced in 2020.

These Net Emission Reductions correlate to the emission reductions per MWh of wind farm generation (the “Net Emissions Reduction Rate”) listed in Table 25 below. This reduction rate was calculated by dividing the Net Emission Reductions, above, by the MWh of wind farm generation for each scenario, predicted in Section 3.

Table 25: Net Emissions Reduction Rate – Annually (lbs/MWh)

Pollutant	CO_2	SO_x	NO_x
2013-Actual	932	0.38	0.23
2020-Forecasted	852	0.04	0.15

As expected, the results are somewhat lower on a per-MWh basis in 2020 than in 2013. The resulting rates are lower than the 2012 O&NG and Emitting LMU emission rates, presented in Section 4 , as a result of:

1. Changes to heat rates (efficiency) between 2012, and 2013 and 2020, outlined in Section 4.1.1 above; and

2. The increased emissions due to fossil fuel cycling, discussed in Section 4.3, above.

5.2. Comparison to NEWIS

While this study could have relied directly on the NEWIS as an independently-commissioned study for the independent system operator, and one directly applicable to New England's power system, for reasons discussed earlier, we expected that doing so may overstate the benefits attributable to wind power in Maine. As noted earlier, the NEWIS predates the best direct emission reduction source available – *the 2012 ISO New England Electric Generator Air Emissions Report* ((ISO-NE, 2014)), and does not separately parse out the direct emission reductions from the indirect emission impacts of increased cycling of operating reserves.

However, the NEWIS does provide a useful benchmark against which to compare our results. As a comparison, the NEWIS presents the following approximate emissions reduction rates associated with wind generation (under the several scenarios it models):

Table 26: NEWIS Emissions Reduction Rates - Annually (lbs/MWh)[61]

Case	NO_x	SO_x	CO_2
20% Best Sites by State	0.43	0.51	910
20% Energy Best Sites	0.4	0.42	850
20% Energy Best Sites Maritimes	0.41	0.31	850
20% Energy Best Sites Offshore	0.41	0.44	860
20% Energy Best Sites Onshore	0.42	0.39	900

Table 27: 2020 Net Emission Reduction Rates Projected in this Paper, as a Percentage of NEWIS Net Emission Reduction Rates (lbs/MWh or %)

Case	CO_2	SO_x	NO_x
NEWIS 20% Energy Best Sites Onshore (lbs/MWh)	900	0.39	0.42
2020 – High Production Scenario (% of NEWIS)	94.68%	9.56%	35.01%
2020 - Low Production Scenario (% of NEWIS)	94.68%	9.56%	35.00%

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[61] The percentages shown in this table, and in the first row of the table below, reflect the wind penetration percentage.

As one can see, the emission reduction rates estimated in this paper are reasonably close to those determined by NEWIS for CO_2. However, as expected, the rates are materially different (lower than NEWIS) for NO_x and SO_x. This result is consistent with the improvements in heat rate among fossil fuel emitting generators, as well as the phasing out of coal as a marginal generation unit, assumed in this paper (as detailed in Section 4). Coal fired generators have significantly higher emission rates of SO_x and NO_x than generators which use natural gas.

5.3. Greenhouse Gas Equivalencies

The Net CO_2 Emission Reduction scenarios presented in Section 5.1 are equivalent to the following impacts summarized in Table 28.

Table 28: CO_2 Emission Reduction Equivalence

Metric	2013-Actual	2020-High Production (Transmission Unconstrained) Scenario	2020-Low Production (Transmission Constrained) Scenario
Miles/year driven by an average passenger vehicle	1.1 Billion	4.8 Billion	4.4 Billion
Passenger vehicles taken off the Road	94,000	423,000	393,000
# of Homes' electricity use for one year	61,000	276,000	257,000

5.4. Key Findings

In addition to the quantitative results summarized above, key findings of this paper include:

- Regardless of the level of transmission expansion carried out by 2020, this paper estimates that 1,782 MW of wind generation in Maine will lead to significant greenhouse gas reductions through net emission reductions of greater than 2 million tons of CO_2 in 2020.

- ISO-NE is implementing a range of ongoing planning and operations initiatives designed to alleviate material operating reserve issues and transmission congestion. If ISO successfully implements such initiatives, they would likely further increase emission benefits towards the higher end of the results projected herein (i.e. closer to the High Production Scenario results).

- Maine, and the rest of New England, already has a relatively clean mix of generation compared to the national average. The New England system mix is becoming progressively cleaner over time due to a combination of switching away from dirtier fuels, increases in fossil fuel generator efficiency, and increased renewable energy penetration. Introduction of additional wind power is one contributor to making the region's supply mix cleaner.

- In 2013, wind generation in Maine displaced primarily natural gas, as well as a very small quantity of coal and oil.[62] Following the announced retirement of two large coal plants in 2014 and 2017, respectively, introduction of additional wind generation to the ISO-NE system in Maine in the future is expected to displace primarily natural gas generation, and a small amount of oil[63]. Due to the retirement of these dirtier plants, the avoided emission *rate* of CO_2 is projected to decrease by approximately 8.6% by 2020. Similarly, wind generation is expected to reduce less SO_x in 2020 than in 2013 - even with four times the amount of wind generation - because fossil fuel generators operating in 2020 will produce significantly less SO_x as a result of the retirement of coal plants.

- As increasing levels of wind generation outstrip the natural variability of electrical demand, ramping and cycling by operating reserves will increase as they respond to the variability of wind generation. This increased ramping and cycling (sometimes referred to as 'wind integration impacts') leads to indirect emission increases, although these increases are estimated to represent a minor erosion of the overall CO_2 emissions benefit (approximately 5%) from increasing levels of wind power in 2020. All recent studies of actual U.S. power systems point to this same conclusion: that cycling impacts are a fraction of the direct emission impacts of wind power. The Net Emission Reductions in this report account for these indirect emission increases.

- In 2013, wind power production in Maine was being curtailed to a moderate degree because of local transmission constraints and transmission lines being temporarily taken out of service during the year as part of construction related to the Maine Power Reliability Program (a transmission system upgrade that will ultimately relieve some transmission constraints). In 2013, such curtailment reduced MWh production and Net Emission Reductions by approximately 5.4-8.2%,[64] relative to uncurtailed quantities. Market incentives have been put in place going forward to encourage wind developers to locate future wind facilities in places that are not transmission constrained; therefore, in 2020, depending on the level of transmission expansion between now and 2020, this paper estimates curtailment could reduce MWh production, and corresponding Net Emission Reductions, by as little as 1.15% (High Production-Transmission Unconstrained Scenario) to a high of 8.2% (Low Production-Transmission Constrained Scenario) from uncurtailed quantities.

5.5. Limitations/Areas for Further Study

The following summarize some limitations of the approach used in this study:

- As discussed in Sections 4.3, ISO-NE specific data would be ideal, particularly for modeling integration, or cycling, impacts, as well as accurately reflecting the impacts of any transmission constraints. Data presented in the NEWIS is somewhat outmoded for the reasons discussed in this paper. ISO-NE currently has no plans to update the NEWIS, i.e. developing an ISO-NE focused study comparable to the PRIS or WWSIS-II. As such, absent a costly and time-consuming (and

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[62] As well as a *de-minimis* amount of biomass fueled generation.

[63] We note that the use of oil will continue to ebb and flow depending upon the relative availability and pricing of both natural gas and oil supplies.

[64] This range takes into account an abnormal level of curtailment levels in 2013 due to the construction of the Maine Power Reliability Project, which resulted in some turbines being curtailed in January and February at triple their normal levels. While the actual production was curtailed by 8.18%, if the abnormal outages are normalized, energy production would have been curtailed by about 5.4%. *See* Section 3.4.1.

less transparent) production simulation exercise, current and future modeling of the emissions impacts of wind generation in ISO-NE and Maine will have to extrapolate study results from the best available information including studies from other regions. While this analysis has been crafted using the authors' best efforts to use available information sources to predict the range of emission impacts from the addition of wind power in Maine which such an updated ISO-NE study would conclude, as well as to err on the side of conservatism, the approaches used here will be less precise than such an updated ISO-NE study would utilize.

- Similarly to the above, due to the complexity of the electricity grid, emissions reductions from wind generation would ideally be estimated by a simulation which models the entire ISO-NE system, and is capable of parsing the impact of wind in Maine to the extent that they would differ from wind in New England more generally[65], rather than by application of results from various studies to the ISO-NE system. Such a simulation would take into account the numerous nuances and intricacies of the production mix and the transmission system, the interplay between the various local load zones, as well as time specific production from generators on the grid. This type of simulation, however, is extremely resource intensive, and is outside the scope of this paper. Furthermore, while commercial models of the New England system exist, only ISO-NE has a complete depiction of actual production and transmission performance parameters and constraints, the majority of which is treated as confidential under ISO New England information policy.[66]

- At present, one of the commercial wind farms in Maine operating as of 2013 is located in the electrically separate portion of New England managed by the Northern Maine Independent System Administrator (NMISA). A non-trivial proportion of planned wind generation is also located in this Aroostook County region of Maine. Due to a lack of available data, this analysis has simplified the treatment of New England as if it were a single system. Because the owners of such resources are expected to transmit their project's energy through New Brunswick and back into Maine in order to participate in the New England Renewable Energy Credit market – as is done for the currently operating plant in this region - the displacement impacts (reductions to fossil fuel use and emissions) are nearly identical to if that project where located in ISO-NE, so this simplification has little effect.[67] In any event, most of the planned projects in the NMISA region of Maine plan to connect directly to ISO-NE facilities, and further, depending on the outcome of an ongoing Reliability docket before the Maine PUC, the NMISA region may not be electrically disconnected from ISO-NE in the long run.[68]

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[65] Because the majority of wind in New England has been and is being developed in Maine, the application of New England-wide data to wind in Maine should not be a material shortcoming.

[66] See ISO-NE Information Policy available at http://www.iso-ne.com/static-assets/documents/regulatory/tariff/attach_d/attachment_d.pdf

[67] For a discussion of the emission impact of moving renewable electricity across market borders, see: Grace, Robert, and Ryan H. Wiser, *Transacting Generation Attributes Across Market Boundaries: Compatible Information Systems and the Treatment of Imports and Exports*, Lawrence Berkeley National Laboratory (Grace, 2002)

[68] See Appendix D for related information on plans for transmission upgrades in Maine.

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Glossary

The following acronyms and abbreviations are used in this paper.

Acronym or Term	Reference or Definition
Capacity Factor	A measure of the ratio of how much energy a power plant actually produces for a specific period of time, compared to the maximum it could produce at continuous full power operation during the same period. It is expressed as a percentage or decimal, with the maximum feasible capacity factor being 100%. Wind generation capacity factor is primarily driven by the availability of wind (and secondarily, by downtime for maintenance required by any power plants), and is typically between 20% and 50% (nationally, depending on location and equipment), and between 28% and 40% for operating and planned modern wind farms in New England.
CELT	ISO New England 2014 Capacity, Energy, Load and Transmission Report (2014)
Curtailment	Decreases in wind turbine operations due to transmission congestion, excess electricity supply relative to demand and must-run generation ("minimum generation" limits), limitations in ramping capability, or availability of adequate operating reserves
Cycling	When a generator shuts down and restarts, ramps up and down, and operates at part-load.
Direct Avoided Emissions	Emissions reductions as the result of wind generation, which has zero-net emissions, displacing a fossil fuel generator, which releases emissions as a byproduct of electricity production.
Emissions Rate	The pounds of a pollutant a generator releases for each MWh of electricity it generates during an identified time period (annually, monthly, and seasonally).
EWITS	Eastern Wind Integration and Transmission Study (2011)
FTA	Fuel Type Assumed. An earlier method used by ISO-NE to estimate marginal emission rates that assumes certain generators which are powered by certain fuels are the marginal unit. This method has been outmoded by the LMU method.
Heat Rate	A measure of efficiency among fossil fuel generators (Btu/kWh). Heat rate and efficiency are inverses of each other; as heat rate decreases, a generator's efficiency increases..
High Production (Transmission Unconstrained) Scenario	A scenario used in this paper in forecasting Net Emission Reductions in 2020, which assumes that there will be a material expansion of transmission infrastructure between 2013 and 2020. As such the effects of curtailment, and Indirect Emissions increases from cycling, are less than under the Low Production Scenario, leading to comparatively higher Net Emission Reductions.
Indirect Emissions Increases	Increased emissions that are the indirect result of wind generation, namely emissions from increased cycling of fossil fuel generators.
ISO-NE	Independent System Operator New England. The independent, non-profit Regional Transmission Organization (RTO), serving Maine. Connecticut, , Massachusetts, New Hampshire, Rhode Island and Vermont.

Acronym or Term	Reference or Definition
Low Production (Transmission Constrained) Scenario:	A scenario used in this paper in forecasting Net Emission Reductions in 2020, which assumes that there will be limited expansion of transmission infrastructure between 2013 and 2020. As such the effects of curtailment, and Indirect Emissions Increases from cycling, are greater than under the High Production Scenario, leading to comparatively lower Net Emission Reductions.
LODO	Low-Offshore, Distributed On-Shore. A modeling scenario used in the PRIS that assumes that limited offshore wind generation will be installed, and that future onshore renewable generation will not always be installed in the best resource locations. In this paper, results under this scenario were used a baseline for estimating Indirect Emission Increases.
LMU	Locational Marginal Unit - The ISO-NE identified marginal unit(s) that set the Energy Market hourly Locational Marginal Price
Marginal Unit (Generator)	The next generator that would be dispatched to provide additional electricity production in the event that the electrical system requires such production.
Marginal Emission Rate	The emission rate for marginal generators.
MPRP	The Maine Power Reliability Project. A $1.4 billion investment in Maine's bulk power transmission system started in 2009 and near completion. “When completed, [the MPRP] will provide basic infrastructure needed to increase the ability to move power from New Hampshire into Maine and will improve the ability of the transmission system within Maine to move power into the local load pockets as necessary.”
Net Emission Reductions	The total decrease to emissions (lbs. or tons) as a result of wind generation, taking into account both Direct Avoided Emission, and Indirect Emission Increases.
NEWIS	New England Wind Integration Study (2010)
O&NG	Oil and Natural Gas. In this paper, this acronym is used to refer to LMU emission rate for oil and natural gas fueled generators.
Penetration (Levels)	MWh of electricity produced by wind energy (or renewable energy) resources, as a percentage of the total MWh within the system.
PRIS	PJM Renewable Integration Study (2014)
WWSIS-II	The Western Wind and Solar Integration Study Phase 2 (2013)

Appendix A: Annotated Table of Sources

Document	Abbreviation Used	Study Funder (Author)	Purpose	Comment
New England Wind Integration Study (2010)	NEWIS	Independent System Operator-New England (Enernex Corporation)	Provides basis for estimating additional marginal non-wind generation for grid operation Also provides Net Emission Reductions estimates for certain wind penetrations of 20%; however these estimates are based on outmoded assumptions regarding marginal generator emission rates.	NEWIS is the most spot-on analysis for estimating unadjusted and adjusted emissions from New England wind power development in Maine, but methodology has been honed in more recent studies from other regions.
Eastern Wind Integration and Transmission Study (2011)	EWITS	National Renewable Energy Laboratory (General Electric)	Provides basis for estimating adjusted non-wind generation costs for grid operation. Gross emissions estimates are provided as well	A more up-to-date Eastern Renewable Generation Integration Study is in progress.
The Western Wind and Solar Integration Study Phase 2 (2013)	WWSIS-II	National Renewable Energy Laboratory (NREL)	An in-depth study providing estimation of renewable energy system impacts on grid operation and the marginal increases of emissions from fossil fuel generation sector as a by-product of increased cycling caused by intermittent wind and solar generation	Conceptual and specific power plant type results applicable. Overall results less applicable because of differences in generation mix and operation of Western Region from New England grid operation
PJM – Renewable Integration Study (2014)	PRIS	PJM Interconnection, LLC. (General Electric International, LLC.)	Provides basis for estimating changes in emissions due to wind induced cycling.	Although much of the data contained in the PJM study is specific to that electrical grid, the study does provide bounds for the potential effects of cycling on emissions.

Document	Abbreviation Used	Study Funder (Author)	Purpose	Comment
2012 ISO New England Electric Generator Air Emissions Report (2014)		ISO New England Inc. (ISO New England Inc.)	Used as the foundation of analysis for gross marginal air emission avoidance; Provides the most recent emissions data	Most up-to-date source. Includes marginal emission rates by State
Maine Wind Assessment 2012, A Report (2012)		Coastal Enterprises, Inc. (Governor's Office of Energy Independence and Security)	Provides a good compiled summary of Maine specific wind issues	State of Maine specific
U.S. Renewable Electricity: How Does Wind Generation Impact Competitive Power Markets? (2012)		Federal Congressional Research Service	General overview of impacts of wind energy on electric markets.	
Avoided Energy Supply Costs in New England; 2013 Report		National Grid - Avoided Energy Supply Component (Synapse, Inc.)	Provides estimates of avoided costs and emissions	
New Wind Power Forecast Integrated into ISO-NE Processes and Control Room Operations (April, 2014)		ISO New England Inc. (ISO Newswire)	Provides description of new wind power forecast process	Implementation of recommendation from NEWIS

Document	Abbreviation Used	Study Funder (Author)	Purpose	Comment
Strategic Transmission Analysis: Wind integration Study – Stage 1 – Maine Regional Constraints (May 2014)		ISO New England Inc.	Discusses limits to additional wind projects in Maine without significant transmission upgrades	The Critical Energy Infrastructure Information (CEII) document not available without ISO-NE permission
Public Meeting Draft 2014 Regional System Plan (August 2014)		ISO New England Inc. (ISO New England Inc.)	ISO-NE planning document	Included in the report is a summary of wind integration efforts and planning
Selected Maine Wind Turbine Operational Data (2013)		Proprietary	Used to calculate Capacity Factors and Curtailment for Wind Generation Facilities	Proprietary Data, not publically available. Results of this data, in aggregate, are included with permission.
How Less Became More...Wind Power and Unintended Consequences in the Colorado Energy Market (2010)		Independent Petroleum Association of Mountain States (Bentek Energy LLC)	Earlier Background Study, Detailing the Effects of Wind and Solar Integration on Emissions	Study serves as a contrast to later PRIS and WWIS-II Studies.
Air Emissions Due to Wind and Solar Power (2009)		Article in Environmental Science and Technology Journal (Warren Katzenstein and Jay Apt)	Earlier Background Study, Detailing the Effects of Wind and Solar Integration on Emissions	Study serves as a contrast to later PRIS and WWIS-II Studies.
ISO New England 2014 Capacity, Energy, Load and Transmission Report	CELT	ISO New England Inc. (ISO New England Inc.)	Provides projections of energy demand and generation levels, as well as transmission expansion levels, in ISO-NE.	

Document	Abbreviation Used	Study Funder (Author)	Purpose	Comment
Wind Power's Impact on Reliability, Backup Supply, and Fossil Fuel Use in New England: A NEWEEP Webinar (2011)		U.S. Department of Energy (Various Authors)	Webinars provide a substantive primer to the issues which are the focus of this white paper	Available online via DOE's WINDExchange Database.
Interviews with ISO-New England staff (ISO-NE)		Several Interviews with ISO-NE System Planning Engineers, conducted by SEA	ISO-NE engineers provided useful guidance and input on the key issues considered in this paper.	
IEA Task 26: The Past and Future Cost of Wind Energy (2012)		International Energy Agency	Study, while focusing on levelized cost of energy, provides robust projections relating to future changes to turbine equipment and capacity factors	
U.S. DOE 2013 Wind Technologies Market Report (2014)		U.S. Department of Energy (Lawrence Berkley National Lab)	Similar to the IEA Task 26 Report, The Market Report provides a good summation of technology and performance trends,	
Avoided Emissions from the Antrim Wind Project		Antrim Wind Energy, LLc. (Resource Systems Group, Inc.)	This study, which also forecasts emissions benefits from wind energy, was reviewed, comparatively to this paper, as a type of benchmark for both methodology and results.	The Antrim study does not model 1.) the effects of integration inefficiencies, and 2.) the effects of future transmission constraints on wind production.

Document	Abbreviation Used	Study Funder (Author)	Purpose	Comment
Wind Energy for a Cleaner America II: Wind Energy's Growing Benefits for our Environment and Health		Environment America (Frontier Group)	The results of the Wind Energy for a Cleaner America II Study, which provides emission reductions given a projected generation amount specific, were compared with this paper's results, as a type of benchmark.	The Wind Energy for a Cleaner America II study does not model 1.) the effects of integration inefficiencies, and 2.) the effects of future transmission constraints on wind. The study also does not use ISO -New England specific emission rates, instead using national rates.

Appendix B: Summary of Curtailment Study Details

Study Name	Definition of Curtailment*	Region Covered	Findings/Key Assumptions
Eastern Wind Integration and Transmission Study (2011)	Operator caused decreases (shutting down) of wind turbine operations due to transmission congestion, excess electricity supply relative to demand and must-run generation ("minimum generation" limits), limitations in ramping capability, or availability of adequate operating reserves	ISO-NE, MISO, NYISO, PJM, SERC, SPP, and TVA Regional Transmission Organizations	• Wind Power is assumed at 20% penetration throughout the study regions. • Curtailment of Operations, where no new transmission infrastructure is built: Curtailment across the entire Eastern Region of between 18-47% (Enernex Corporation, 2011, p. 120). • Curtailment percent, where significant transmission expansion is modeled and where significant offshore wind energy capacity is not assumed, is below 1.0% for ISO-NE. (Enernex Corporation, 2011, pp. 120-125)
New England Wind Integration Study (2010)	Not Explicitly defined, however implicitly defined to be operator induced changes to operation as a result of: 1.) Transmission congestion, 2.) Minimum generation events, where nuclear is on the margin, 3.) Minimum generation events due to the under forecasting of wind, 4.) limitations in ramping capability.	ISO-NE	• Wind Power is at 20% penetration in New England. • Curtailment of operations is 1.15%. • Assumes that material transmission expansions will occur. Specifically, the build-out of the "Governors' 4 GW Overlay", (General Electric, 2010, p. 110). This overlay was specifically modeled in the NEWIS to be able "to robustly deliver a total additional generation nameplate capacity (of Wind Energy) of 4 GW" (General Electric, 2010, p. 119).
Western Wind and Solar Integration Study (2013)	Not Explicitly defined, however implicitly defined to be operator induced changes to operation as a result of: 1.) Transmission congestion, 2.) Minimum generation events.	States and Regional Transmission Organizations that comprise the Western Electricity Coordinating Council	• Wind Power is at >25% penetration in the entire Western Interconnection; Total Renewable Penetration is at 33%. • Curtailment is 3% of operations. • Assumes that sufficient intra-zonal transmission capacity was built for each additional (modeled) plant, largely eliminating curtailment from local congestion (NREL, 2013, p. xiii).

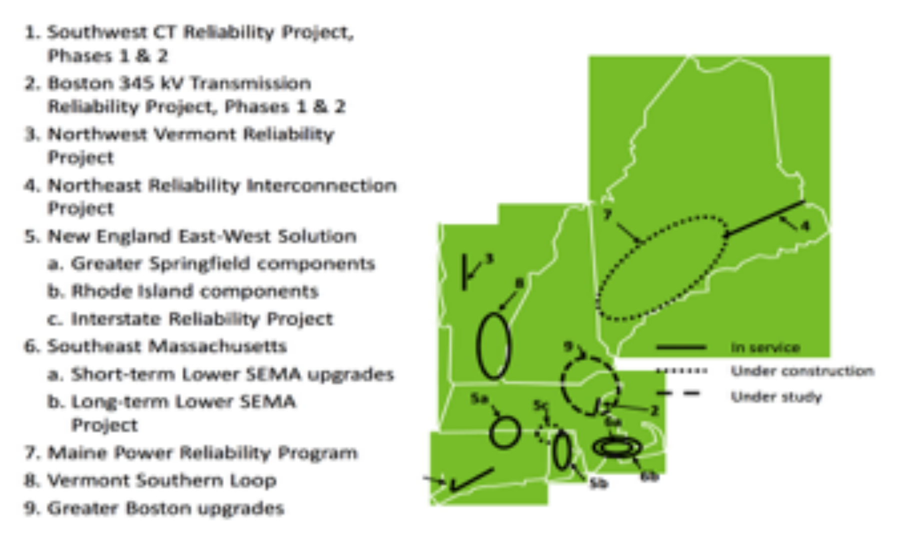
*These definitions are based on descriptions in text of studies.

Appendix C: Current ISO-NE Initiatives to Reduce Curtailment

Initiative	Short Description and Source
Energy Market Offer Flexibility	Adopted in December 2013, ISO now allows a floor to energy price bids of -$150 per MWh. This address artificial creation of Minimum Generation Emergencies that have historically caused curtailment of wind energy in New England. *See* (Order Conditionally Accepting Tariff Revisions, 2013), (ISO-NE, 2013)
Improving Wind Forecasting/Dispatch	Improving Wind Forecasting and Dispatch (Phase 1) by commencing "*incorporating wind forecasting into ISO processes, scheduling, and dispatch services.*" (ISO-NE, RE0, 2014, p. 21)
Improving Planning Improvements	Planning Improvements to the elective transmission expansion process , which may help reduce curtailments by allowing more efficient identification of marginal interconnections and transmission constraints. (Wilkinson, 2013, p. 4)
Improving Integration of Intermittent Resources	Improving Integration of Intermittent Resources. "*The ISO is working to put in place by 2015 dispatch enhancements and associated market rule changes to more effectively use wind resources.*" (ISO-NE, RE0, 2014, p. 21)

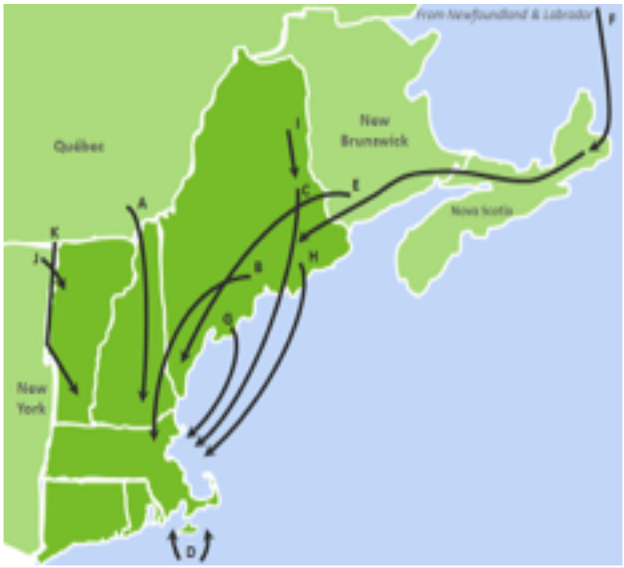
Appendix D: Under-Construction, Planned and Proposed Transmission Upgrades

Figure 10: Major Transmission Projects in New as of June 1, 2014.



Source: (ISO-NE, RSP, 2014)

Figure 11: Potential Large-scale Transmission Projects in New England, including some proposed direct-current transmission.



Representative Projects and Concept Proposals

- **A Northern Pass**—Hydro Québec/Northeast Utilities
- **B Northeast Energy Link**—Emera Maine/National Grid
- **C Green Line**—New England ITC
- **D Bay State Offshore Wind Transmission System**—Anbaric Transmission
- **E Northeast Energy Corridor**—Maine/New Brunswick/Irving
- **F Muskrat Falls/Lower Churchill**—Nalcor Energy
- **G Maine Yankee**—Greater Boston
- **H Maine**—Greater Boston
- **I Northern Maine—New England**
- **J Plattsburgh, NY—New Haven, VT**
- **K New England Clean Power Link**—TDI New

Source: (ISO-NE, RSP, 2014, p. 182)