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SPI 581C
Energy Economics

Modeling Wind Integration in New England

The Impact of King Pine Wind Farm on Marginal CO2 Emissions Rates

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1 Background

In June 2019, Maine Governor Janet Mills signed into law LD 1494, which increased the state's renewable portfolio standard (RPS) to 80% by 2030 and 100% by 2050.[1] Maine is well positioned to achieve its 2030 target on time, with more than 72% of the state's electricity already coming from renewable sources in 2021. The remainder of the portfolio is almost entirely natural gas, as petroleum has been phased out gradually over the past twenty years. Maine has abundant hydro and wind resources, each of which account for roughly a quarter of its generation. With over 1,000 MW of capacity currently in operation, Maine produces more electricity from wind than any other state in New England. However, due to the 1997 closure of the state's largest power plant, an 860 MW nuclear reactor in Wiscasset, in-state generation is roughly half of what it was in the 1990s. Imports now make up about three tenths of the state's total demand, much of which comes from Hydro-Québec in Canada.[2]

1.1 The NECEC Controversy

Recently, the state's relationship with Hydro-Québec has been the subject of some controversy. In 2017, one of Maine's two investor-owned utilities, Central Maine Power (CMP), submitted a bid in response to a Massachusetts request for proposal (RFP) for renewable energy that would bring excess hydropower from Hydro-Québec through the largely uninhabited and heavily forested northwestern portion of Maine to an interconnection point

[1] "An Act to Reform Maine's Renewable Portfolio Standard," Maine State Legislature, accessed December 16, 2022, https://legislature.maine.gov/bills/display_ps.asp?PID=1456&snum=129&paper=SP0457.
[2] "Maine: Profile Analysis," U.S. Energy Information Administration, accessed December 16, 2022, https://www.eia.gov/state/analysis.php?sid=ME.

with the region's grid. [**Figure 1**] Controversially, CMP began construction on the $1B transmission line, known formally as New England Clean Energy Connect (NECEC), without explicitly seeking the consent of the Maine Legislature, although the company had applied for and received the required state and federal permits ahead of time. What ensued was a divisive battle over the transmission line's environmental impact and the Maine Legislature's role in approving similar projects moving forward, which culminated in the state's most expensive referendum ever. In November 2021, voters decided to block the completion of NECEC, despite CMP already having spent four years and $350M clearing much of the forest through which the corridor passed.[3]

In the lead up to the referendum, there was a heated debate over the transmission line's potential impact on New England's greenhouse gas (GHG) emissions and wholesale electricity market, which is managed by New England's Independent System Operator (ISO-NE). CMP tried to market the project to Maine residents by claiming it would lower carbon emissions and make electricity cheaper, but opponents of NECEC argued that Hydro-Québec would not be required to meet its contractual obligations with hydropower and could instead resell electricity that had been generated using fossil fuels in neighboring provinces.[4] This and other unverified claims were circulating on the eve of the referendum, making it difficult for voters to know for certain how the project would affect the region's environmental ambitions.

[3] Tux Turkel, "Here's what you need to know about Question 1," The Portland Press Herald, October 17, 2021, https://www.pressherald.com/2021/10/17/qa-on-question-1-will-transmission-line-be-clean-energy-link-or-scar-on-maines-landscape/.
[4] "Greenwashing and Carbon Emissions: Understanding the True Impacts of New England Clean Energy Connect," Energyzt Advisors, LLC, October 2018, https://www.nrcm.org/wp-content/uploads/2018/10/ENERGYZTreportNECECImpacts.pdf.

1.2 The Northern Maine Renewable Energy Development Program

In June 2021, two years after revamping the state's RPS, the Legislature established the Northern Maine Renewable Energy Development Program, which required the Maine Public Utilities Commission (PUC) to procure significant new renewable generation and transmission capacity in Aroostook County by November 2022.[5] With such an ambitious timeline for developing the state's renewable resources, the ability to reliably estimate the impact of projects on the region's GHG emissions is more important than ever.

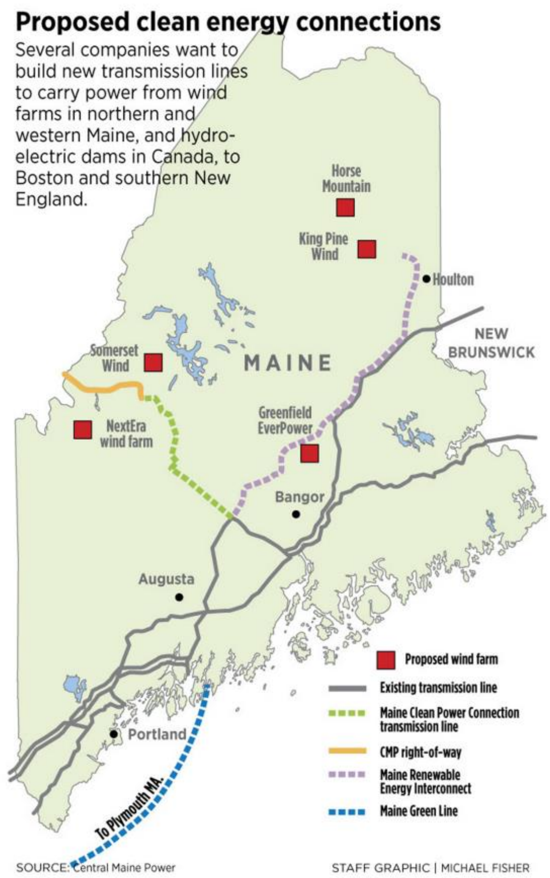

Figure 1: planned transmission lines in Maine.

The PUC approved its first contracts under the program in October 2022, including a $2B contract with Longroad Energy for a 1,000 MW wind farm in the northeastern corner of Maine known as King Pine.[6] Because that area is currently export constrained, the PUC also approved a $2.9B contract with LS Power for a transmission line that would connect King Pine to the ISO-NE system so as to reduce instances of curtailment. According to the developers, the project

[5] "An Act To Require Prompt and Effective Use of the Renewable Energy Resources of Northern Maine," Maine State Legislature, accessed December 16, 2022, https://www.maine.gov/mpuc/sites/maine.gov.mpuc/files/inline-files/LD%201710%20Maine%20130%20-%20SP%20563.pdf.
[6] Ethan Howland, "LS Power, Longroad Energy win contracts for Maine transmission line, 1,000-MW King Pine wind farm," UtilityDive, October 27, 2022, https://www.utilitydive.com/news/ls-power-longroad-maine-puc-transmission-line-wind-farm/635096/.

would reduce electricity costs in Maine by $100M over 20 years and mitigate New England's exposure to volatile LNG prices, since consumption by natural gas fired power plants currently exceeds the region's pipeline capacity.[7] Although the PUC must determine by December 31 whether the project aligns with Maine's energy and environmental priorities, there has been no publicly available study that quantitatively estimates the project's impact on the MER.

The goal of this paper is to look at the King Pine wind farm's unique specifications and calculate a reasonable estimate of its impact on the marginal CO2 emissions rate (MER) of ISO-NE's system using publicly available data. These findings should serve as a shared baseline that allows voters and policymakers to weigh policy options and make informed decisions about the future of New England's energy system.

[7] "King Pine Wind: Aroostook County," Longroad Energy, accessed December 16, 2022, https://www.aroostook.me.us/images/pdf/information/agendas/2022_09_13_HOULTON_PACKET.pdf.

2 Literature Review

This paper is a simplified version of a resource integration study, which typically seek to characterize how capacity additions will impact grid operations by looking at the project's location with respect to the transmission and distribution (T&D) system and its expected generation profile, which may vary based on factors like the weather. Whereas studies conducted by grid operators like ISO-NE employ production cost models to simulate how generators are dispatched in real-time and capacity expansion models to account for the evolution of the T&D system moving forward, this paper only looks at the short-term impact of a new wind capacity based on historical grid performance and the project's forecasted output. In other words, the goal is not to understand how the ISO-NE system as a whole will change in response to the King Pine wind farm, but rather how the addition of new capacity will affect which unit type is on the margin and its associated CO2 emissions rate.

ISO-NE routinely conducts resource integration and grid planning studies to inform the procurement of new assets in its service area, but their primary goal is identifying transmission upgrades and optimizing the interconnection of new resources, not predicting emissions impacts. ISO-NE also periodically studies the future of renewable resources in their service area, but the most recent analysis of onshore wind in Maine is from 2011 when developers were interested in building 650 MW of capacity in the western part of the state. The study includes no discussion of the project's impact on emissions.[8] More recently, ISO-NE performed an

[8] "2011 Economic Study," ISO-NE (March 31, 2014): 9, https://www.iso-ne.com/static-assets/documents/committees/comm_wkgrps/prtcpnts_comm/pac/reports/2014/2011_eco_study_final.pdf.

economic analysis of offshore wind in southern New England. Although "not part of the original scope of work," the study briefly discusses the emissions impact of varying levels of added capacity. Specifically, they found that the MER stood to decrease anywhere from around 1% compared to baseline with 1,000 MW of installed capacity to 50% at 8,000 MW of installed capacity.[9] While these types of analyses are inherently context-specific, the offshore wind results could help determine whether the MER calculated in this paper is the right order of magnitude for a similarly sized project.

Although unrelated to estimating the impact of specific projects, ISO-NE also publishes an annual Electric Generation Air Emissions Report that informs this paper's method for calculating the MER using a load-weighted, as opposed to time-weighted, approach.[10] However, ISO-NE performs their calculations at the unit level whereas this paper only looks at unit types due to the lack of more granular data.

[9] "2019 Economic Study: Offshore Wind Integration," ISO-NE (June 30, 2020): 26, https://www.iso-ne.com/system-planning/system-plans-studies/economic-studies.
[10] "2020 ISO New England Electric Generator Air Emissions Report," ISO-NE (April 2022): 8, https://www.iso-ne.com/static-assets/documents/2022/05/2020_air_emissions_report.pdf.

3 Methodology

The basic methodology of this paper is to: 1) simulate the hourly generation of the King Pine wind farm, 2) identify the marginal unit type and associated CO2 emissions rate based on historical dispatch data from ISO-NE, 3) calculate how much wind generation is dispatched based on the locational marginal price (LMP) at the closest pricing node, 4) compare the marginal CO2 emissions rate (MER) of the ISO-NE system before and after the addition of new wind generation. Each step is explained in detail below. Note that without access to a unit-level dispatch stack at each pricing node, several simplifying assumptions must be made about the ISO-NE dispatch stack, some of which likely have a substantial effect on the results. These considerations and more are discussed in greater detail in **Section 4**.

3.1 Simulating Wind Generation

The National Renewable Energy Laboratory (NREL) offers a piece of free techno-economic software known as the System Advisor Model (SAM) that can modeling the hourly performance of wind farms based on a set of user-defined inputs, such as the project's location, turbine layout pattern, and turbine design characteristics.[11] SAM takes as input a weather resource file from NREL's Wind Integration National Dataset (WIND) Toolkit, which contains representative windspeeds for multiple turbine hub heights at a 5-minute and 2-km x 2-km resolution across the continental United States.[12] The weather resource file used for this analysis is specific to the

[11] Janine Freeman et al., "Reference Manual for the System Advisor Model's Wind Power Performance Model," National Renewable Energy Laboratory, August 2014, https://www.nrel.gov/docs/fy14osti/60570.pdf.
[12] "Wind Integration National Dataset Toolkit," National Renewable Energy Laboratory, accessed December 16, 2022, https://www.nrel.gov/grid/wind-toolkit.html.

coordinates of King Pine's proposed location (46.918, -68.169) and the applicable turbine hub height (120 m). The turbine layout pattern was left to the default setting, but the spacing was adjusted to match the proposed site area (175,000 acres). According to the term sheet submitted to the PUC by Longroad Energy, King Pine will consist of 179 5.6-MW turbines, which are assumed to be Vestas V150s.[13] Since the V150 is a new model, SAM does not yet have a matching configuration file in its library, so this paper uses the NREL's 5.5 MW reference turbine instead, the power curve for which can be seen in **Figure 2**.

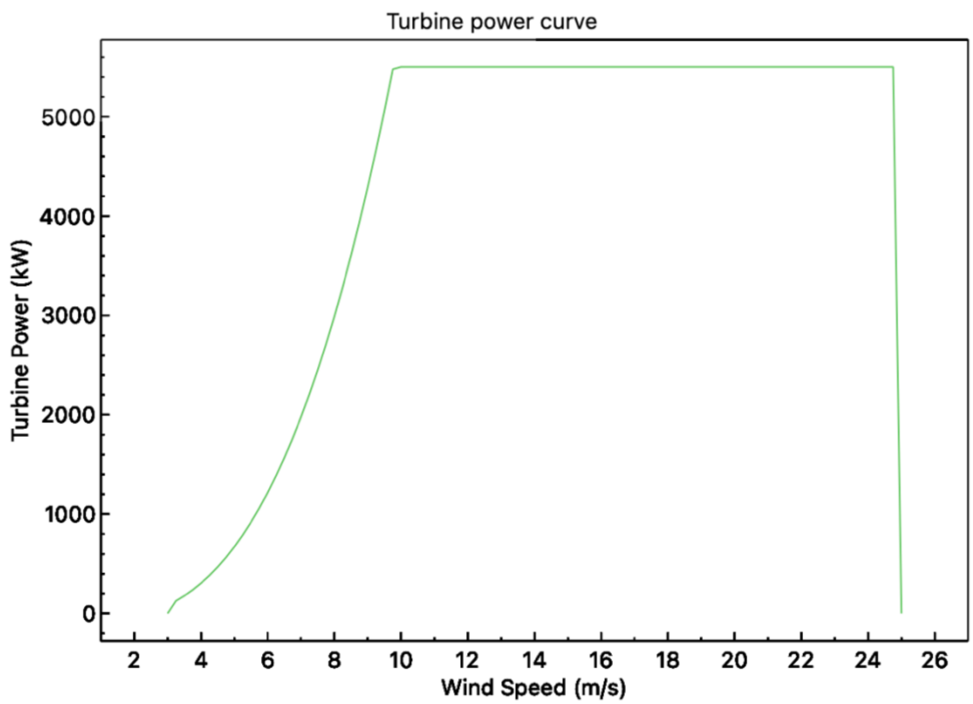

Figure 2: NREL's 5.5 MW reference turbine power curve.

[13] "Cover Letter for Generation Bidder Term Sheet: Northern Maine Procurement," Longroad Energy, accessed December 16, 2022, https://drive.google.com/file/d/13T8MuiGM2SGzF0wRa7ImoSFIBGVolzXH/view.

3.2 Identifying the Marginal Unit Type and CO2 Emissions Rate

ISO-NE publishes the system's dispatch fuel mix up to 12 times per hour with an indicator of which "unit types" – meaning a fossil fuel resource (e.g., natural gas, oil, coal) or a renewable resource (e.g., solar, wind, etc.) – are marginal. Unfortunately, ISO-NE does not publish a unit-level dispatch stack, which would be necessary to identify the precise impact of wind generation on the MER. Instead, each data point includes the amount of generation by unit type during that interval and an indicator of which are marginal. Note that multiple unit types can be on the margin at the same time if there is a binding transmission constraint on the grid, although ISO-NE does not indicate which unit type is marginal at which node.[14] To ensure the dispatch fuel mix data is compatible with the wind generation data, each sub-hourly interval is aggregated by unit type. The hourly generation for each unit type is estimated by averaging the power output (MW) for each interval and multiplying it by an hour of production (MWh).[15] If a unit type is marginal at the beginning of an hour, it is assumed to be marginal for the remainder of that hour.

The MER before the addition of wind generation is calculated by taking the load-weighted average of the CO2 emissions rates (lbs CO2/MWh) for each unit type on the margin. The values themselves are pulled from the U.S. Environmental Protection Agency's (EPA) Emissions & Generation Resource Integrated Database (eGRID) for the Northeast Power Coordinating Council (NPCC) grid subregion corresponding to ISO-NE's service area. [**Appendix**] eGRID

[14] When no marginal unit type is indicated, which happens a handful of hours per year, the default is natural gas.
[15] While this likely masks some variation in the performance of units, it is a necessary modification to match the resolution of available wind generation data.

calculates average CO2 emissions rates for each unit type based on Continuous Emissions Monitoring Systems (CEMS) data reported as part of the Clean Air Markets Program Data (CAMPD).[16] Note that fuels derived from biomass (e.g., wood and refuse) are considered part of the carbon cycle, so their CO2 emissions rates are zero. The assumption for landfill gas is that it would be flared if not used for electricity generation, so no additional CO2 emissions rates are incurred.[17] The "Other" category represents energy storage and demand response, so the CO2 emissions rate is also assumed to be zero.

3.3 Dispatching Wind Generation

ISO-NE publishes detailed market and operational data on their website, including real-time LMPs for each of the 1,000+ pricing nodes in their service territory on an hourly basis. Since it is unclear which pricing node would determine the LMP for electricity supplied by King Pine to a new substation, the load-weighted average of the LMPs at all pricing nodes within the Maine load zone is used as a proxy. The LMP has three components: energy, congestion, and loss. Together, these reflect the current balance of supply and demand on the system as a whole, transmission constraints affecting the node, and physical losses related to transmission.[18]

[16] "Clean Air Markets Program Data," U.S. Environmental Protection Agency, accessed December 16, 2022, https://campd.epa.gov.
[17] Susy S. Rothschild and Art Diem, "Total, Non-baseload, eGRID Subregion, State? Guidance on the Use of eGRID Output Emission Rates," accessed December 16, 2022, https://www3.epa.gov/ttnchie1/conference/ei18/session5/rothschild.pdf.
[18] "FAQs: Locational Marginal Pricing," ISO-NE, accessed December 16, 2022, https://www.iso-ne.com/participate/support/faq/lmp.

To identify when wind generation is curtailed, this paper uses a threshold price of \$4/MWh for onshore wind generation. ISO-NE assigns these values to renewable resources to "facilitate the analysis of load levels where the amount of \$0/MWh resources exceeded the system load, which leads to oversupply."[19] In other words, the threshold price is not a reflection of variable cost but rather a mean of differentiating which renewable resources should be curtailed first based on factors like intermittency and dispatchability. When the LMP is lower than the threshold price, wind generation is curtailed, meaning it does not affect dispatch stack or, consequently, the MER.

3.4 Calculating the Change in the Marginal CO2 Emissions Rate

As discussed above, the MER before the addition of wind generation is calculated by taking the load-weighted average of the CO2 emissions rates for each unit type on the margin. The crux of the methodology for this paper is calculating the corresponding MER after the addition of wind generation. If a renewable resource is on the margin, it is assumed that wind generation has no impact on the MER. If a fossil fuel resource is on the margin, there are two possible scenarios. Because ISO-NE does not make a unit-level dispatch stack available to the public, it is assumed all units of the same type are next to each other in the dispatch stack.[20] This means the MER only changes when wind generation exceeds total generation by the marginal unit type. Example 1 demonstrates a situation where no change in the MER occurred because wind generation (830.69 MWh) did not exceed natural gas generation (6905.16 MWh)

[19] "2019 Economic Study," ISO-NE, 12.
[20] See Section 4 for a detailed discussion of this assumption.

during the hour. Example 2, however, illustrates how the MER changes when wind generation (616.93 MWh) exceeds coal generation (288.20 MWh).

Table 1: Impact of Wind Generation on MER

Example 1: No Change in MER	**Example 2: Change in MER**
Date: 01-20 07:00 *Marginal unit type*: Natural gas *Natural gas generation (MWh)*: 6905.16 *Wind generation (MWh)*: 830.69 *MER - Before (lbs CO2/MWh)*: 850.53 *MER - After (lbs CO2/MWh)*: 850.53	*Date*: 01-12 20:00 *Marginal unit type*: Coal *Coal generation (MWh)*: 288.20 *Wind generation (MWh)*: 616.93 *MER - Before (lbs CO2/MWh)*: 2277.02 *MER - After (lbs CO2/MWh)*: 0.00

When the MER does change as a result of adding wind generation, the new value is calculated by taking the load-weighted average of the CO2 emissions rate for all units not on the margin. Although this is not an accurate representation of the dispatch stack, it is the best possible approximation given the available data. The percentage change in MER is calculated using a simple (time-weighted) average of the MER before and after wind generation is added.

4 Assumptions and Limitations

This paper makes several assumptions about the ISO-NE system based on the limited availability of modeling tools and data.

Curtailment is driven solely by locational marginal prices. Because the new transmission capacity being developed alongside King Pine is expected to relax export constraints between northern Maine and the rest of the ISO-NE grid, the model relies solely on LMPs to indicate whether wind generation is curtailed. LMPs contain a congestion component which, if sufficiently negative, should drive the overall LMP below the threshold price of $4/MWh. Note that the model also does not account for imports from and exports to Canada because the dispatch fuel mix data does not include these flows, although their impact is discussed qualitatively in **Section 6**.

Locational marginal prices are based on the existing grid configuration. Without access to a production cost model, it is necessary to use LMPs generated for the existing grid configuration under the new paradigm. While new transmission capacity would likely lower congestion charges for the Maine load zone, this is not likely to have a significant impact on the results given how infrequently wind generation is curtailed under the current model, which already assumes no binding transmission constraints.

Units of the same type are next to each other on the dispatch stack. ISO-NE provides access to hourly generation by unit type and indicates which unit type is on the margin, but it is impossible to know what the remainder of the dispatch stack looks like. Therefore, this paper assumes all units of the same type are next to each other on the dispatch stack. In other words, if a natural gas unit is on the margin before the addition of wind generation, then it is assumed all other natural gas units will be on the margin before any coal units are on the margin. In reality, the merit order is determined by many other factors, such as variations in operating costs between facilities and transmission constraints. What this assumption means for the results of this paper, however, is that the MER only changes when wind generation exceed the sum of generation across all units of the same type as the marginal unit. This is not likely realistic, but it is necessary given the availability of data and modeling tools.

Marginal units serve all parts of the grid equally. ISO-NE publishes the dispatch fuel mix for the region as a whole, not each pricing node. In other words, although the model incorporates the LMP into its decision of whether to dispatch wind generation, it does not incorporate the location of the marginal unit into its MER calculation. Instead, it assumes that the marginal units indicated in the aggregate dispatch fuel mix serve all pricing nodes in proportion to their share of load. Note that the MER calculation is still load-weighted, but weights are based on the proportion of load serving the region as a whole rather than the proportion of load serving the pricing node closest to King Pine.

5 Results

Based on the specifications outlined in Longroad Energy's term sheet, the annual energy generation of King Pine wind farm is modeled at 3,984,822 MWh, or approximately 25% more than the 3,182,611 MWh Longroad Energy estimated as part of its bid. However, applying the industry-standard 90% probability of exceedance in SAM yields an annual total of 3,341,590 MWh, which is within 5% of Longroad Energy's estimate. This is roughly 4% of total generation for the ISO-NE system each year.

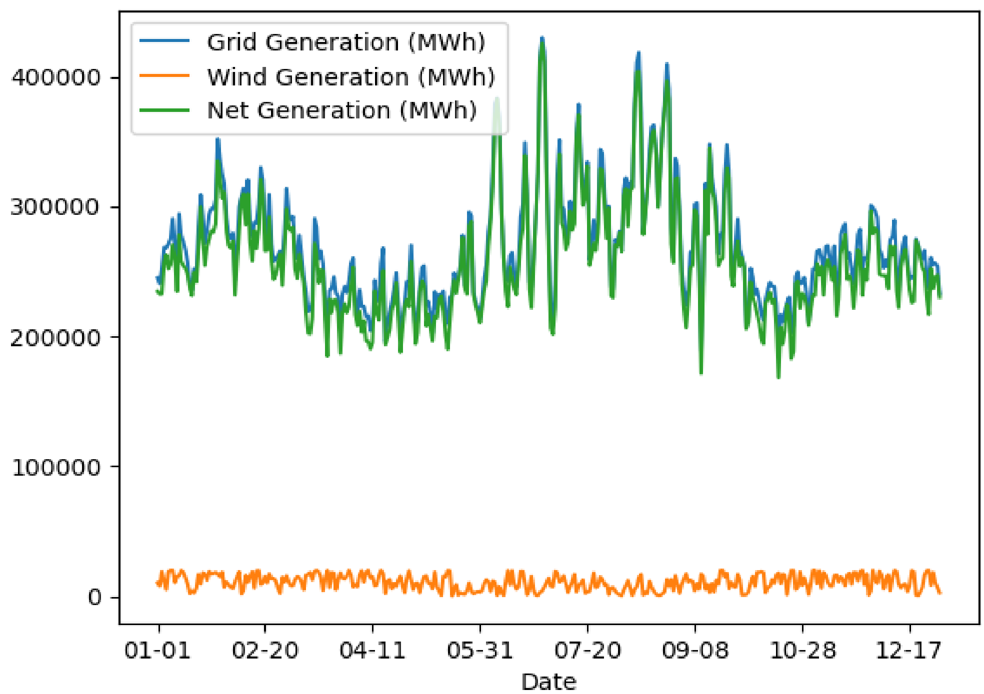

Figure 3: generation by King Pine and all of ISO-NE.

Notably, eliminating export constraints in northern Maine means that wind generation is curtailed just 50 hours annually, which is visible at the lower end of the load duration curve in **Figure 4.** When curtailment does occur, it is because LMPs have fallen below the threshold price of $4/MWh. In total, curtailment accounts for just 27,8181 MWh of King Pine's annual energy generation, or less than 1%. The overall capacity factor of King Pine is 45.6% and its maximum power output of 830 MW after losses due to turbine available, wake effects, and more are considered. The upper end of the load duration curve illustrates how the wind farm operates at its maximum power output more than 30% of the time, suggesting the proposed location has an abundance of wind resource for much of the year.

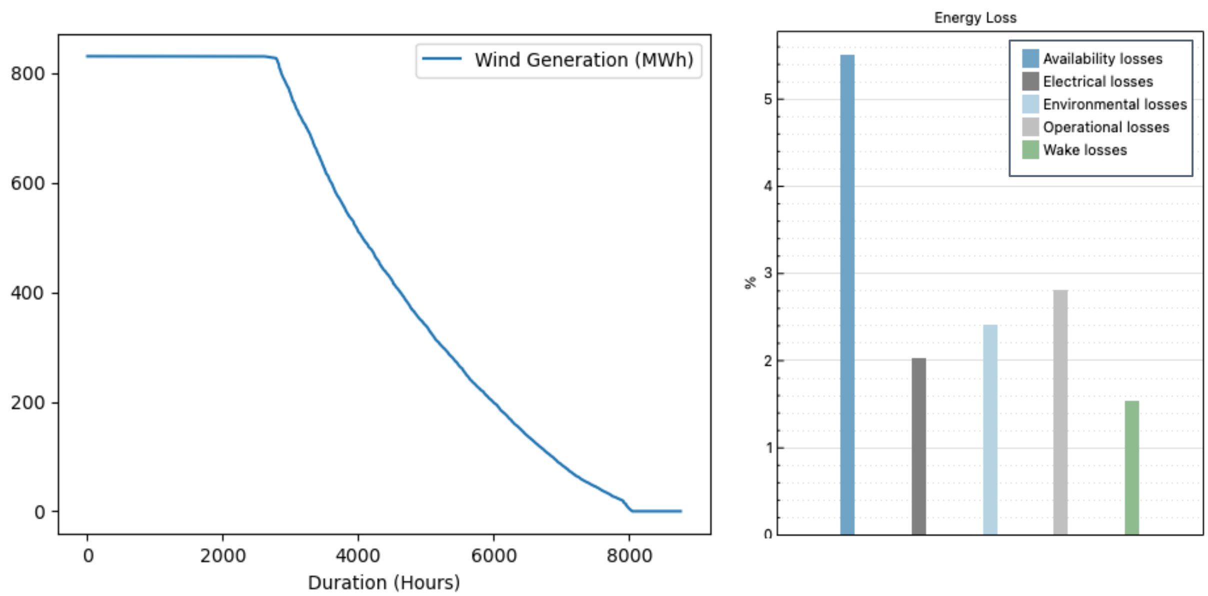

Figure 4: wind farm load duration curve and losses.

The percentage change in MER caused by King Pine is estimated to be **-0.47%**, or a decline from 799 lbs CO2/MWh to 795 lbs CO2/MWh. While this is a modest figure in isolation, the 2019 ISO-NE economic study on the integration of offshore wind in southern New England found that increasing installed capacity from 0 MW to 1,000 MW stood to decrease the MER by roughly 1%. The suggests the estimate for King Pine, with a nameplate capacity of 1,000 MW, is in the ballpark based on the size of the project and the resource type. However, a more nuanced discussion of how King Pine stands to impact emissions in New England follows.

6 Discussion

Although King Pine's output does not appear to vary significantly from season to season when observed in one dimension, a heat map with hours on one axis and days on the other reveals a significant dip in wind generation during daylight hours in the summer months. As a result, one might expect to see both LMPs and the MER for the Maine load zone decrease in the winter months and the evenings on average, but increase on summer days.

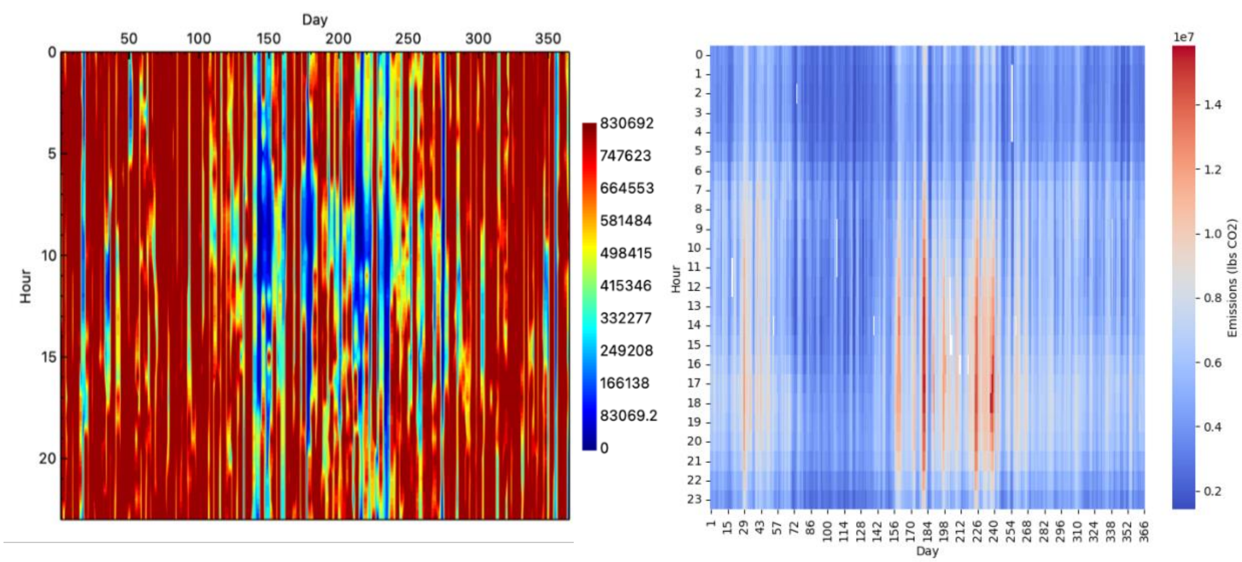

Figure 5: King Pine generation (left) compared to ISO-NE emissions (right).

Bushnell and Novan (2021) demonstrate the heterogenous effect of renewable capacity on wholesale electricity prices and emissions in their study on utility-scale solar in California.[21] Their findings suggest that while an increase in solar capacity reduces average prices, this tends to mask an increase in shoulder-hour prices when there is higher demand for quick-ramping combustion gas turbines, which are less efficient and cost more to operate. Although this paper

[21] James Bushnell and Kevin Novan, "Setting with the Sun: The Impacts of Renewable Energy on Conventional Generation," Journal of the Association of Environmental and Resource Economists, Vol. 8(4), May 2021, https://doi.org/10.7910/DVN/6XQZ3L.

does not investigate unit-level emissions, it is reasonable to assume a similar pattern could emerge in Maine with the addition of King Pine to the dispatch stack. The heatmaps in **Figure 5** illustrate how the lull in wind generation closely mirrors the most emissions intensive time of year for the ISO-NE grid. Additional wind capacity may have the undesirable effect of undermining the economic viability of baseload generators during much of the year while also increasing demand for quick-ramping units needed to meet surging demand in the afternoon hours of summer months when wind generation is weakest.

Another observation related to the pattern of wind generation modeled above and its impact on the MER is that additional wind capacity may have the opposite effect in New England as it does in other regions, such as Texas. Novan (2015) found that marginal emissions avoided in the Electric Reliability Council of Texas (ERCOT) system were increasing during low demand hours since coal is the dominant baseload generator, which favored increasing amounts of wind capacity over solar.[22] However, the ISO-NE system has virtually no coal generation and significant amounts of hydropower, meaning each additional unit of wind capacity will likely displace more and more hydropower, which can be stored for later use or exported elsewhere. Although this is not necessary a bad outcome in and of itself, since the environmental benefits of hydropower would simply be pushed to another time and location, the result could be heavier reliance within New England on natural gas generators capable of

[22]Kevin Novan, “Valuing the Wind: Renewable Energy Policies and Air Pollution Avoided,” American Economic Journal: Economic Policy, Vol. 7(3): 291-326, August 2015, http://dx.doi.org/10.1257/pol.20130268.

responding quickly to fluctuations in wind generation. Further research is necessary to understand how such a dynamic stands to impact the region's environmental ambitions.

7 Appendix

CO2 Emissions Rates by Unit Type for NPCC New England Subregion (EPA eGRID 2020)	
Oil	3374.67 lbs CO2/MWh
Coal	2277.02 lbs CO2/MWh
Natural Gas	850.54 lbs CO2/MWh
Refuse	0.00 lbs CO2/MWh
Wood	0.00 lbs CO2/MWh
Landfill Gas	0.00 lbs CO2/MWh
Nuclear	0.00 lbs CO2/MWh
Hydro	0.00 lbs CO2/MWh
Solar	0.00 lbs CO2/MWh
Wind	0.00 lbs CO2/MWh
Other	0.0 lbs CO2/MWh

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