EAEE E4220 – Energy System Economics and Optimization

Wind Integration in ISO New England

Final Project

Proj.1 Team #10

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1. Introduction

ISO New England is a not-for-profit corporation which is responsible for the reliable operation of New England’s power generation, demand response, and transmission system. It has the responsibility to protect the short-term reliability and plan for the long-term reliability of the Balancing Authority Area, a six-state region that includes approximately 6.5 million businesses and households[1].

New England’s power grid is part of the Eastern Interconnection, one of four large power grids in North America and has multiple ties to neighboring power systems in the U.S. and Eastern Canada. The annual growth rate for overall electricity use is 0.4%. In 2020, 20% of the region’s energy needs were met by imports.

There are 350 dispatchable generators in this region with a total 31,500 MW of generating capacity, also wind, solar, and storage proposals offer over 24,000 MW of proposed generation in the ISO Queue. While roughly 7,000 MW of generation have retired or will retire in the next few years, wind and solar power generation plays an more important role in the electricity market. With a proposed capacity of 15,133 MW, wind power comprises two thirds of new resource proposals in the ISO Interconnection Queue[2].

In this project, as the policymaker of ISO New England, we are given a one-bus system model with the data of 76 different generators, 90 scenarios of wind capacity factor and demand data over 96 hours. Generators data includes fuel type, capacity, minimum generation, minimum uptime and downtime, ramp rate and cost parameters.

By conducting the unit commitment analysis with increasing wind generation capacity, we are able to investigate the commitment status of generators with different fuel types, the average daily total operating cost of the ISO-NE system, average daily electricity price and profit received by generators. Another objective of this study is to figure out how much wind capacity is needed to retire all coal generators (BIT and SUB) from the system.

2. Method

2.1. *Choose the Representative Scenarios*

When choosing the representative scenarios, we calculate the hourly average electricity demand and average wind capacity factor over 96 hours and make the plot. Then we divide the points into a reasonable number of clusters using the K-means clustering method. And the nearest point to the center of each cluster is chosen as the representative scenario of that cluster.

2.2. *Define the Objective Function*

$$min \sum_t \sum_i (MRC_i g_{i,t} + NLC_i u_{i,t} + SUC_i v_{i,t})$$

$g_{i,t}$: production of generator i during time period *t*

$u_{i,t}$: 1 if generator i is on during time period *t*, otherwise 0

$v_{i,t}$: 1 if generator i is turned on at the start of time period *t*, otherwise 0

2.3. *Define the Constraints Functions*

$$Gmin_i u_{i,t} \le g_{i,t} \le Gmax_i u_{i,t}$$

$$- RR_i \le g_{i,t} - g_{i,t-1} \le RR_i + Gmin_i v_{i,t}$$

$$v_{i,t} - z_{i,t} = u_{i,t} - u_{i,t-1}$$

$$v_{i,t} + z_{i,t} \le 1$$

$$\sum_{\tau=max\{t-Tup_i+1,1\}} v_{i,\tau} \le u_{i,t}$$

$$\sum_{\tau=max\{t-Tdn_i+1,1\}} z_{i,\tau} \le 1 - u_{i,t}$$

$$\sum_i g_{i,t} + w_t = D_t : \lambda_t$$

$$\sum_i r_{i,t} \geq 3\%\, D_t + 5\%\, w_t$$

$$r_{i,t} \leq Gmax_i u_{i,t} - g_{i,t}$$

$$r_{i,t} \leq RR_i$$

$$w_t \leq \alpha_t W$$

$z_{i,t}$: 1 if generator i is turned off at the start of time period *t*, otherwise 0

W : installed wind capacity

α_t : wind capacity factor during time period *t*

D_t: system demand during time period *t*

$r_{i,t}$: hourly reserve generator i could provide during time *t*

w_t: wind power generation during time period *t*

2.4. *Optimization Set-up*

The optimization of the defined objective function and constraints are conducted by GUROBI using Python in Jupyter Notebook. In the first part of the project, the accuracy of optimization is 0.0001 by default. And in the second part, in order to shorten the running time of the code, we set the accuracy of optimization as 0.05.

2.5. *Problems*

In this project, what we are concerned about is how the electricity market responds to the expanding installation of the wind turbines, and how much does the mandatory shutdown of all coal-fired generators cost under different scenarios.

So, in the first part of our project, we will investigate the changing trend of 1) *Daily Average Operating Cost*, 2) *Daily Average Supplier Profit*, 3) *Daily Electricity Marginal Price*, 4) *Commitment Status of Generators* grouped by fuel type and ramp rate, with the increase of *Installed Wind Capacity* during the given 96-hour length in the representative scenarios.

Then in the second part of our project, the market situation without coal-fired generators is investigated. Assuming all the coal-fired generators are mandatory shut down, we calculate the *Daily Average Operating Cost* under different *Installed Wind Capacity*, and compare them to the result in the previous part to calculate 1) the point of *Installed Wind Capacity* that could make up all the extra cost of mandatory shutdown, 2) the cost to phase out per megawatt coal electricity.

3. Results

3.1. *Choosing Representative Scenarios*

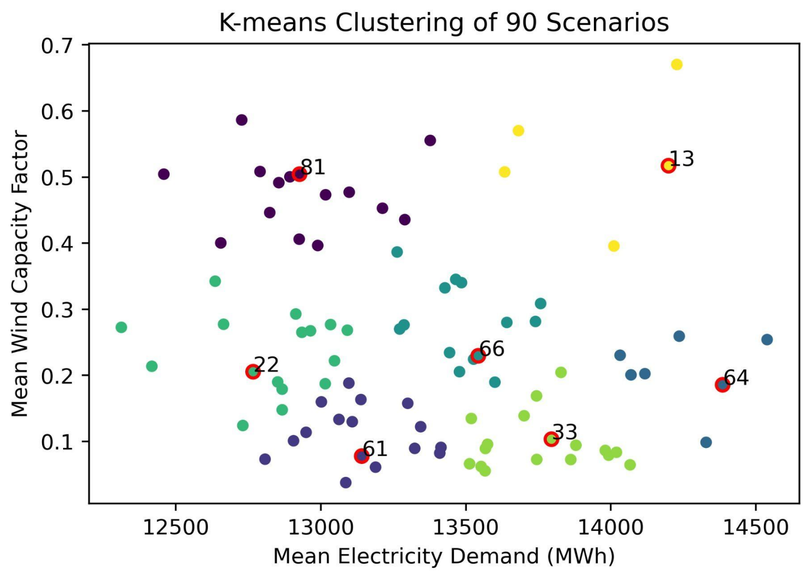


Figure 1. Result of K-means Clustering on 90 given scenarios

Figure 1 shows the K-means Clustering result of 90 scenarios. The resulting clusters are presented in different colors, and the chosen representative scenario in each cluster is highlighted with a red edge and number. According to the result, we select 7 representative scenarios with serial numbers 61, 33, 22, 66, 64, 81, and 13, which would form the best possible clusters with obvious differences.

As a brief summary of the clustering result, we find that these clusters are divided into three levels according to *Wind Capacity Factor*, and each level is divided into two or three subgroups according to the *Electricity Demand.* So the attributes of each cluster could be described by their *Wind Capacity Factor* and *Electricity Demand* in the following Figure 2.

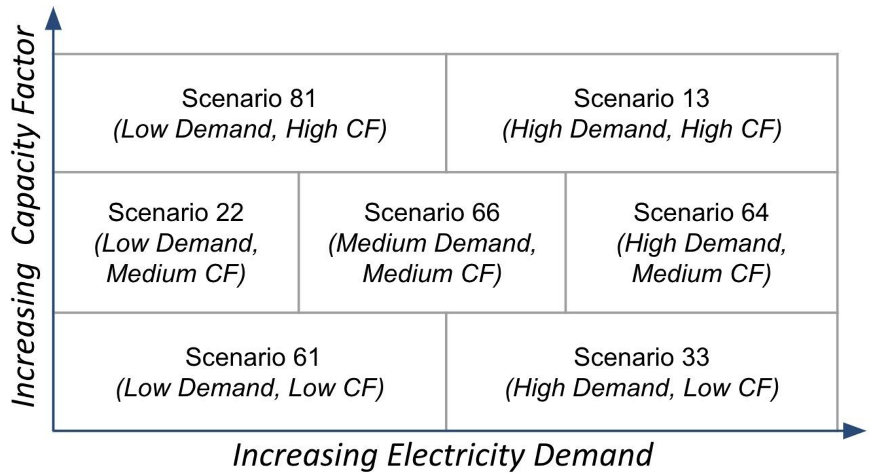


Figure 2. Representative scenarios described by Wind Capacity Factor and Electricity Demand

3.2. Market Response to Increasing Installed Wind Capacity

3.2.1. Scenario 66 — a detailed optimization

As a detailed example of our optimization result, we made a thorough analysis of Scenario 66 (Medium Demand and Medium Capacity Factor) to show some regular pattern of the unit commitment result under the increasing *Installed Wind Capacity.*

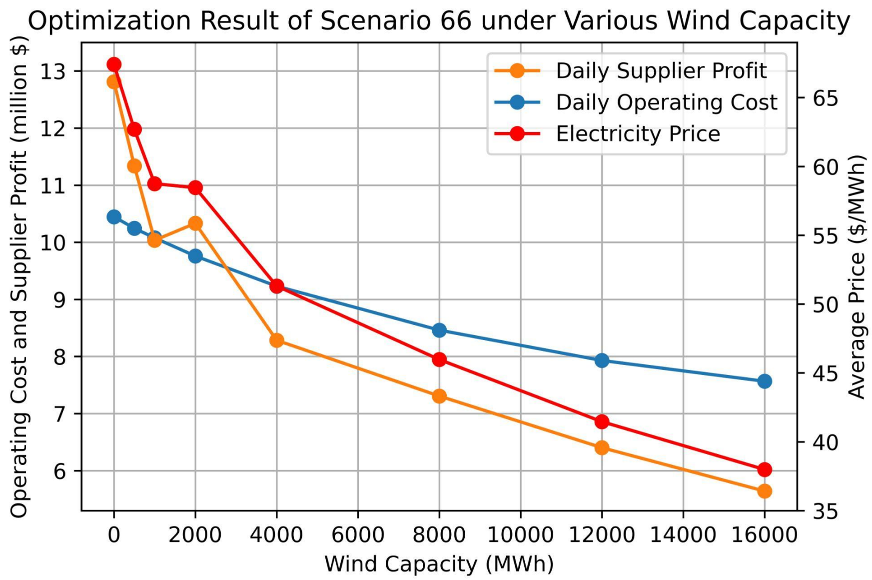


Figure 3. Optimization result of Scenario 66 with increasing Wind Capacity

The result of the market situation is shown in Figure 3. With the increasing wind capacity, average daily total operating cost decreases from 10.4 MD to 7.6 MD, average daily supplier profit drops by over 50%, from 12.8 MD to 5.6 MD and average electricity price has a similar trend with supplier profit, declining from $67.4/MWh to $38.0/MWh.

Table1. Commitment status of generators (working time/96 hrs)

Fuel Type	0	500	1000	2000	4000	8000
NGMN	1.000	1.000	1.000	1.000	1.000	1.000
NUC	1.000	1.000	1.000	1.000	1.000	1.000
SUB	1.000	1.000	1.000	1.000	1.000	1.000
BIT	1.000	1.000	1.000	1.000	1.000	0.998
NGLN	1.000	1.000	1.000	1.000	0.995	0.969
NGIR	0.958	0.958	0.958	0.948	0.938	0.927
NGT4	0.917	0.917	0.927	0.917	0.906	0.896
NGA4	0.841	0.852	0.806	0.778	0.719	0.689
NGA1	0.646	0.505	0.484	0.401	0.255	0.245
RFO	0.072	0.071	0.071	0.068	0.068	0.064
NGTN	0.204	0.200	0.199	0.199	0.199	0.195
NGT2	0.326	0.289	0.289	0.326	0.286	0.263
NGPN	0.352	0.286	0.286	0.286	0.255	0.253
NGT1	0.188	0.188	0.188	0.188	0.188	0.115

Table 1 shows the running duration of different types of generators, with *Installed Wind Capacity* ranges from 0 to 8000 MWh. Generally, generators can be divided into 4 categories based on working time percentile. NGMN, SUB and NUC generators work all the time; BIT, NGLN, NGIR and NGT4 work over 90% of the time; commitment status of NGA4 and NGA1 change drastically with increasing wind capacity; RFO, NGTN, NGT2, NGPN, NGT1 generators are offline most of the time. When wind capacity is 8000 MWh, coal generators (BIT & SUB) work almost 96 hrs, indicating a challenging objective to phase out all coal generators.

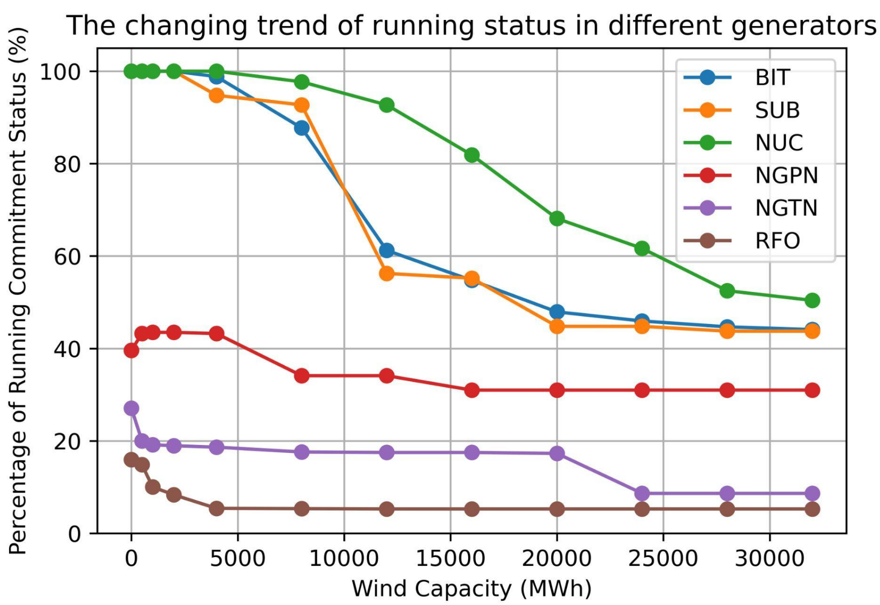


Figure 4. Commitment status of different generators with increasing Wind Capacity

Figure 4 shows the commitment result of typical types of generators when we further increase the *Installed Wind Capacity* to 32,000 MWh. With the increase of *Installed Wind Capacity*, fuel oil generators, which is the type with most expensive running costs, would first decrease to a low level of generation. And almost simultaneously, the electricity generation by natural gas starts to decrease, and finally remains stable at a low level. Then, with the further increase of *Installed Wind Capacity*, the coal generators start to decrease their electricity generation and finally come to an approximately 50% level. Lastly, when the *Installed Wind Capacity* is as high as 15000 MW, nuclear generators start to decrease their generation.

One thing that is worth noting is, even *Installed Wind Capacity* comes to an extremely high level, none of the four types of generators is completely phased out by the market, instead, those generators with high generation costs would still remain running at a relatively low frequency and capacity. This phenomenon indicates the fact that it is impossible to completely phase out any kind of generators with the increase of *Installed Wind Capacity* solely. So, in order to eliminate all the production by coal burning, a mandatory shutdown should be taken place.

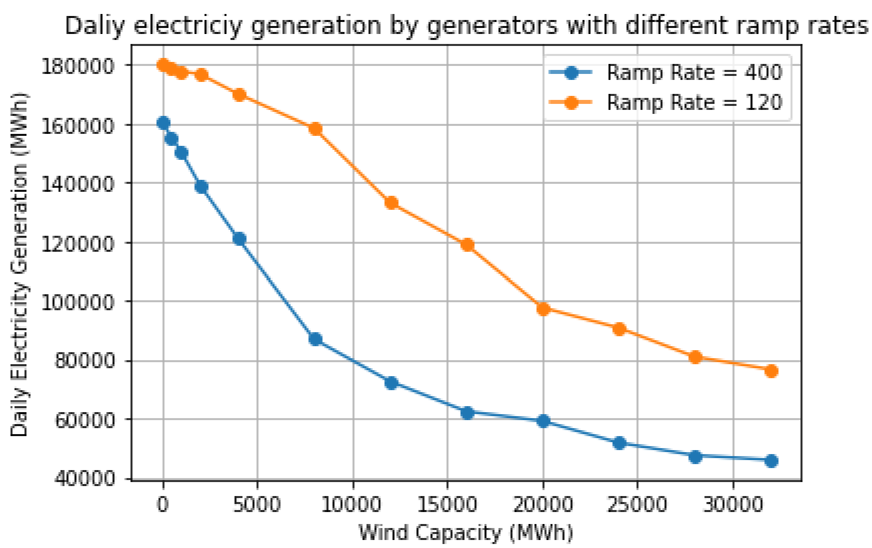


Figure 5. Daily electricity generation by generators with different ramp rates

Figure 5 shows the generator with a higher ramp rate has a sharper drop in electricity generation when first importing wind energy, which means it's more responsive than a generator with lower ramp rate.

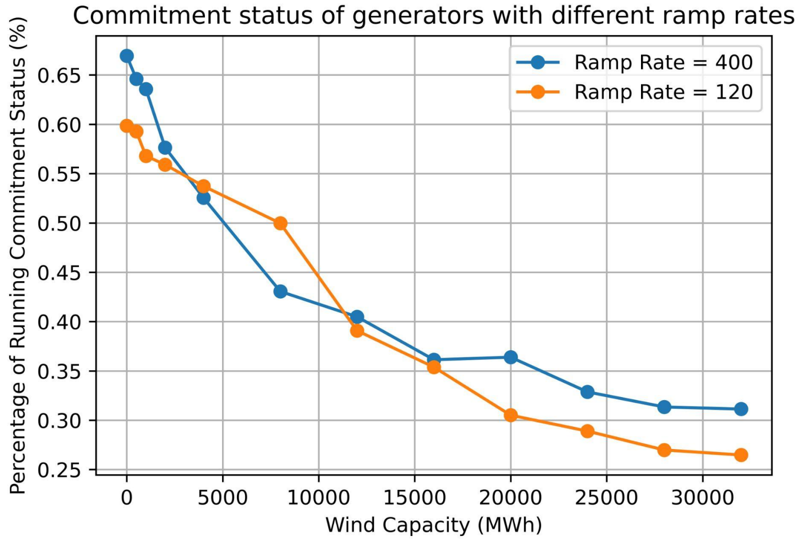


Figure 6. Commitment status of generators with different ramp rates

Figure 6 shows the generators with higher ramp rates have larger proportions of shutting down due to importing wind energy in the first place. Which is coordinated with the figure of ramp rate where generators with larger ramp rate can be more sensitive in regard to commitment changes and generators with low ramp rate are less responsive to the changes. Furthermore, the immediate decreasing rate of high ramp rate is also coordinated with its high operating expense, which has been depressed by introducing wind capacity.

3.2.2. Comprehensive analysis across different scenarios

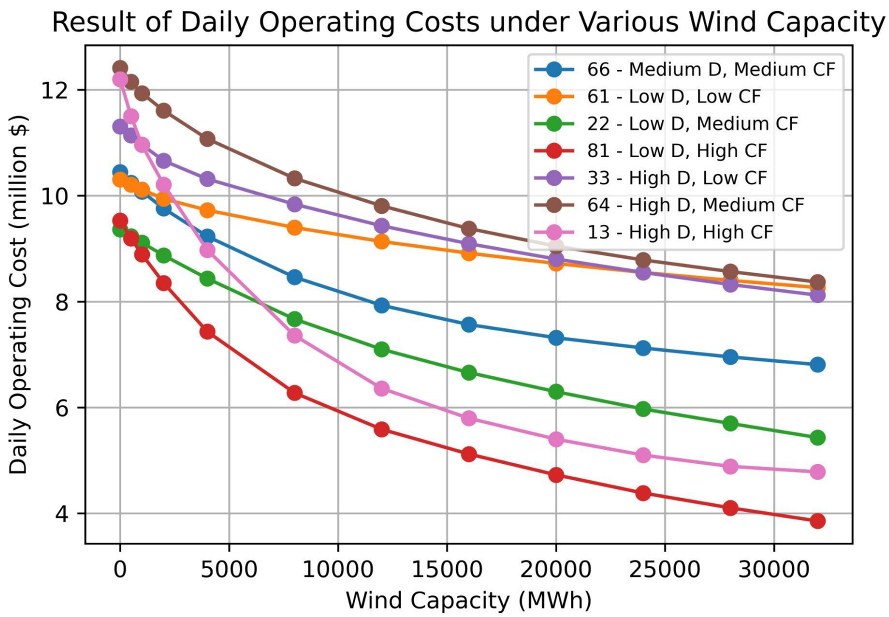


Figure 7. Operating cost of different scenarios with increasing Wind Capacity

When comparing the operation costs of different scenarios, as we can see in the plot, scenario 13 (high Demand, high Wind CF) reveals a different pattern from other scenarios. As the wind capacity increases, operation cost of scenario 13 declines more rapidly than others, which contributes to the high Wind CF that makes wind power plays an important role in the electricity supply.

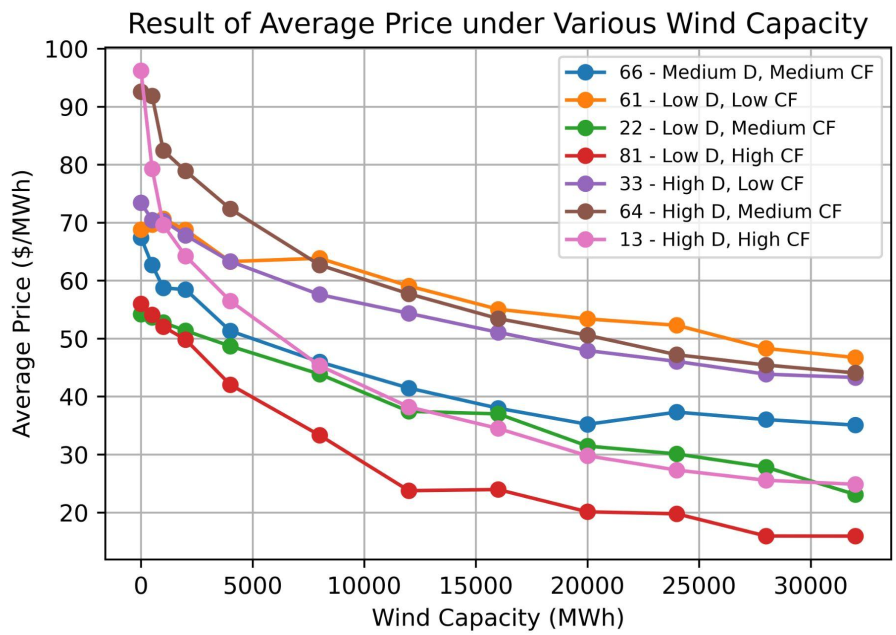


Figure 8. Average electricity price of different scenarios with increasing Wind Capacity

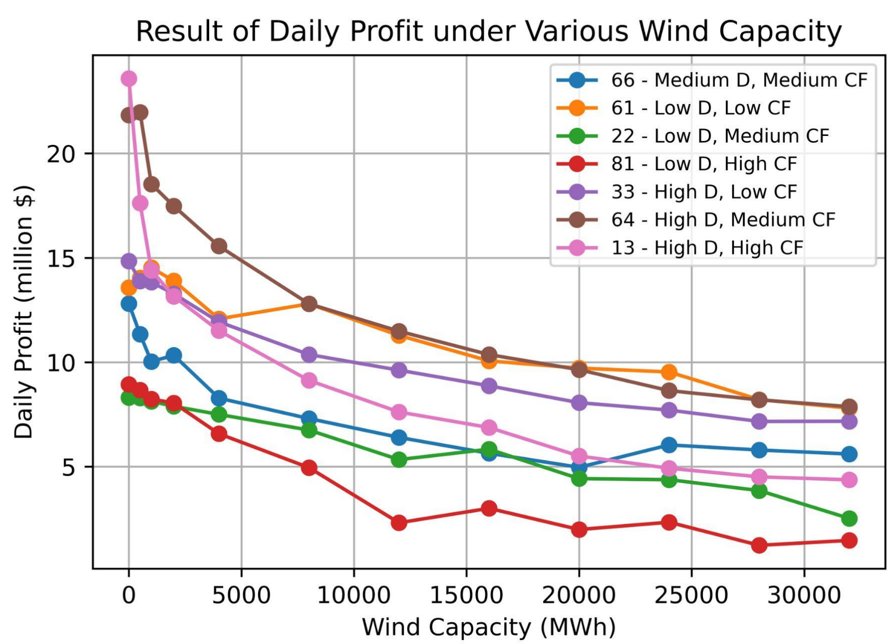


Figure 9. Daily profit of different scenarios with increasing Wind Capacity

Daily average electricity price and daily profit of different scenarios decline with increasing wind capacity and reveal similar patterns. From 0 to 5000 MWh wind capacity, average electricity price and daily profit of scenario 13 (high demand, high wind CF) decline more rapidly than other scenarios. There are also some fluctuations in the pattern: when wind capacity increases, daily electricity price and daily profit sometimes go up, which means that increasing wind generation substitutes some coal generators with lower operation costs and make generators with higher cost become the marginal generator.

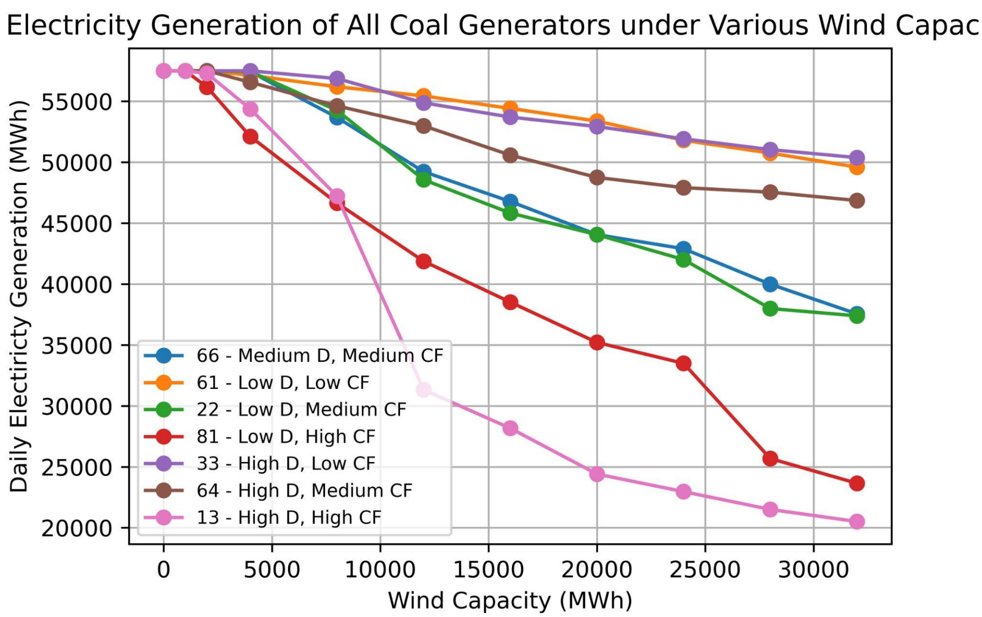
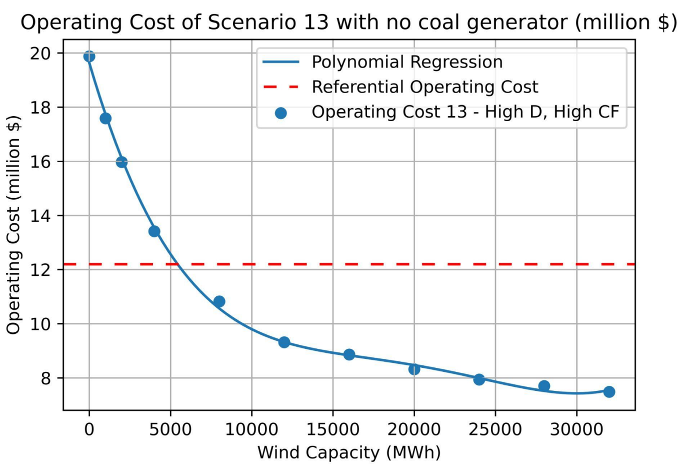


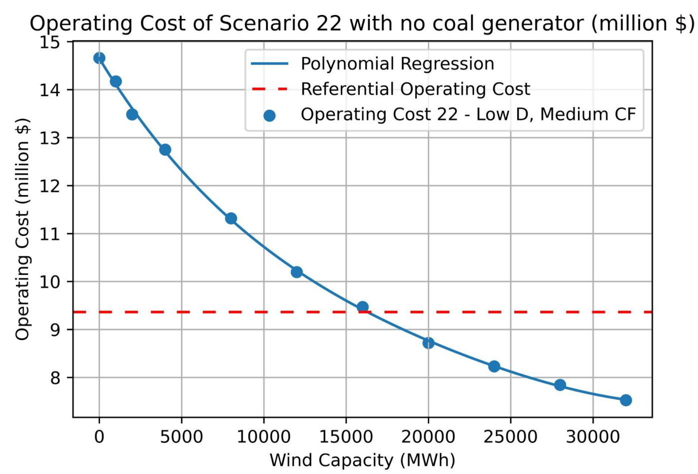
Figure 10. Electricity generation of coal generators with increasing Wind Capacity

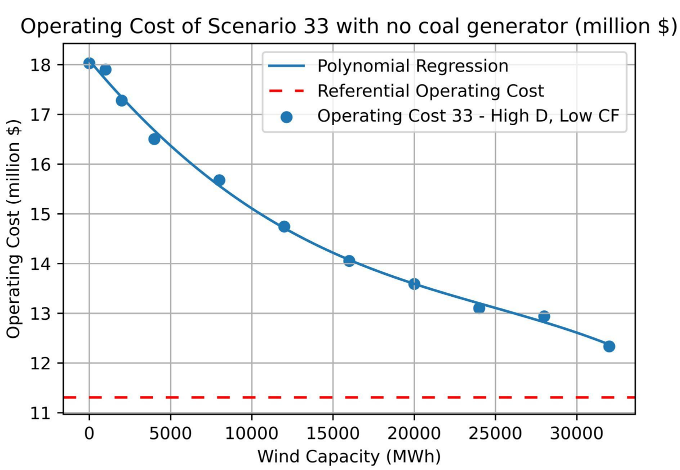
When wind generation increases, the electricity generation of coal generators declines as we imagine: generation declines rapidly in scenarios with high Wind CF, slowly in scenarios with low Wind CF and medium Wind CF scenarios in the middle. Also, when wind capacity is 36,000 MWh, the generation of coal generators in all scenarios is still higher than 20,000 MWh, also indicating phasing out all coal generators is a challenging objective with tremendous cost.

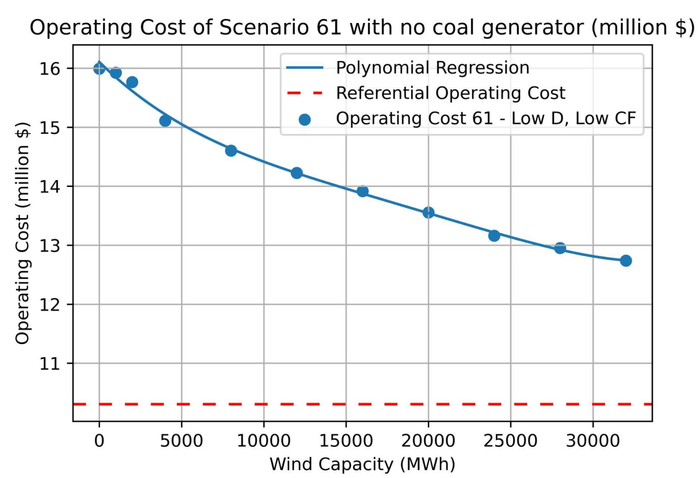
3.3. Cost of phasing out coal generators

In this part, how much wind capacity is adequate enough to phase out coal generators in ISO New England is analysed. By shutting down the coal generators in scenarios, operating cost has been spiked up because of phasing out the cheapest generators. It drops down by importing wind energy which is of no operating cost. Therefore, our method compares the starting operating cost of original scenarios which simulate in part 2 with the new operating cost curve. Starting point of the based simulation is the operating cost when no wind energy is considered but includes the contribution of coal generators. Hence the intersection of the operating cost curve when phasing out coal generators and the baseline operating cost will be the wind capacity in need of phasing out all the coal generators.









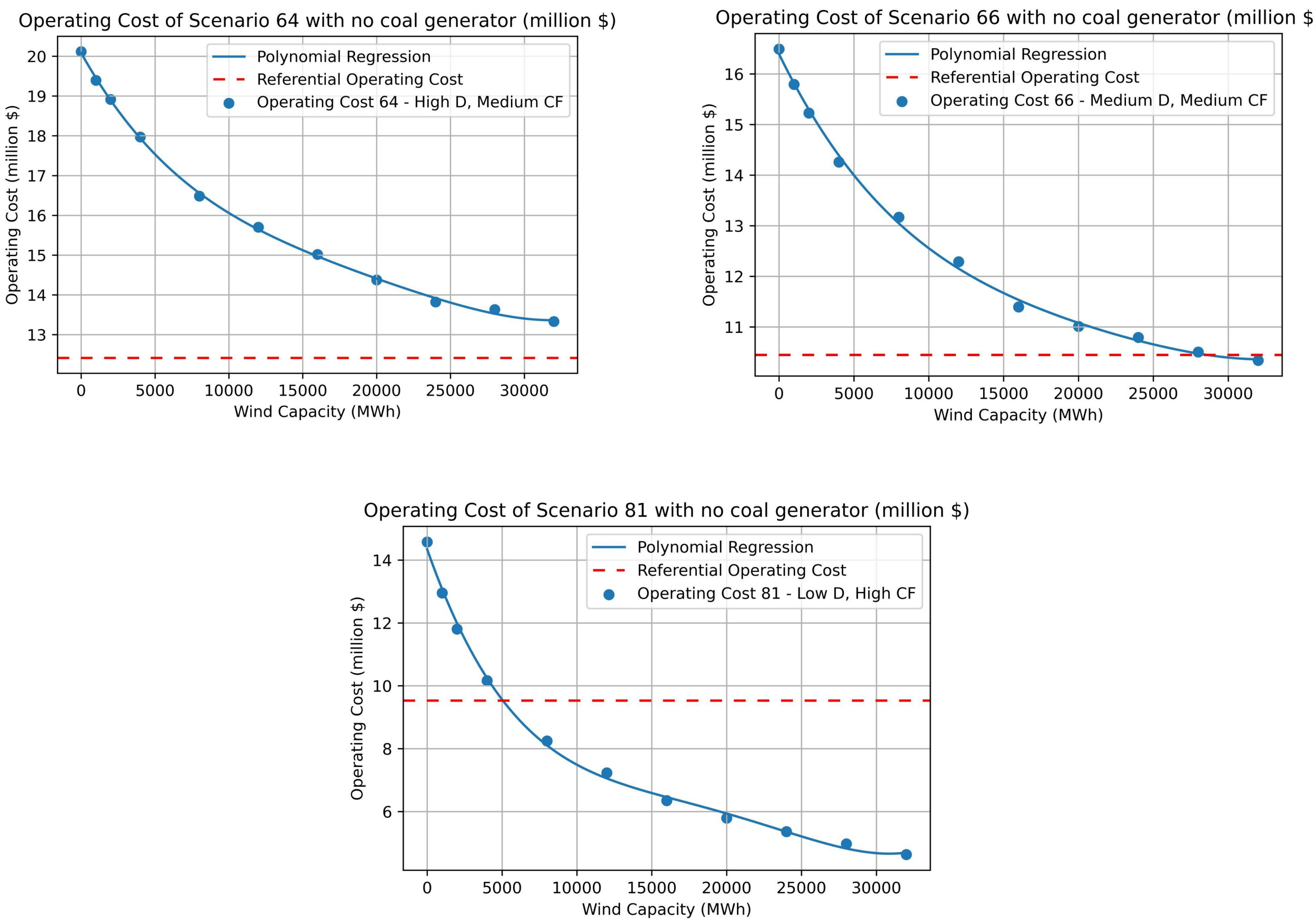


Figure 11. Operating Cost of Scenarios with no coal generator (million $)

Phasing out coal generators means a further step of transitioning to cleaner energy, but in the meantime, increasing the operating cost because of removing the most flexible and cheapest generators. Scatter points for each wind capacity are simulated using Gurubi while the polynomial function is derived from the scatter points using polynomial regression, dimension as 4.

From the above graphs, scenario 13 (High Demand, High Wind CF) has the predicted wind capacity of 5436 MWh, scenario 22 (Low Demand, Medium Wind CF) has the predicted wind capacity of 16291 MWh, scenario 66 (Medium Demand, Medium Wind CF) has the predicted wind capacity of 28580 MWh and scenario 81 (Low Demand, High Wind CF) needs 5054 MWh to phase out coal generators. In comparison, scenario 33, 61 and 64 cannot meet the requirement of phasing out coal generators within the simulated wind capacity. All of these scenarios need higher wind capacity (>32000 MWh) in regions to satisfy the market.

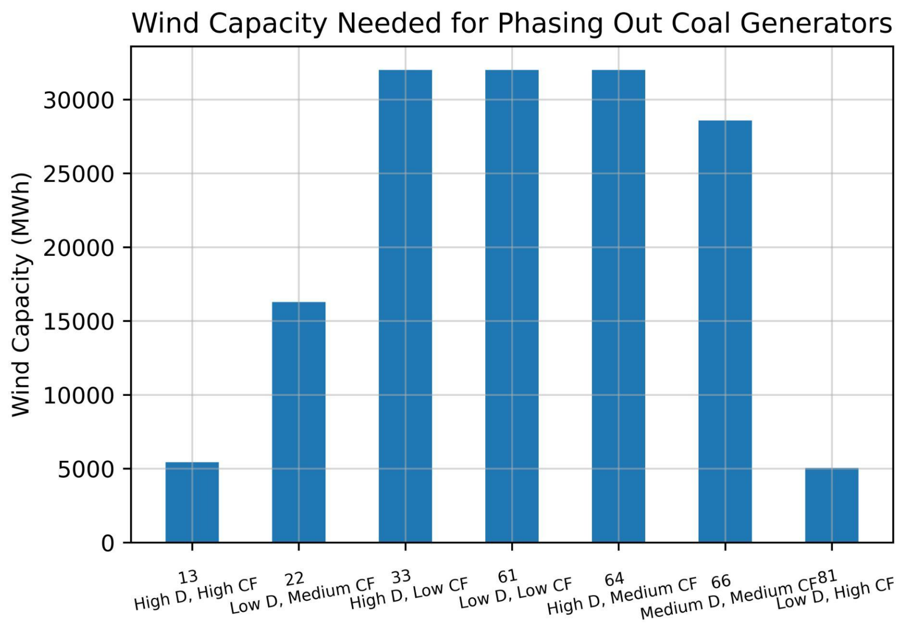


Figure 12. Wind Capacity needed for phasing out coal generators (MWh)

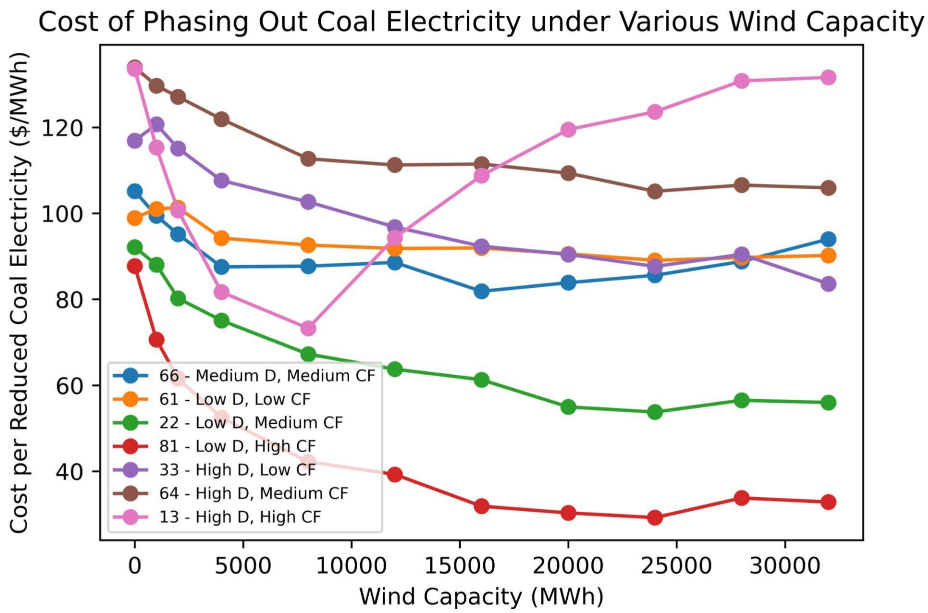


Figure 13. Cost of phasing out coal electricity under various Wind Capacity

Analysis has been done on the cost of phasing out per Megawatt electricity from coal generators. In general, the cost drops in the first place. It is because after giving up coal generators and by importing wind capacity, wind energy can partially replace the other generators that have higher cost than wind. Therefore, in this stage, the cost of phasing out per unit coal electricity is dropped. The most significant price decrease happened in Scenario 13 (high demand and high capacity factor). It is an economic sign of phasing out coal generators, especially when wind capacity is between 5000 to 10000. A twist point can be witnessed when introduced wind capacity grows. This is due to the resilience of some generators which are of higher economical or flexible priority than wind energy, such as nuclear generators (shown in Figure 4.) and natural gas generators. Henceforth, coal generators can be more economically shut down by importing more wind capacity, but the unit coal generating cost cannot be ultimately decreased by introducing more wind capacity after the turning point.

4. Conclusion

To conclude the result of our project, we conducted optimization on the given data in ISO New England under different assumed installed wind turbine capacities, in order to explore the potential behavior of generators and the whole electricity market, as well as the cost of the further policy under the expanding installation of wind turbines.

Before the analysis and optimization, we selected 7 representative scenarios out of 90 given scenarios with K-means clustering on average demand and average wind capacity factor.

And in the first part of the project, we investigated the market response with the increasing installed wind capacity, where we presented a detailed analysis on scenario 66, and a comprehensive comparison between different scenarios. As we discussed in the first part, we found the fact that coal generators could not be utterly phased out by market balance, so we concluded that mandatory shutdown should be taken place, in order to eliminate the burning of coal in the electricity generation industry.

And in the second part of our project, we take further steps to analyze the cost to phase out all coal generators. Starting from the calculation of the needed wind capacity to recover the operating cost to the base case after the mandatory shutdown of all coal generators, where we used polynomial regression to derive the actual value, we found in cases with low wind capacity factor, it is nearly impossible to reduce the operating cost to the baseline even with an extremely high capacity of the wind turbine. Then additionally, we calculated the cost of phasing out unit coal electricity under different conditions, where we found, with the increasing wind capacity, the cost to phase out remaining coal electricity in the market would first decrease, then show a tendency to increase, which indicates a complex nature of the actual cost of the policy.

References

[1] G. Hinkle, R. Piwko, et al. (2010). *New England Wind Integration Study Executive Summary.* GE Energy Applications and Systems Engineering. https://www.nrcm.org/documents/ISO_NE_integration_report_execsummary.pdf

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