

Environmental Impacts of Capacity Expansion: Manipulating Carbon Penalties and Uncertainty Analysis to Reach Goal Resource Mix

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Introduction, Motivation, and Scope:

This project studies the environmental impacts of capacity expansion in New York State. In particular, it examines the effect of carbon penalties on the state's energy mix. The state of New York has recently outlined several sustainability goals with regard to its energy production. This project focuses on achieving one of those goals in particular, which is to reach 70% renewable energy generation by 2030. The goal of the project is to understand the necessary modifications to the current energy mix in order to achieve this benchmark, and how carbon penalties can be implemented in order to reach it.

The motivation for this project was found in recent government policies that have affected energy production in New York and the United States as a whole. The group is interested in how government policies, such as carbon penalties, can be implemented to promote renewable energy production.

To analyze this question, a base case was modeled after the 11-zone NYISO capacity expansion model from homework 6. The main modification to the existing formulation was the addition of a carbon tax. Modifying the value of the carbon tax over several iterations changed the resource mix, and helped to determine the necessary carbon tax to reach 70% renewables.

The project also studies some other aspects of the design, besides the effect of carbon penalties on the resource mix. It investigates some of the other effects of carbon penalties, such as how they would impact the cost of energy generation in New York State. The model also considers certain variable conditions that might affect the necessary carbon tax to reach the 70% renewable target. These conditions include weather and inflation, which introduce uncertainty to the model due to their variability.

Literature Review:

Most sources recommended implementing a carbon tax based on greenhouse gas emissions. These numbers were initialized between \$20/metric ton to \$60/metric ton, with a steady increase each year according to the graph below.

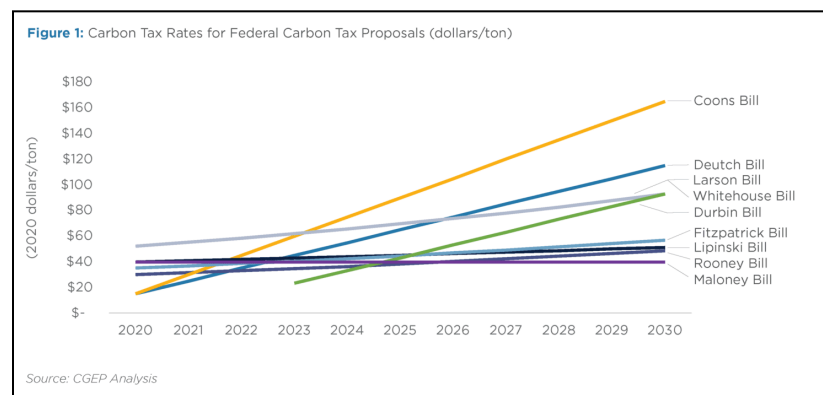


Figure 1 - Carbon tax rates for various federal carbon tax proposals

The group decided to model the carbon tax portion of the project as an addition to the objective function. A conversion factor was sourced from the U.S. Energy Information Administration using the following table:

U.S. utility-scale net electricity generation and resulting CO ₂ emissions by fuel in 2023				
	Electricity generation	CO ₂ emissions		
	million kWh	million metric tons	million short tons	pounds per kWh
Coal	675,115	709	781	2.31
Natural gas	1,806,063	790	871	0.96
Petroleum	16,233	18	20	2.46
All other energy sources	4,183,271	1,532	1,688	0.81

Figure 2 - US utility-scale net electricity generation and resulting CO₂ emissions by fuel in 2023

[Source: <https://www.eia.gov/tools/faqs/faq.php?id=74&t=11>]

The load zones were determined using homework 6 and the NYISO load zones map shown in Figure 3 below.

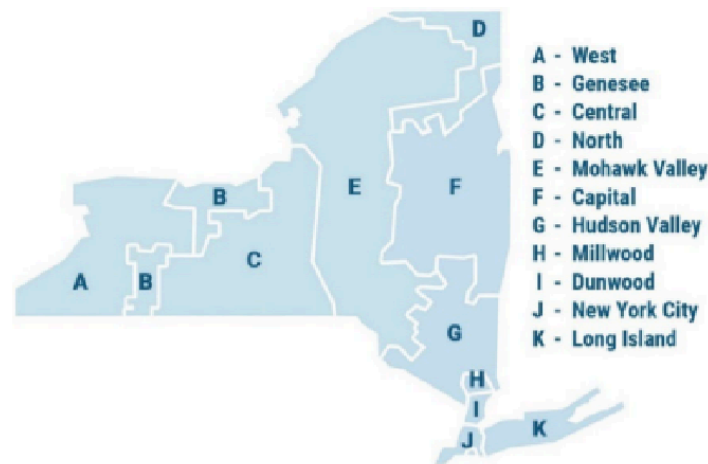


Figure 3. NYISO Load Zones Map

Methods:

Base Case with Carbon Tax

The base case model was formulated as a capacity expansion model using 11-zone NYISO fixed demand data with transmission limitations. The model applies a resource mix that includes solar, wind, gas, four-hour batteries, and the existing nuclear capacity in New York state. The following assumptions were made: it is not possible to install new nuclear, only retire the existing capacity, wind production is not possible in zones G, H, and I, wind resources in zones J and K are offshore and therefore more expensive, and no new transmission can be introduced.

The model converts energy produced by gas in each zone to metric tons of CO2 and multiplies by the chosen carbon tax as shown;

```
#add carbon tax amount
param tax >= 0; # $/metric ton
param conversion = 0.435449; #metric ton/MWh
```

(1)

The following addition was made to the objective function:

```
+ sum {z in ZONES, t in TIMES} p_gt['GAS',z,t] * tax * conversion
```

(2)

Sensitivity Analysis

Interannual and seasonal variations in wind and solar output can be significant, motivating the adoption of a 30% availability scaling factor for this analysis. The conventional approach would involve using time series historical data and performing data analysis to determine characteristic availability years. However, our team was not able to get access to the 20-year time series data in time to perform the necessary data analysis in a timely manner. Therefore, the 30% scaling factor is being used. This approach is supported by studies done in the capacity expansion and energy space. The U.S. Department of Energy's National Renewable Energy Laboratory (NREL) has demonstrated that the seasonal weather of sun and wind can vary greatly, but tend to vary within 30% of the seasonal means (NREL). Although NREL normally specifically focuses on the technology aspects of renewable energy, the magnitude of the 30% variation effectively captures the range of fluctuations due to interannual variability and transient weather conditions. This similarity in scale justifies the use of a $\pm 30\%$ adjustment when modeling characteristic years, as it reflects realistic best- and worst-case resource scenarios

The Scaling factors were applied to the constraints as shown:

```
subject to wind_availability {t in TIMES, z in ZONES}:
    p_gt['WIND',z ,t] <= wind_avail[t,z] * 0.7 * x_g['WIND',z]
subject to solar_availability {z in ZONES, t in TIMES}:
    p_gt['SOLAR',z ,t] <= solar_avail[t,z] *0.7 * x_g['SOLAR',z]
```

(3)

```
subject to wind_availability {t in TIMES, z in ZONES}:
    p_gt['WIND',z ,t] <= wind_avail[t,z] * 1.3 * x_g['WIND',z]
subject to solar_availability {z in ZONES, t in TIMES}:
    p_gt['SOLAR',z ,t] <= solar_avail[t,z] *1.3 * x_g['SOLAR',z]
```

(4)

Once applied, the production, total costs per MW, and share of renewables were displayed:

```
display x_g, b;
display (Total_Expenses)/(sum {g in GENERATORS, z in ZONES, t in TIMES} x_g[g,z]);
display (sum {z in ZONES, t in TIMES} p_gt['GAS',z,t]) / (sum{t in TIMES, z in ZONES} fixed_demand[t,z]);
```

(5)

Key Assumptions and Justification:

We encountered several limitations in our project that warrant careful discussion. First, our scenario analysis does not capture multi-year trends, such as inflation and extended weather patterns, that could influence energy demand or resource costs over time. However, we partially mitigate this shortcoming through our sensitivity analysis, which explores the effects of weather-driven fluctuations in renewable availability. By testing different wind and solar scenarios, we gain valuable insight into how the inherent uncertainty in weather patterns can impact the energy mix, even if long-term economic trends are not explicitly modeled.

In addition, the current model does not account for the potential expansion of transmission capacity. While the incorporation of transmission enhancements could certainly influence the optimal resource mix, our focus is deliberately kept on isolating the effects of carbon penalties and renewable availability. This targeted approach allows us to clearly discern the relationship between the carbon tax and the renewable share, unconfounded by other infrastructural changes. Similarly, we have not incorporated constraints on facility expansion in certain zones, except the no-build constraint of wind in zones G, H, and I. This omission is particularly relevant for urban areas where renewable installations might face physical or regulatory limits. Although such limitations could influence the mix in practice, excluding them at this stage simplifies the analysis, enabling us to isolate the effect of the carbon tax on an idealized system.

Additionally, our study does not explore the potential interactions between carbon penalties and other government policies—such as tariffs—that could also shape energy sourcing and distribution decisions. While these policy interactions are important, their exclusion is justified by our goal of assessing the direct impact of carbon taxation on renewable integration. The sensitivity analysis, wherein we adjusted wind and solar availability and recalibrated the carbon tax accordingly, further fortifies our findings by accounting for key uncertainties without overcomplicating the model.

Despite these limitations, our assumptions are intentionally designed to create a focused framework for understanding how carbon penalties influence the renewable energy mix. By isolating the effect of the carbon tax and incorporating a complementary sensitivity analysis, we provide a robust basis for interpreting the results, and a strong foundation for future analysis. While future work could—and indeed should—integrate longer-term trends, expanded transmission capacity, urban-specific expansion constraints, and additional policy measures, the current model offers clear, targeted insights that are both manageable and informative for preliminary policy evaluation.

Results & Analysis

Base Case

The ‘tax’ parameter was changed to different multiples of \$5 per tonne and the model was resolved each time until the goal was reached. The following is a graph of the result:

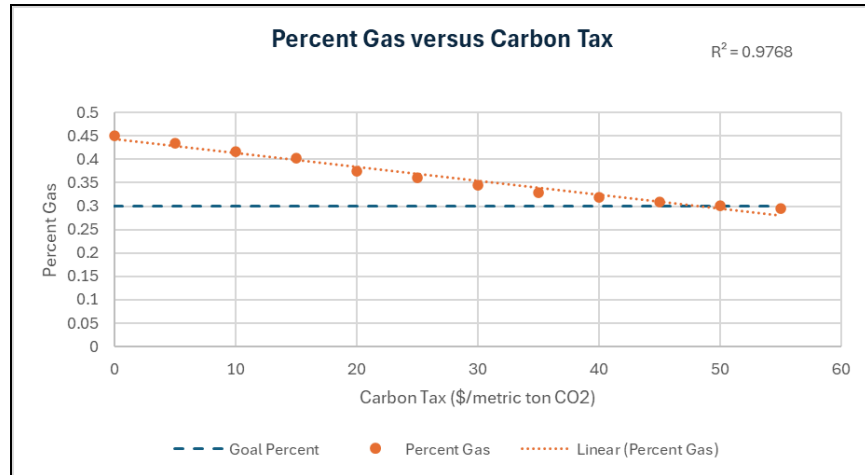


Figure 4 - Relationship between carbon tax value and percentage of gas in the resource mix

Carbon Tax (\$/tonne)	0	5	10	15	20	25	30	35	40	45	50	55
Total Expenses (\$)	9.18 E+09	9.34 E+09	9.49 E+09	9.63 E+09	9.77 E+09	9.89 E+09	1.00 E+10	1.01 E+10	1.03 E+10	1.04 E+10	1.05 E+10	1.06 E+10
Percent Gas	0.450	0.434	0.417	0.403	0.376	0.360	0.345	0.330	0.319	0.310	0.302	0.295

Table 1 - Total cost and percentage of gas in the resource mix based on carbon tax value

The model reached a 70% renewable production at a carbon tax of \$55 / metric ton of CO₂. This is in the upper range of starting values in the proposal chart, which acts as a good sanity check for the model. Additionally, there appeared to be some transmission capacity bottlenecking, especially as the transmission reached closer to New York City, such as between the upstate and downstate zones like EG, FG, and IJ. This could serve as evidence that transmission capacity is an important factor in deciding where new generation capacity is built and that it is likely that some of that load could be alleviated by investing in new transmission lines and implementing such in future models.

Cost Evaluation

The carbon tax was modeled linearly. The initial case with no carbon tax had a total cost of \$9.18 billion. This cost increased to \$10.6 billion with the \$55/metric ton carbon tax. This cost is a 15% increase which is significant since it would also cause the normalized cost to increase from \$57 to \$65 per megawatt. The iterative results are displayed in Figure 5 below.

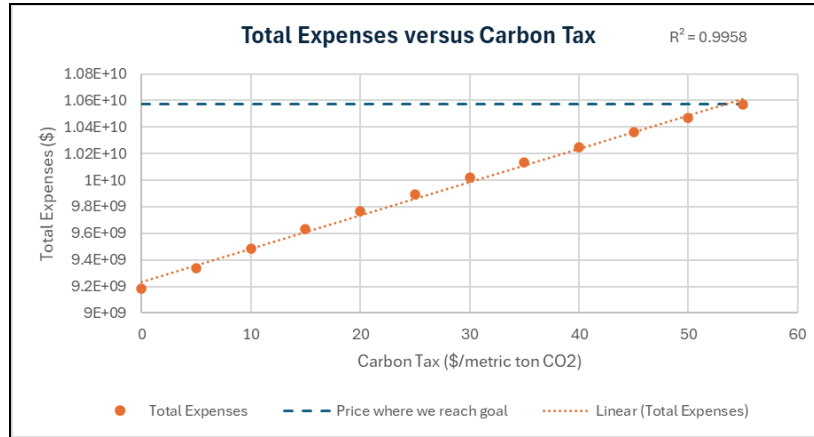


Figure 5 - Relationship between carbon tax value and total cost of energy generation

Additionally, the consumer price was modeled using the dual of the model's power balance constraint multiplied by the fixed demand as shown below:

```
let paid_price := sum{z in ZONES, t in TIMES} demand_constraint[z,t]*fixed_demand[z,t]; (6)
```

The result showed that adding a carbon tax of \$55/metric ton shifted the total paid price for energy by consumers from \$10.8 billion to \$12.8 billion which is a 2 billion dollar increase. There are 19.8 million New Yorkers served by NYISO (EPSA). If it is assumed that these are the only consumers paying for electricity, it could be said that the price per person would increase by over 100 dollars. While this is an extremely rough generalization, it puts into perspective the massive effect that this carbon tax could have on consumers.

Sensitivity Analysis

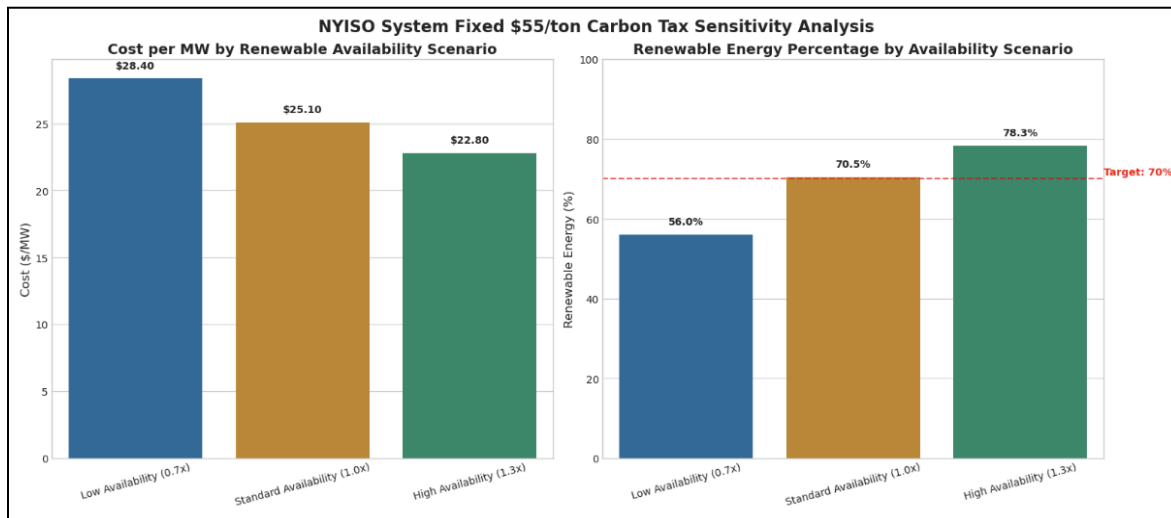


Figure 6 - Cost of energy generation (left) and percentage of renewables in the resource mix (right) based on renewable availability, using a fixed carbon tax value

In this analysis, the base availability profiles for wind and solar were modified by applying a homogeneous scaling factor uniformly across all times and zones. A 30% increase (denoted by 1.3x in Figure 6) represents a highly favorable renewable resource year, while a 30% decrease (denoted by 0.7x in Figure 6) simulates conditions where renewable output is notably diminished. This method preserves the inherent seasonal trends while allowing for a controlled investigation of how such variations affect the achievement of the 70% renewable target. The results indicate that at a carbon tax of \$55/ton, the baseline scenario meets the policy goal; however, in the case of low renewable availability, renewables account for only about 56% of the total supply. In contrast, high availability conditions can exceed the 70% benchmark, emphasizing the sensitivity of the model outputs to renewable resource fluctuations.

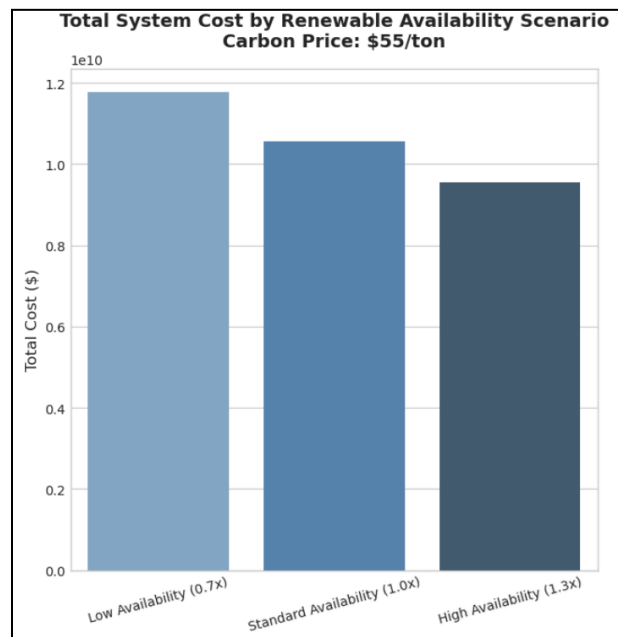


Figure 7 - Total energy generation system cost based on renewable availability, using a fixed carbon tax value

Furthermore, across all scenarios, increased availability for renewables consistently resulted in lower total energy generation costs, a reduction of \$2 billion from worst-case to best-case (Shown in Figure 7), and reduced cost per megawatt. This economic trend underscores the dual environmental and financial benefits of expanding renewable capacity. Importantly, regardless of the 30% variation implemented, the modeled energy system maintained a balanced supply without any surpluses or deficits across zones and time periods, affirming the robustness of the capacity expansion model under a range of operational conditions.

These findings raise critical policy considerations for New York State as it determines the appropriate carbon tax level. A key question emerges: should the state design its policy to achieve robust performance under worst-case availability scenarios or target an outcome that works on average? That decision is inevitably up to the state to decide, but is great fuel for

thought experiments. For example, if the state opts to account for the worst-case scenario with the carbon tax as its sole instrument for adjusting the energy mix, our analysis indicates that a tax of \$120/ton would be required to prevent renewable output from dipping below the 70% target. A 118% increase from the \$55/tonne tax set forth in this analysis. Under these conditions, the total cost per megawatt would be \$27.36, and countless impacts on the investor and energy landscape. This thought experiment not only highlights the sensitivity of renewable penetration to availability but also underscores the important connection between policy design and investor confidence. Ultimately, the sensitivity analysis demonstrates that relying solely on one regulatory mechanism makes the energy mix vulnerable to the inherent uncertainties in renewable production, suggesting that a more diversified set of incentives may be necessary to consistently achieve New York's renewable energy goals.

Conclusion/Discussion:

Our analysis demonstrates that implementing a carbon tax can be an effective lever to shift New York State's energy mix toward a higher share of renewables. In the base case, a tax of \$55 per metric ton brings renewable production up to the targeted 70%, albeit at an increased total cost from \$9.18 billion to \$10.6 billion. This finding highlights the important trade-off between environmental goals and energy costs. Moreover, the sensitivity analysis reveals that renewable availability plays a pivotal role: favorable conditions further reduce the cost per megawatt, while adverse weather conditions necessitate a considerably higher tax—up to \$120 per metric ton—to prevent renewable production from falling below 70%. The model consistently maintained energy balance across zones and time periods despite these variations, underscoring the robustness of the system design.

This study also raises critical policy considerations. Relying solely on a carbon tax to recalibrate the energy mix exposes the system to risks from weather-related uncertainties and local constraints on renewable expansion. While the tax is an effective economic signal to drive investment in renewables, its success is highly contingent on external factors that can fluctuate from year to year. Hence, it is essential for policymakers to consider complementing carbon penalties with additional incentives—such as support for expanded transmission infrastructure, targeted subsidies for renewable installations in urban areas, and battery storage solutions—to build a more resilient and diversified portfolio of interventions. This multi-pronged approach, or one similar, would help mitigate the risks associated with weather variability and other operational uncertainties.

Looking forward, future research should aim to integrate longer-term economic trends, such as inflation and multi-year weather patterns, to refine these policy tools. Incorporating potential expansions in transmission capacity and developing approaches to model urban-specific constraints will provide a more granular understanding of the challenges and opportunities in reaching New York State's renewable targets. Furthermore, exploring the combined effects of other relevant policies—such as tariffs or direct subsidies—will offer valuable insights into how

comprehensive policy frameworks can better align investor confidence with environmental objectives.

Thus, our findings not only affirm the potential of carbon taxation to significantly alter the energy mix but also emphasize the need for a balanced policy strategy. By combining carbon penalties with other supportive measures and continually refining our models to include broader operational and market uncertainties, decision-makers can more effectively navigate the complexities of energy policy in an era of rapid technological and environmental change.

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