Supporting Information for:

Power System Decarbonization: A Comparison Between Carbon Taxes and Forcing Coal Power Plant Retirements

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I. Supplementary 8760-hour Simulation

In addition to the simulation with four representative hours in a year, we performed an additional simulation over all hours (i.e., 8760 hours) in a year for 11 years to explore the impacts of renewable intermittency on capacity expansion and system reliability.

The hourly load profile was created using 2013 PJM load data [1] and was scaled to vary between 450 and 850 MW, which is approximately the same range as used in the four-hour model. Since wind and solar power are the major renewable resources in the U.S., we constructed the renewable capacity factor using wind and solar data obtained from the EIA database [2]. We collected wind and solar capacities, along with hourly generation data for the year 2021 in the U.S. lower 48 states. The hourly renewable capacity factors are calculated by dividing the total wind and solar generation by total wind and solar capacities. The resulting hourly capacity factors range from approximately 10% to 60%, with a mean of 30%. Both the load profile and renewable capacity factors are provided in [3].

Following any retirement, renewable capacity is added so that its expected generation (physical capacity times yearly average capacity factor) matches the retired capacity. The renewables are then dispatched with its $P^{\max}$ set as the product of the renewable capacity and the hourly capacity factor.

II. Results and Discussion

Fig. 1 illustrates the yearly emissions, generation, and regulation capacity of each generator type under carbon taxes. It shows that the 8760-hour simulation yields similar yearly changes as observed in the 4-hour simulation. For example, all three carbon taxes lead to retirements in year 0 and subsequent years, whereas no retirements occur until year 5 in the no-policy scenario. Fig. 2 shows the yearly system emissions and costs in carbon tax scenarios. Table I summarizes the total and average emissions and costs. Again, these results show that the emissions paths resulting from the 8760-hour simulation are similar to those in the 4-hour simulation. Notably, the 8760-hour simulation also shows that higher carbon taxes do not always lead to lower emissions. Additionally, the system operation costs and carbon tax payments decrease rapidly as fossil-fuel generators retire.

The hourly variability in renewable generation does not significantly impact the overall results and conclusions qualitatively because the 4-hour model is able to capture the average changes in dispatch and profits, which ultimately lead to similar retirement sequences. However, the 8760-hour simulation also shows that our renewable expansion method could potentially result in load curtailment in certain hours due to renewable intermittency. The load curtailment is higher with increasing renewable capacities, with the highest observed curtailment being 1.8% of total load in a year. Furthermore, Table II shows that there are no retirements in certain years after the first retirement(s) in the carbon tax scenarios (e.g., in years 7 to 10 in \$50/ton and \$100/ton). This is because the remaining generators gain more profit as they are needed to provide more energy when the renewable power production is low. This effect could be amplified by higher renewable penetrations and increased energy prices resulting from high carbon taxes.

References

[1] PJM, "Data miner 2: Hourly load." [Online]. Available: https://dataminer2.pjm.com/feed/hrl_load_metered/definition

[2] U.S. Energy Information Administration, "U.S. electricity generation by energy source." [Online]. Available: https://www.eia.gov/electricity/gridmonitor/dashboard/electric_overview/US48/US48

[3] J. Peng, "PSdecarbonization," 2023. [Online]. Available: https://github.com/JPengUMich/PSdecarbonization

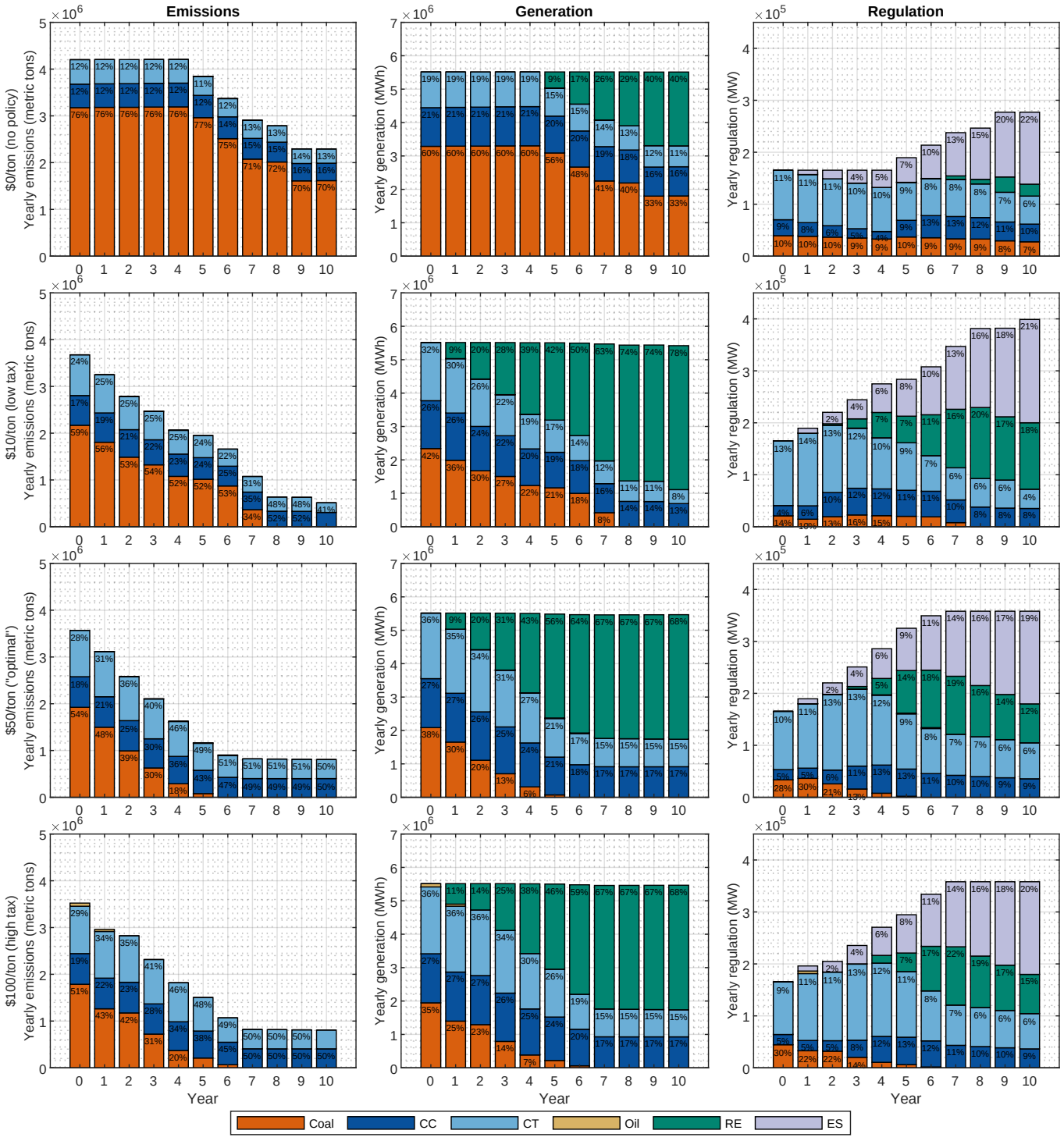

Fig. 1. Yearly system emissions, generation, and regulation capacity from each type of generator under carbon taxes in 8760-hours/year simulation.

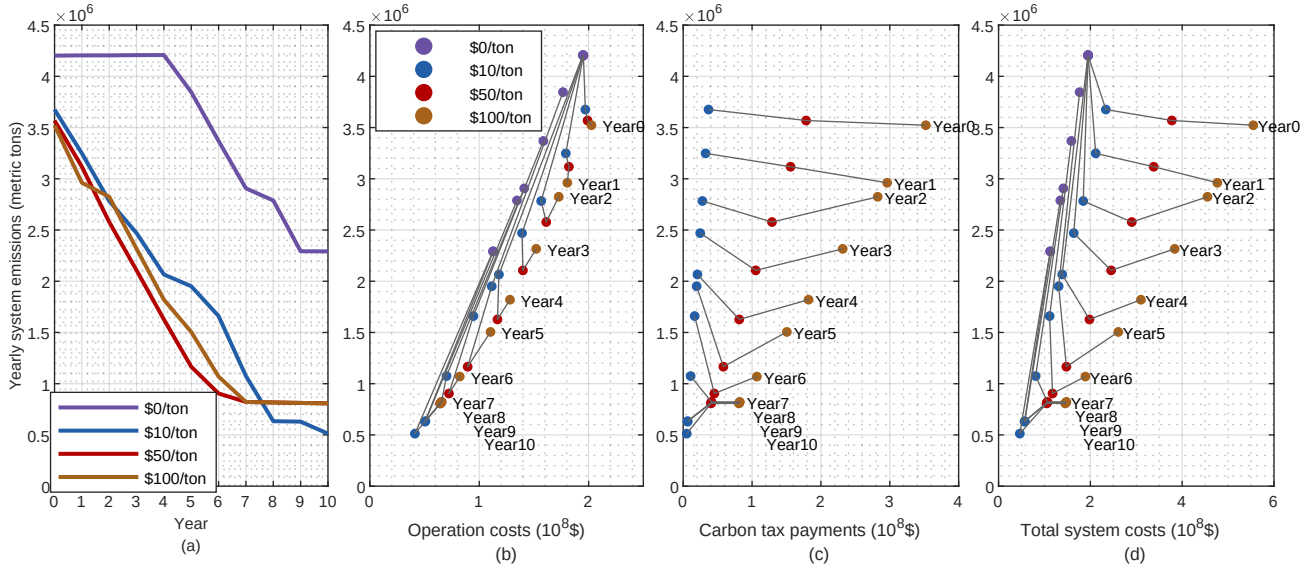

Fig. 2. Yearly system emissions (a) per year, (b) per operation costs, (c) per carbon tax payments, and (d) per total system costs under carbon taxes in 8760-hours/year simulation.

TABLE I
CUMULATIVE (AVERAGE YEARLY) COSTS, PAYMENTS, AND EMISSIONS, ALONG WITH EMISSIONS AT THE END OF YEAR 10, UNDER CARBON TAXES IN 8760-HOURS/YEAR SIMULATION

	System operation costs	Carbon tax payments	System emissions	Emissions at end of year 10
	10^8 $		10^6 metric ton	
$0/ton	18.11 (1.65)	0.00 (0.00)	38.52 (3.50)	2.29
$10/ton	12.02 (1.10)	2.07 (0.19)	20.71 (1.88)	0.51
$50/ton	12.20 (1.11)	9.16 (0.83)	18.33 (1.67)	0.81
$100/ton	12.88 (1.17)	19.28 (1.75)	19.28 (1.75)	0.81

TABLE II
SEQUENCE OF GENERATOR RETIREMENTS UNDER EACH CARBON TAX SCENARIO IN 8760-HOURS/YEAR SIMULATION

Year	0	1	2	3	4	5	6	7	8	9	10
$0/ton					CT6	Coal1	Coal2	Oil	Coal3		CT4
$10/ton	Coal2	Coal3	Coal1	Coal4	Oil	CT6	Coal6	Coal5		CT5	CT4
$50/ton	Coal2	Coal3	Coal4	Coal5	Coal6	Coal1	Oil				
$100/ton	Coal3	Oil	Coal4	Coal5	Coal1	Coal6	Coal2				