Modeling the Contribution of Offshore Wind to the Grid Mix and Air Quality Implications: National Approach Results and Analysis

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09 December, 2019

Contents

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1 Scenarios

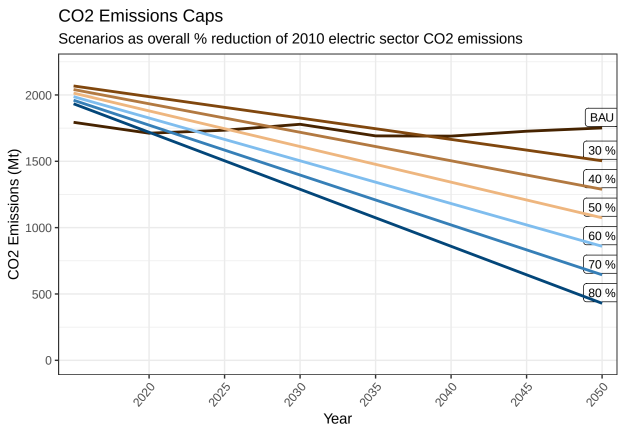
The nested parametric sensitivity analysis was built on combinations of two sets of scenarios:

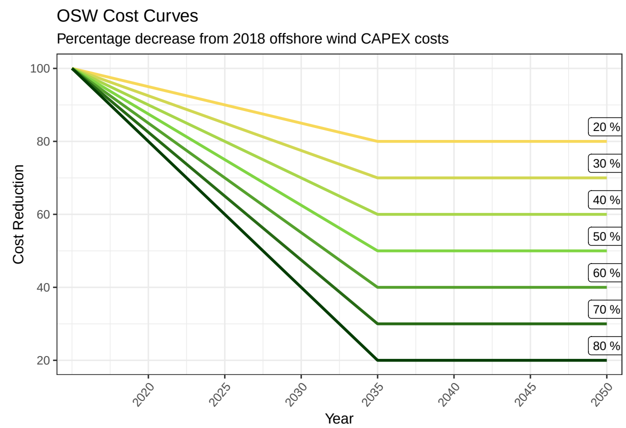
1. Electric sector CO_2 emissions caps, as a linear decrease to a given % decrease from 2010 emissions by 2050

- Business and usual emissions represent approximately a 20% reduction in CO_2 emissions

2. Cost reductions of offshore wind, as a linear decrease to a given % decrease from 2010 costs by 2035, then level costs to 2050

- A 20% cost reduction is used as the base case, assuming very conservative technological advancement and little benefit of economies of scale
- Cost curves are set to resolve by 2035 as estimated based on NREL LCOE cost projections for offshore wind





2 LCOE

EIA's AEO 2019 provides the following values for the estimated levelized cost of electricity (capacity-weighted average) for new generation resources entering service in 2023 (2018 $/MWh). Offshore wind has the highest total LCOE by a large margin. The second most expensive technology is biomass. The AEO LCOE was used in the calculation of offshore wind costs for the above cost curves, but LCOE is not directly used in the model.

Table 1: Estimated LCOE capacity-weighted average for new generation resources entering service in 2023 (2018 $/MWh)

Plant Type	Capacity Factor (%)	Levelized capital cost	Levelized fixed O&M	Levelized variable O&M	Levelized trans-mission cost	Total system LCOE	Levelized tax credit	Total LCOE including tax credit
Dispatchable technologies								
Conventional CC	87	8.1	1.5	32.3	0.9	42.8	NA	42.8
Advanced CC	87	7.1	1.4	30.7	1.0	40.2	NA	40.2
Advanced CT	30	17.2	2.7	54.6	3.0	77.5	NA	77.5
Geothermal	90	24.6	13.3	0.0	1.4	39.4	-2.5	36.9
Biomass	83	37.3	15.7	37.5	1.5	92.1	NA	92.1
Non-dispatchable technologies								
Wind, onshore	44	27.8	12.6	0.0	2.4	42.8	-6.1	36.6
Wind, offshore	45	95.5	20.4	0.0	2.1	117.9	-11.5	106.5
Solar PV	29	37.1	8.8	0.0	2.9	48.8	-11.5	37.6
Hydroelectric	75	29.9	6.2	1.4	1.6	39.1	NA	39.1

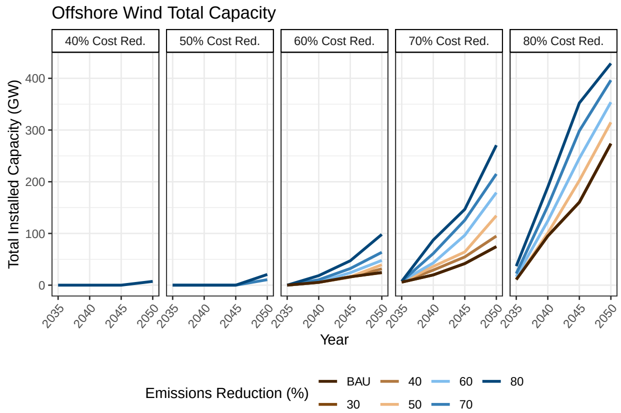
Note:
U.S. EIA Annual Energy Outlook 2019

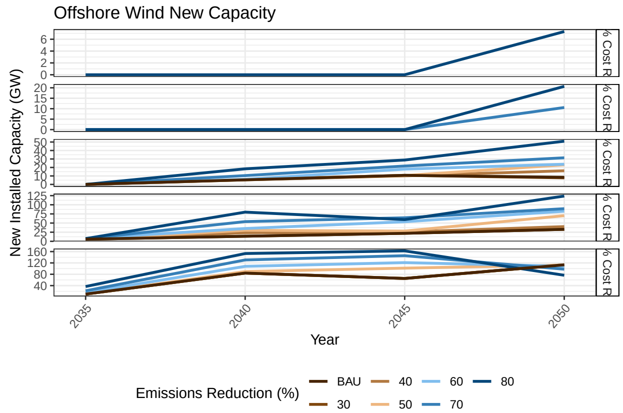
3 Offshore Wind

As offshore wind is the primary technology being assessed in this research, we have explored many facets of offshore wind buildout. These facets are explored below, both at a regional and national cumulative level.

3.1 Capacity Buildout

Cumulative and new addition offshore wind capacity across all nine census regions, by cost and emissions reduction scenario.





3.2 Total Capacity

Total offshore wind capacity across all nine census regions in 2050, by cost and emissions reduction scenario.

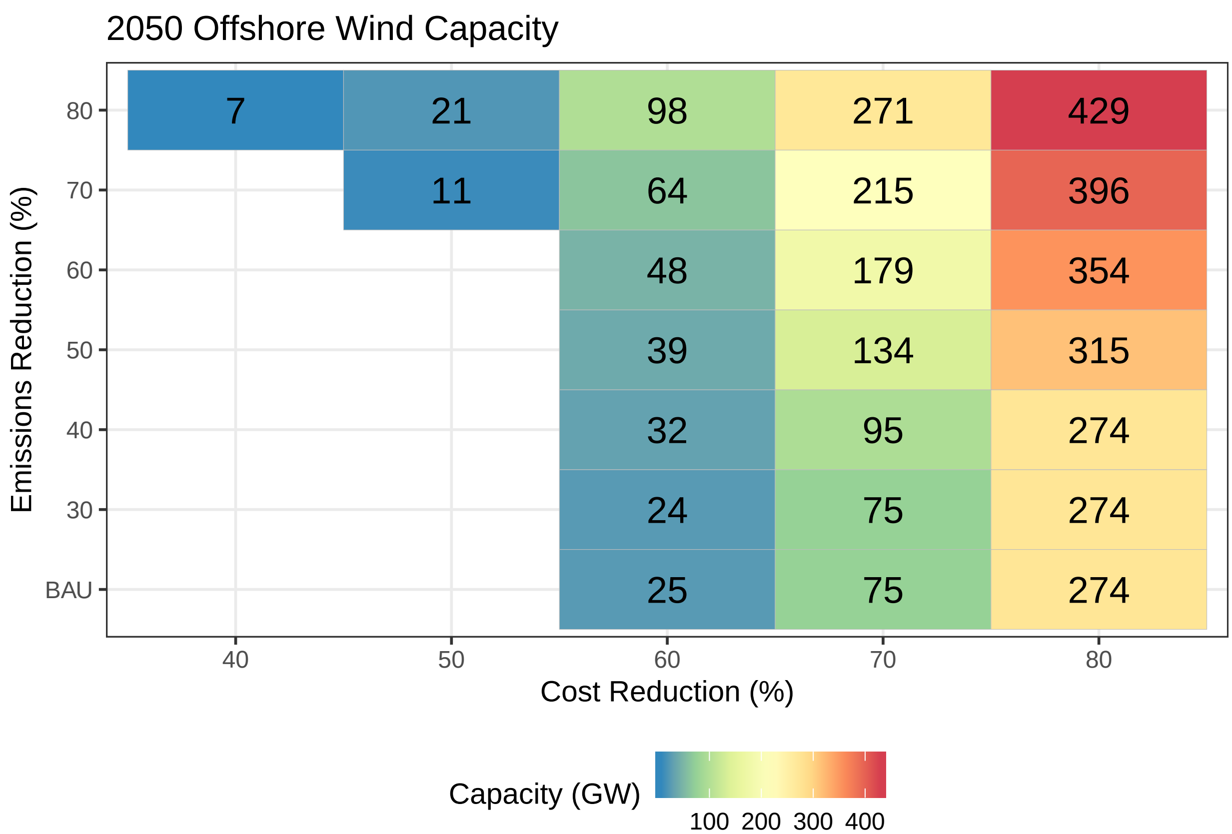


Table 2: Offshore Wind Total Installed Capacity (GW): 2050

CO2 Emissions Reduction (%)	Cost Reduction (%)				
	40	50	60	70	80
BAU	-	-	25	75	274
30	-	-	24	75	274
40	-	-	32	95	274
50	-	-	39	134	315
60	-	-	48	179	354
70	-	11	64	215	396
80	7	21	98	271	429

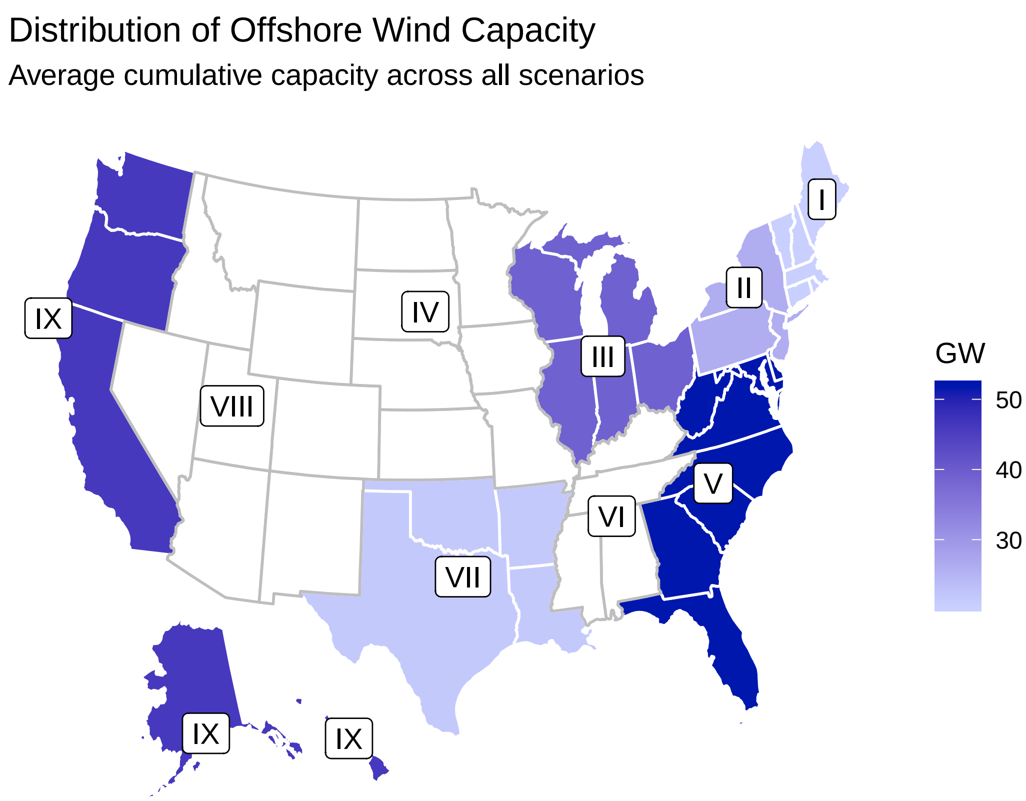
3.3 Regions

Cumulative and new addition offshore wind capacity by region, emissions reduction, and cost reduction.

Table 3: Average Installed Capacity (GW)

Region	2050 Total
R1	20.6
R7	21.7
R2	26.2
R3	39.1
R9	46.1
R5	51.8

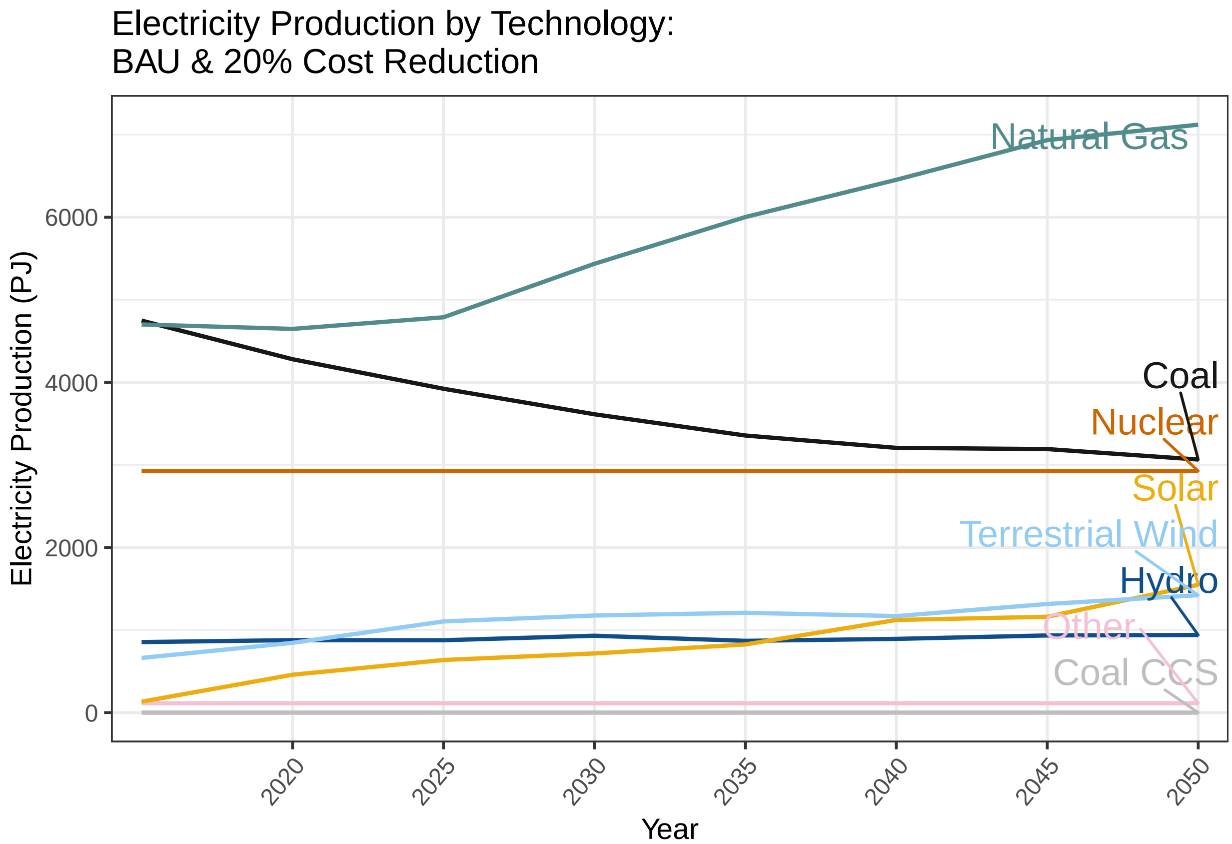
Note:
Average is across all scenarios

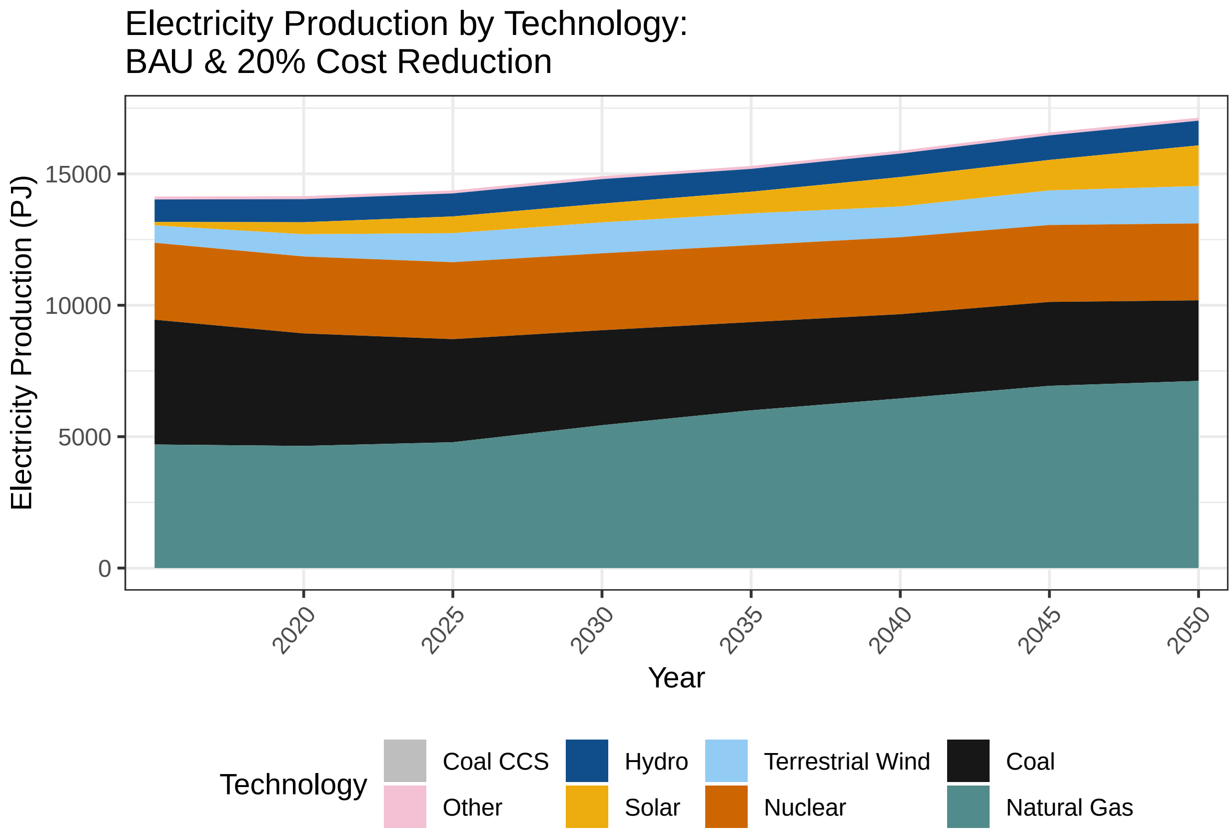


4 Grid Mix

4.1 Baseline Production

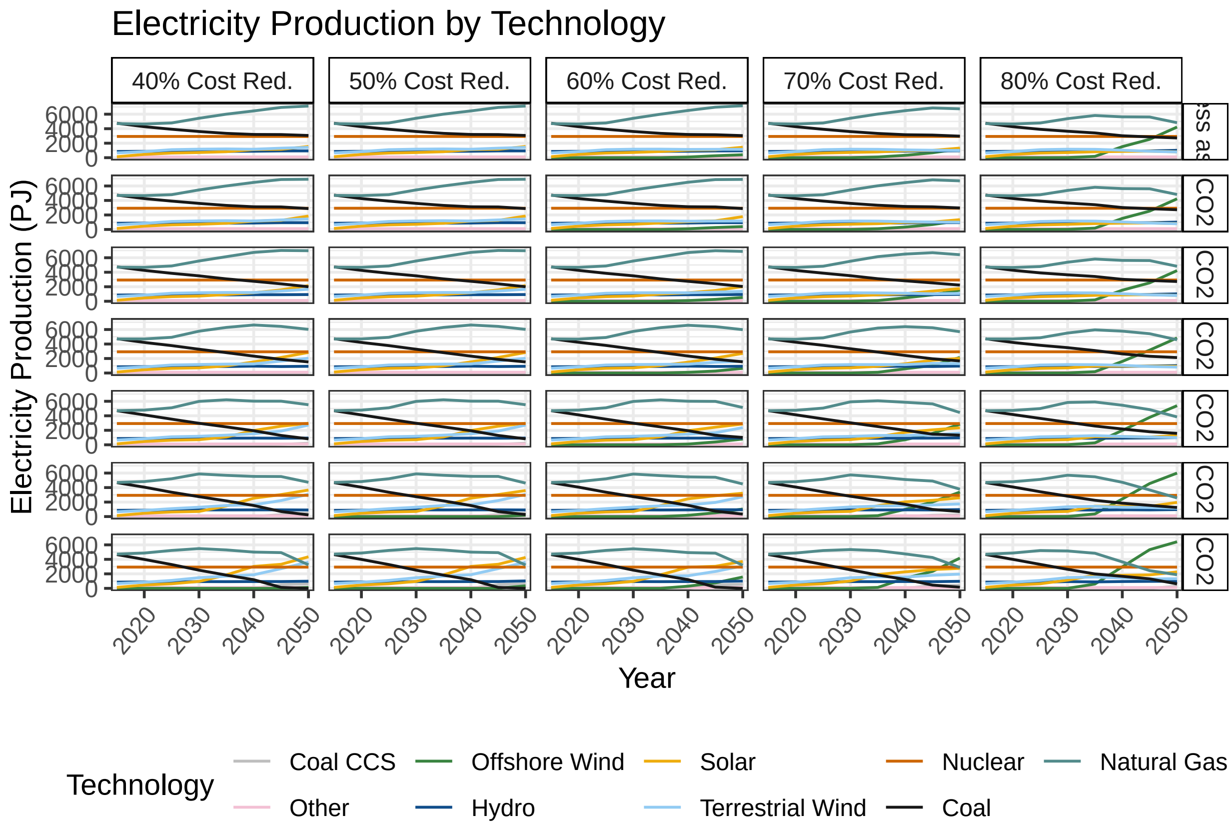
Grid mix without any offshore wind cost reduction or emissions cap.


Electricity Production by Technology:
BAU & 20% Cost Reduction
Natural Gas
Coal
Nuclear
Solar
Terrestrial Wind
Hydro
Other
Coal CCS
Electricity Production (PJ)
6000
4000
2000
0
2020
2025
2030
2035
2040
2045
2050
Year



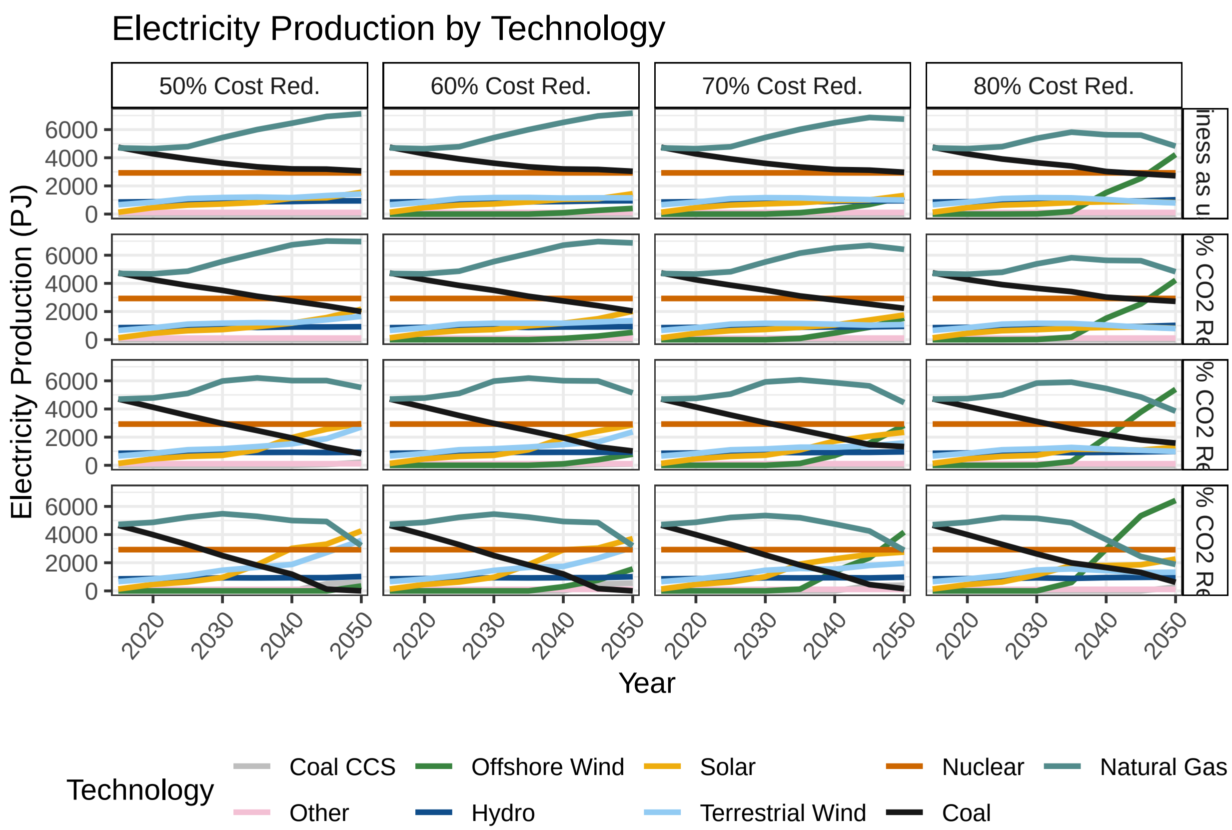
4.2 All Scenarios

Complete Set

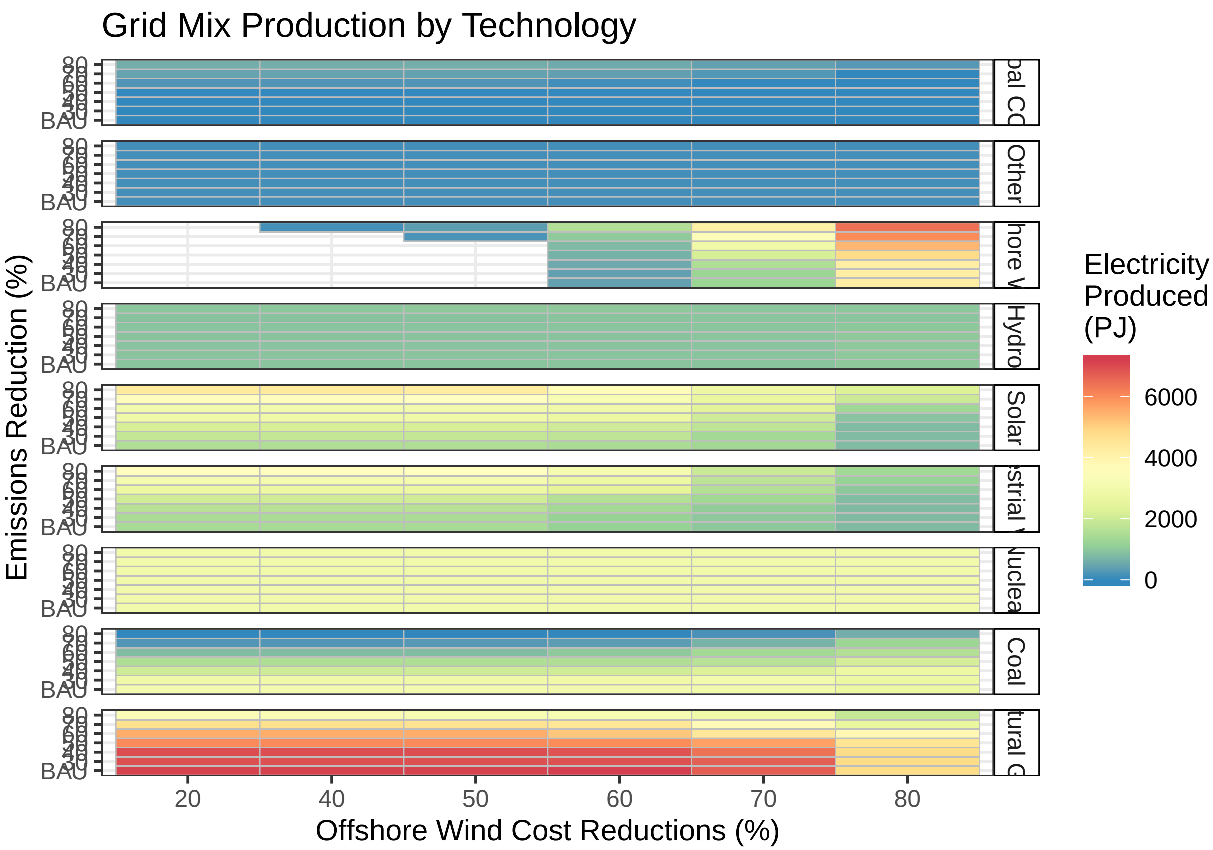


Electricity Production by Technology
40% Cost Red.
50% Cost Red.
60% Cost Red.
70% Cost Red.
80% Cost Red.
Electricity Production (PJ)
6000
4000
2000
0
CO2
2020
2030
2040
2050
Year
Technology
Coal CCS
Other
Offshore Wind
Hydro
Solar
Terrestrial Wind
Nuclear
Coal
Natural Gas

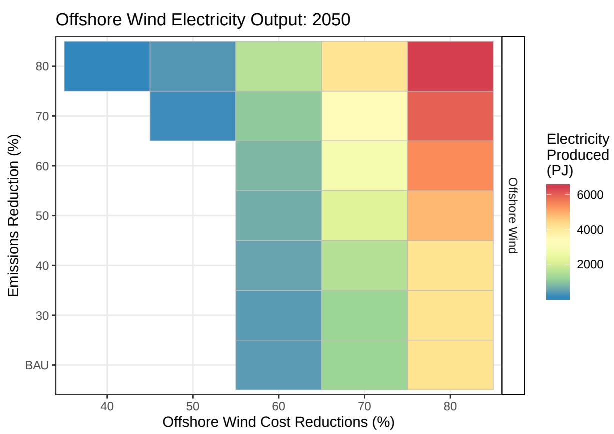
Parsed Set


Electricity Production by Technology
50% Cost Red.
60% Cost Red.
70% Cost Red.
80% Cost Red.
iness as u
% CO2 Re
% CO2 Re
% CO2 Re
Electricity Production (PJ)
6000
4000
2000
0
2020
2030
2040
2050
Year
Technology
Coal CCS
Offshore Wind
Solar
Nuclear
Natural Gas
Other
Hydro
Terrestrial Wind
Coal

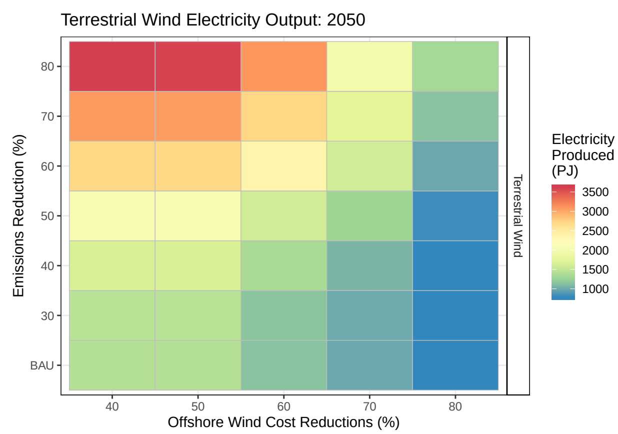
4.3 Heatmaps



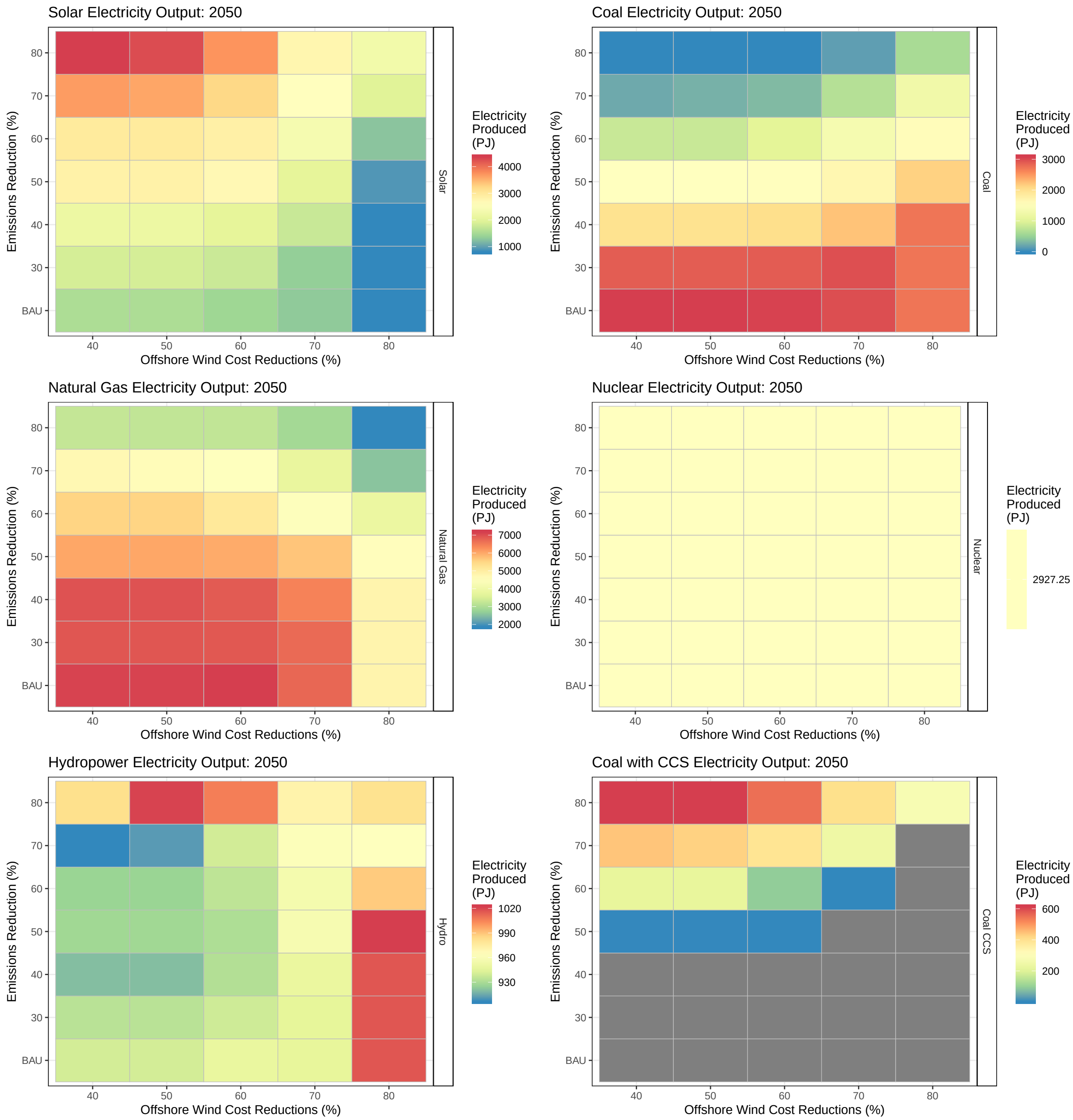
Grid Mix Production by Technology
Emissions Reduction (%)
Offshore Wind Cost Reductions (%)
20
40
50
60
70
80
Other
Hydro
Solar
Coal
Electricity Produced (PJ)
6000
4000
2000
0

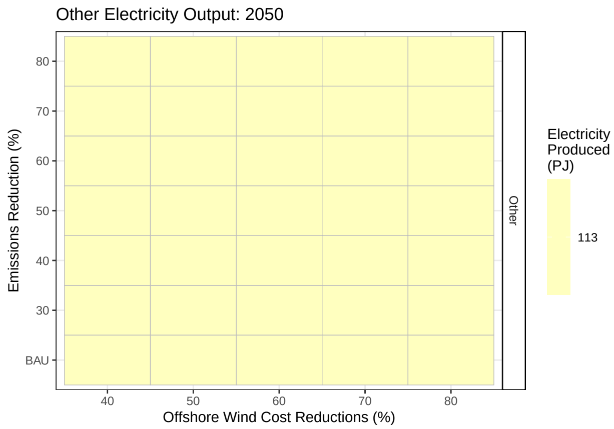


Offshore Wind Electricity Output: 2050
Emissions Reduction (%)
80
70
60
50
40
30
BAU
40
50
60
70
80
Offshore Wind Cost Reductions (%)
Offshore Wind
Electricity Produced (PJ)
6000
4000
2000



Terrestrial Wind Electricity Output: 2050
Emissions Reduction (%)
80
70
60
50
40
30
BAU
40
50
60
70
80
Offshore Wind Cost Reductions (%)
Terrestrial Wind
Electricity Produced (PJ)
3500
3000
2500
2000
1500
1000


Solar Electricity Output: 2050
Emissions Reduction (%)
80
70
60
50
40
30
BAU
40
50
60
70
80
Offshore Wind Cost Reductions (%)
Solar
Electricity Produced (PJ)
4000
3000
2000
1000
Coal Electricity Output: 2050
Coal
3000
2000
1000
0
Natural Gas Electricity Output: 2050
Natural Gas
7000
6000
5000
4000
3000
2000
Nuclear Electricity Output: 2050
Nuclear
2927.25
Hydropower Electricity Output: 2050
Hydro
1020
990
960
930
Coal with CCS Electricity Output: 2050
Coal CCS
600
400
200

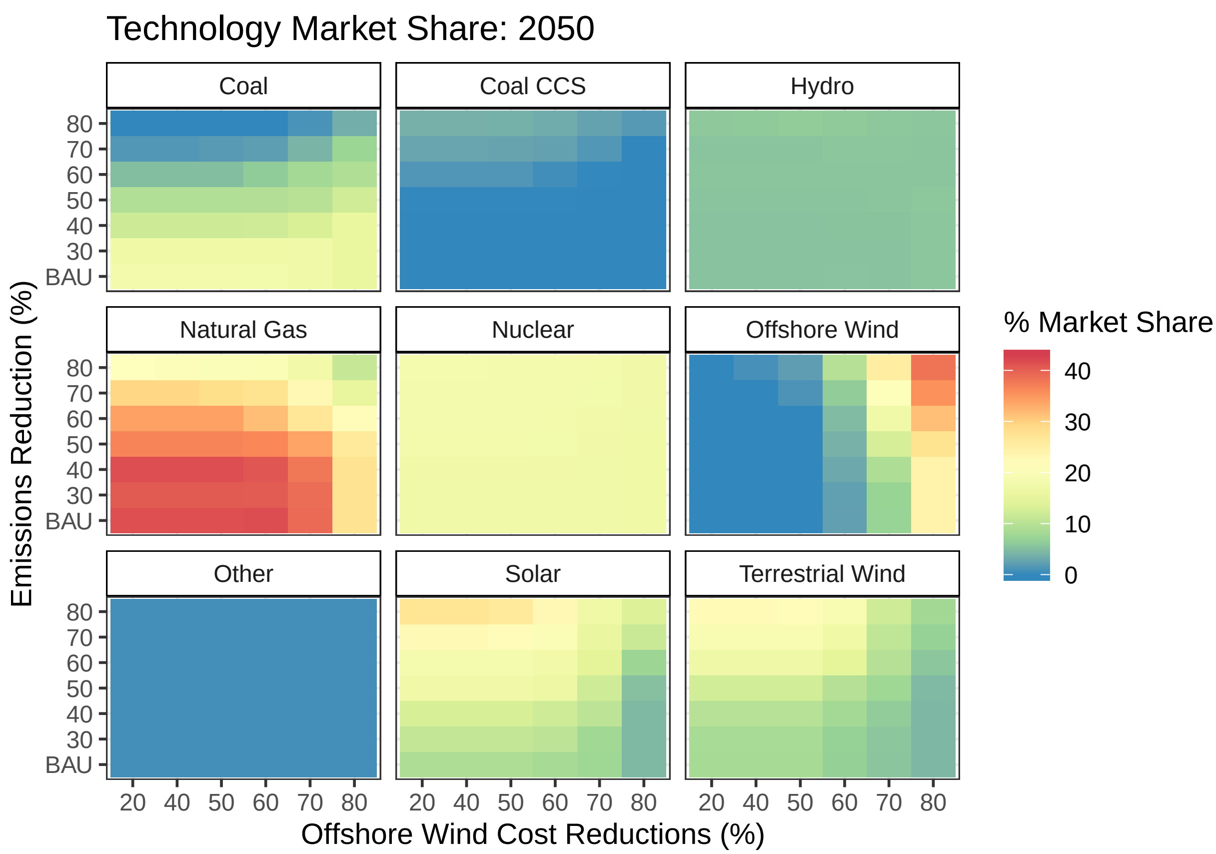


4.4 Market Share

Table 4: 2050 Percent Market Share by Technology

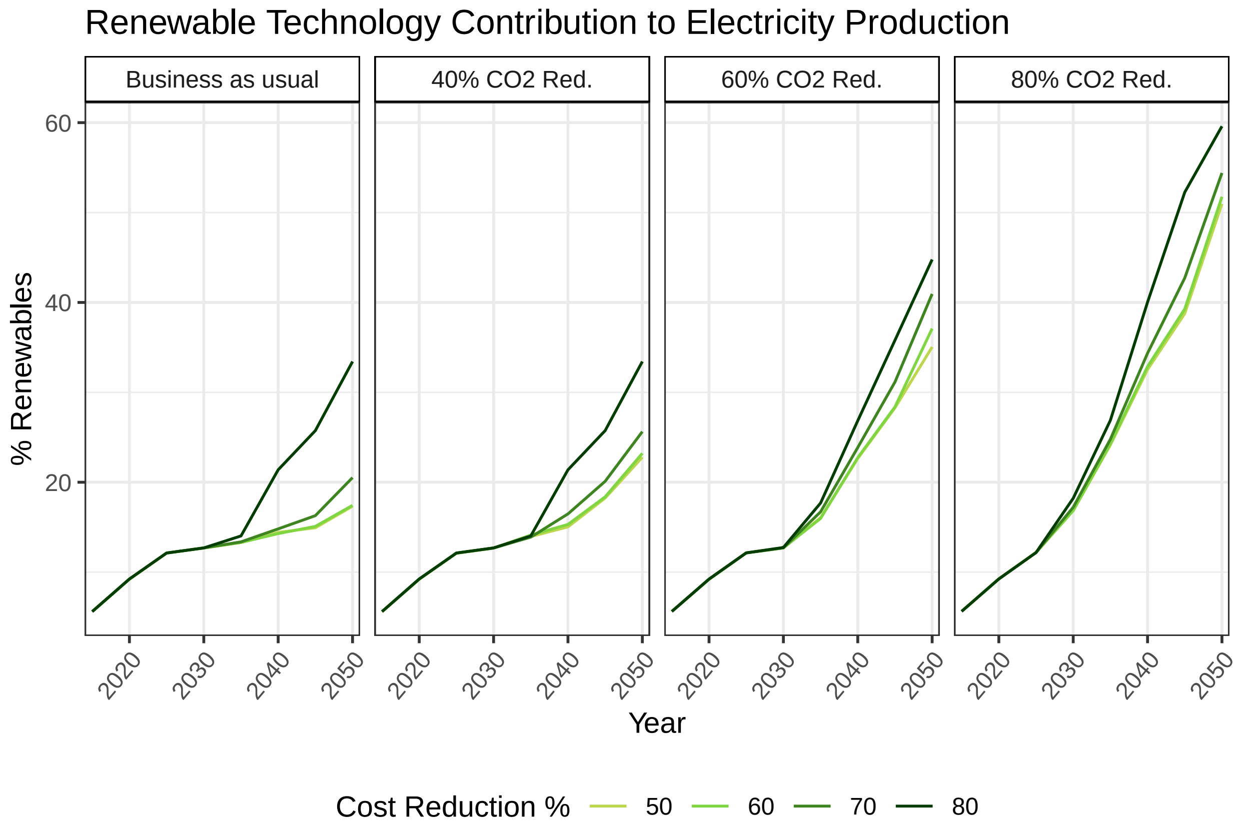
		Cost Reduction (%)					
Technology	CO2 Cap	20	40	50	60	70	80
Coal	BAU	17.9	17.9	17.9	17.7	17.2	15.6
	30	16.9	16.9	16.9	16.9	17.2	15.6
	40	11.9	11.9	11.9	12.1	13.1	15.6
	50	9.3	9.3	9.3	9.4	9.9	12.3
	60	5.1	5.1	5.1	6.2	8.0	9.2
	70	1.4	1.4	1.7	2.1	4.2	7.4
	80	0.0	0.0	0.0	0.0	0.9	3.6
Coal CCS	BAU	0.0	0.0	0.0	0.0	0.0	0.0
	30	0.0	0.0	0.0	0.0	0.0	0.0
	40	0.0	0.0	0.0	0.0	0.0	0.0
	50	0.0	0.0	0.0	0.0	0.0	0.0
	60	1.3	1.3	1.3	0.6	0.0	0.0
	70	2.8	2.8	2.6	2.4	1.5	0.0
	80	3.8	3.8	3.8	3.4	2.5	1.6
Hydro	BAU	5.5	5.5	5.5	5.5	5.5	5.8
	30	5.5	5.5	5.5	5.5	5.5	5.8
	40	5.5	5.5	5.5	5.5	5.6	5.8
	50	5.7	5.7	5.7	5.7	5.7	5.9
	60	5.7	5.7	5.7	5.8	5.8	5.8
	70	5.6	5.6	5.7	5.8	5.9	5.7
	80	6.1	6.2	6.3	6.2	5.9	5.8
Natural Gas	BAU	41.5	41.5	41.5	41.7	39.1	27.7
	30	40.5	40.5	40.5	40.4	38.9	27.7
	40	41.6	41.6	41.6	41.0	37.8	27.7
	50	36.7	36.7	36.7	36.4	33.9	26.4
	60	34.1	34.1	34.1	31.6	26.9	22.5
	70	29.4	29.4	28.7	27.8	23.0	15.2
	80	21.1	20.3	20.0	19.8	17.6	11.2
	BAU	17.1	17.1	17.1	17.0	17.0	16.8
	30	17.1	17.1	17.1	17.1	17.0	16.8
	40	17.5	17.5	17.5	17.4	17.2	16.8

Nuclear	50	17.9	17.9	17.9	17.8	17.4	16.9
	60	18.1	18.1	18.1	18.0	17.7	17.1
	70	18.2	18.2	18.2	18.1	17.8	17.3
	80	18.3	18.3	18.2	18.1	17.9	17.4
Offshore Wind	BAU	0.0	0.0	0.0	2.3	7.1	24.2
	30	0.0	0.0	0.0	2.3	7.1	24.2
	40	0.0	0.0	0.0	3.1	9.0	24.2
	50	0.0	0.0	0.0	4.0	12.8	27.9
	60	0.0	0.0	0.0	4.8	17.1	31.5
	70	0.0	0.0	1.1	6.4	20.6	35.4
	80	0.0	0.8	2.1	9.7	25.5	38.2
Other	BAU	0.7	0.7	0.7	0.6	0.6	0.6
	30	0.7	0.7	0.7	0.7	0.6	0.6
	40	0.7	0.7	0.7	0.7	0.7	0.6
	50	0.7	0.7	0.7	0.7	0.7	0.6
	60	0.7	0.7	0.7	0.7	0.7	0.7
	70	0.7	0.7	0.7	0.7	0.7	0.7
	80	0.7	0.7	0.7	0.7	0.7	0.7
Solar	BAU	9.0	9.0	9.0	8.4	7.7	4.7
	30	10.8	10.8	10.8	10.3	7.8	4.7
	40	12.9	12.9	12.9	12.0	10.3	4.7
	50	17.3	17.3	17.3	16.5	12.0	5.3
	60	18.3	18.3	18.3	17.6	14.2	7.5
	70	22.8	22.8	22.3	19.9	15.8	11.6
	80	27.3	27.3	26.5	23.0	16.9	13.5
Terrestrial Wind	BAU	8.3	8.3	8.3	6.7	5.8	4.5
	30	8.5	8.5	8.5	6.8	5.8	4.5
	40	9.9	9.9	9.9	8.1	6.3	4.5
	50	12.4	12.4	12.4	9.7	7.7	4.7
	60	16.8	16.8	16.8	14.6	9.6	5.8
	70	19.1	19.1	19.0	16.9	10.6	6.8
	80	22.6	22.6	22.3	19.1	12.0	7.9



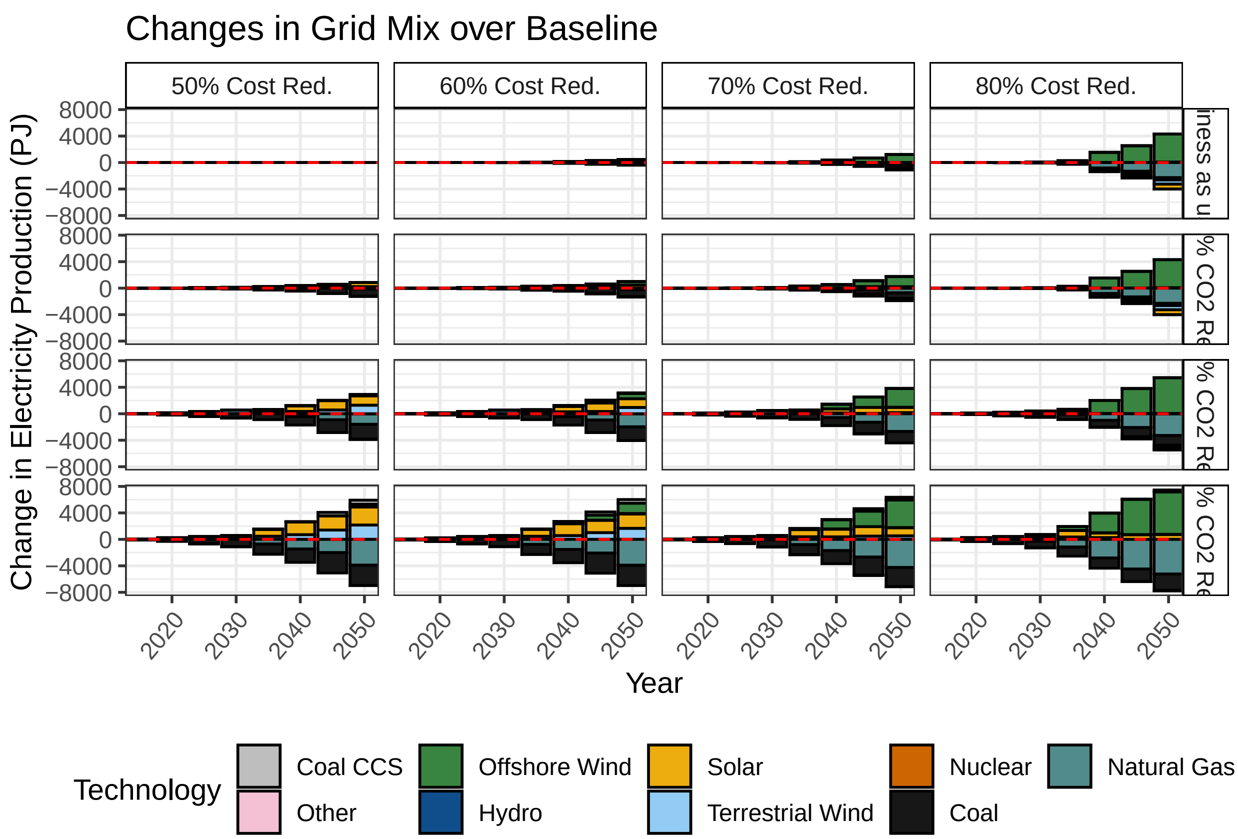
Technology Market Share: 2050
Coal
Coal CCS
Hydro
Natural Gas
Nuclear
Offshore Wind
Other
Solar
Terrestrial Wind
80
70
60
50
40
30
BAU
Emissions Reduction (%)
20 40 50 60 70 80
Offshore Wind Cost Reductions (%)
% Market Share
40
30
20
10
0

4.5 Renewable Contributions



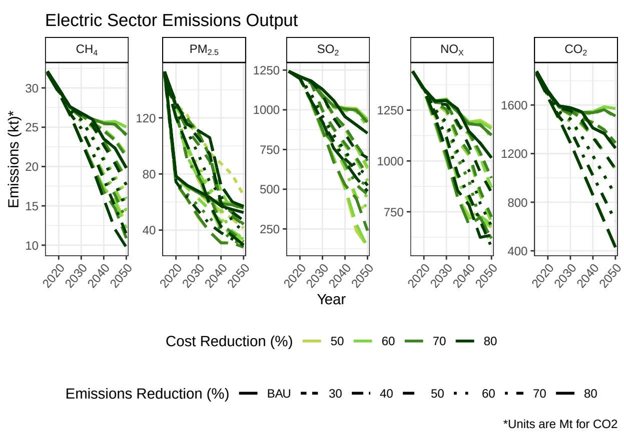
4.6 Retirements and Additions

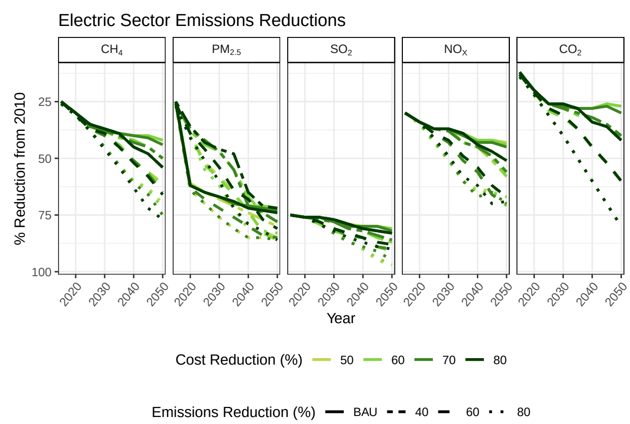
Summary Graph



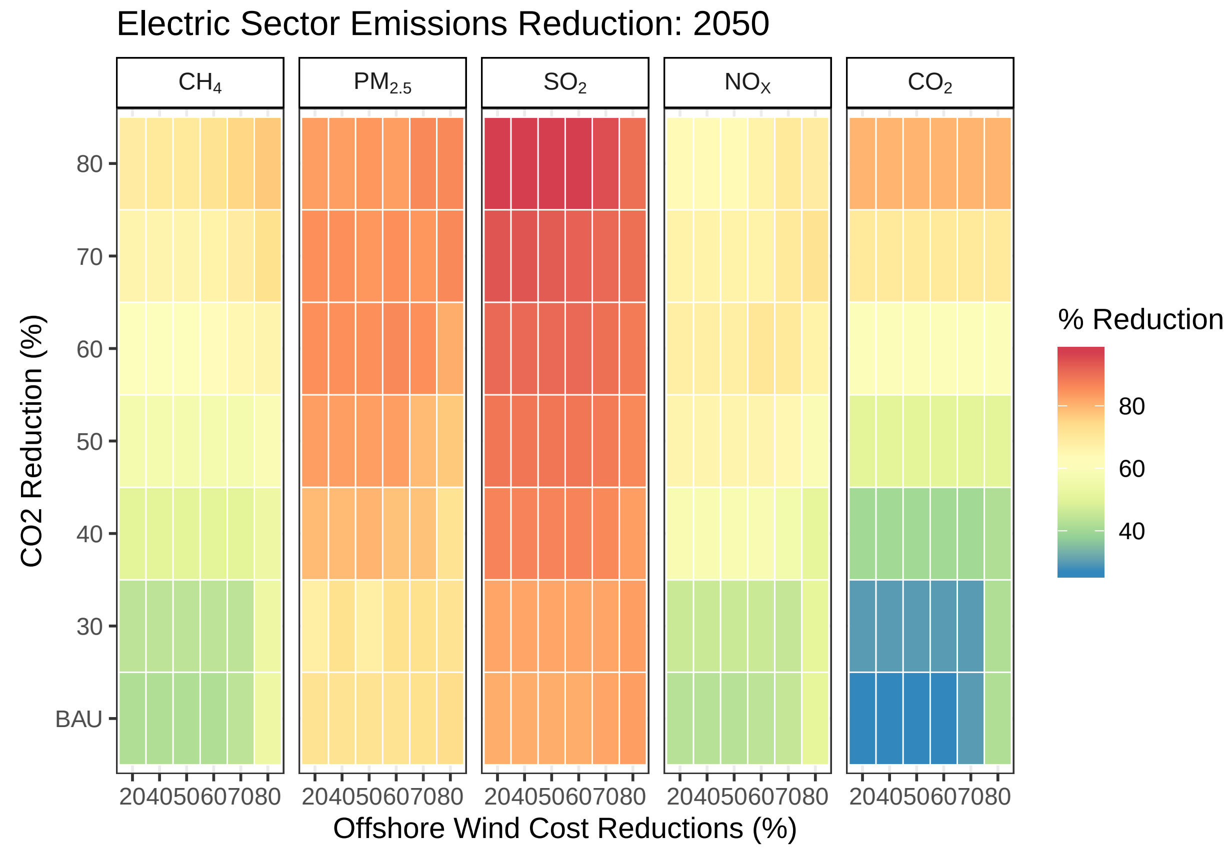
5 Emissions

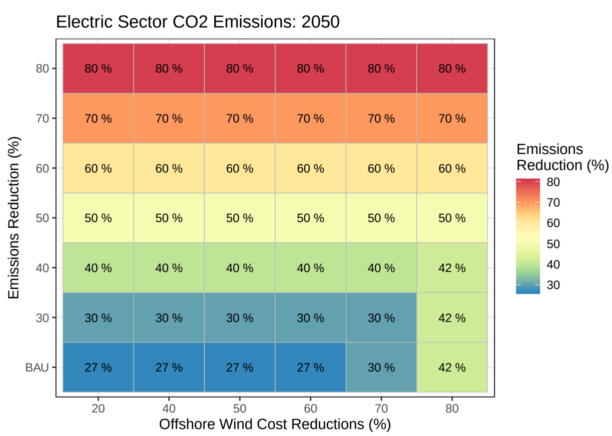
5.1 Emissions by Scenario and Commodity

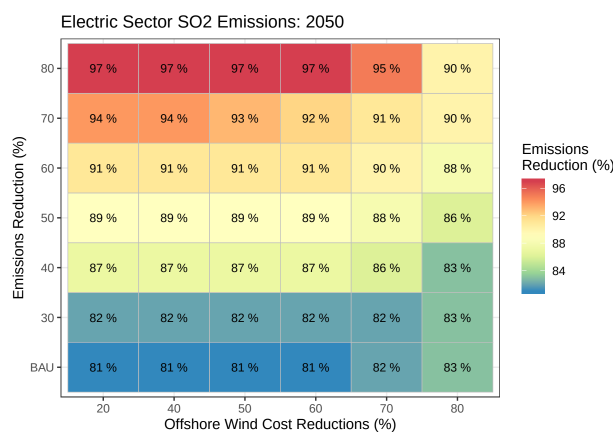


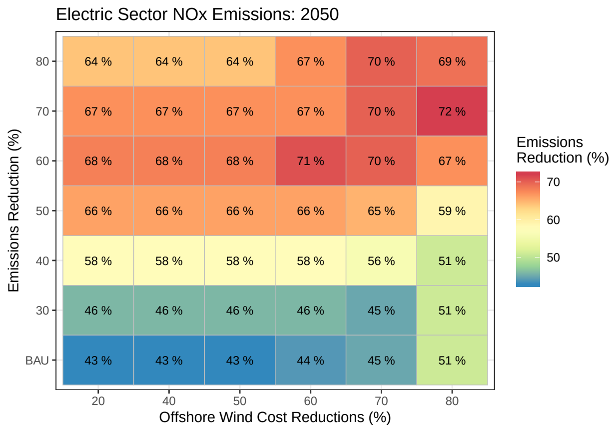


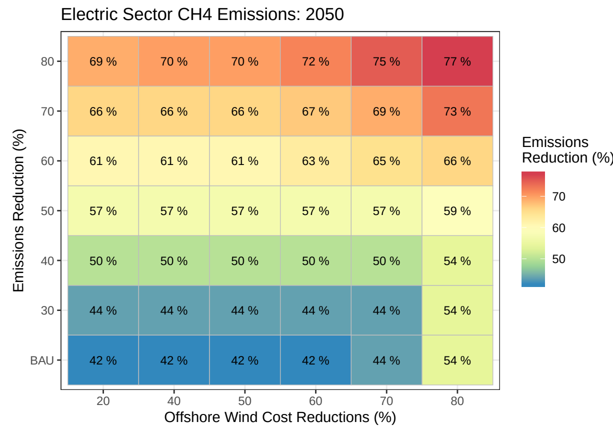
5.2 Emissions by Commodity - Percent Reduction

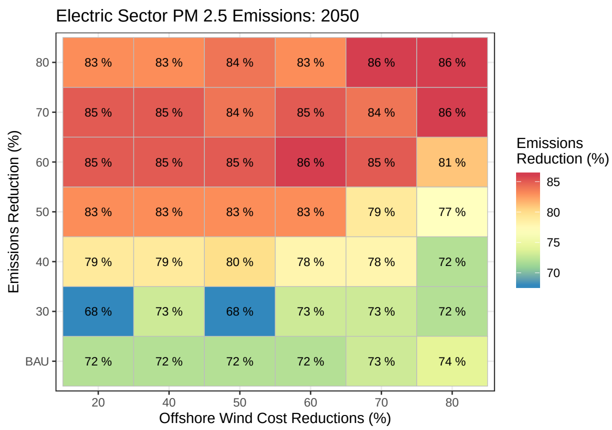




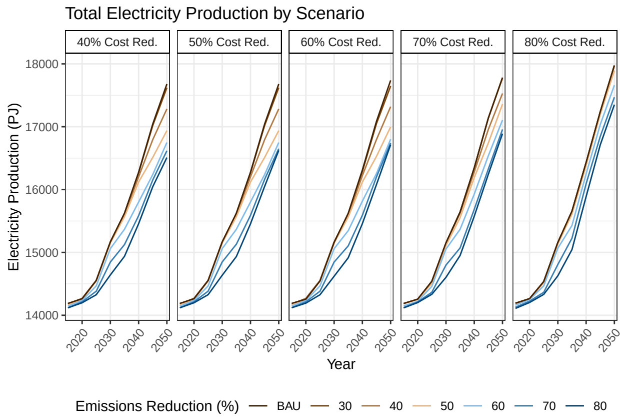


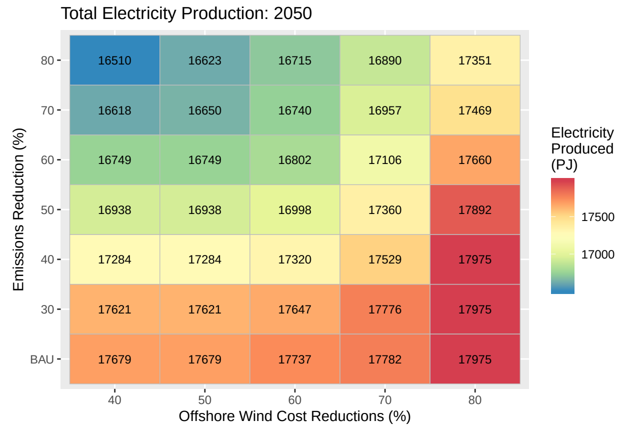




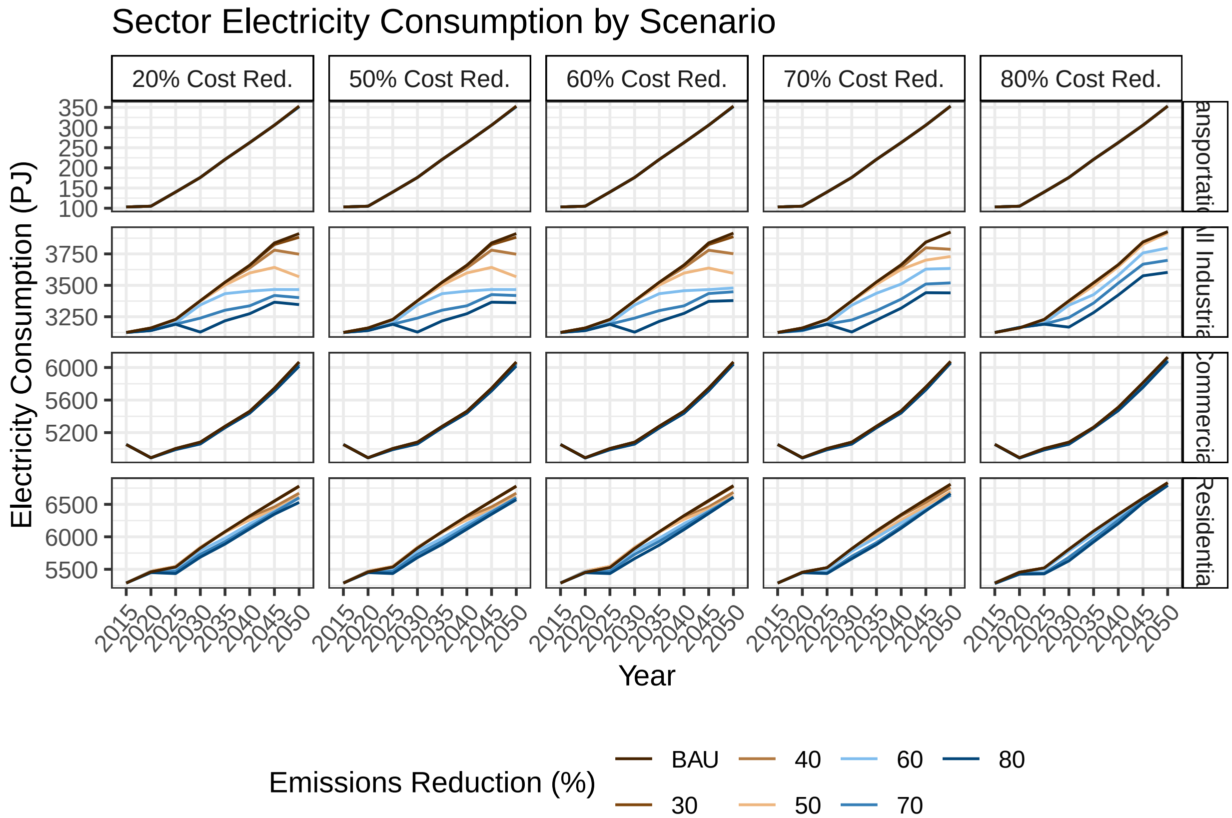


6 Total Electricity Production

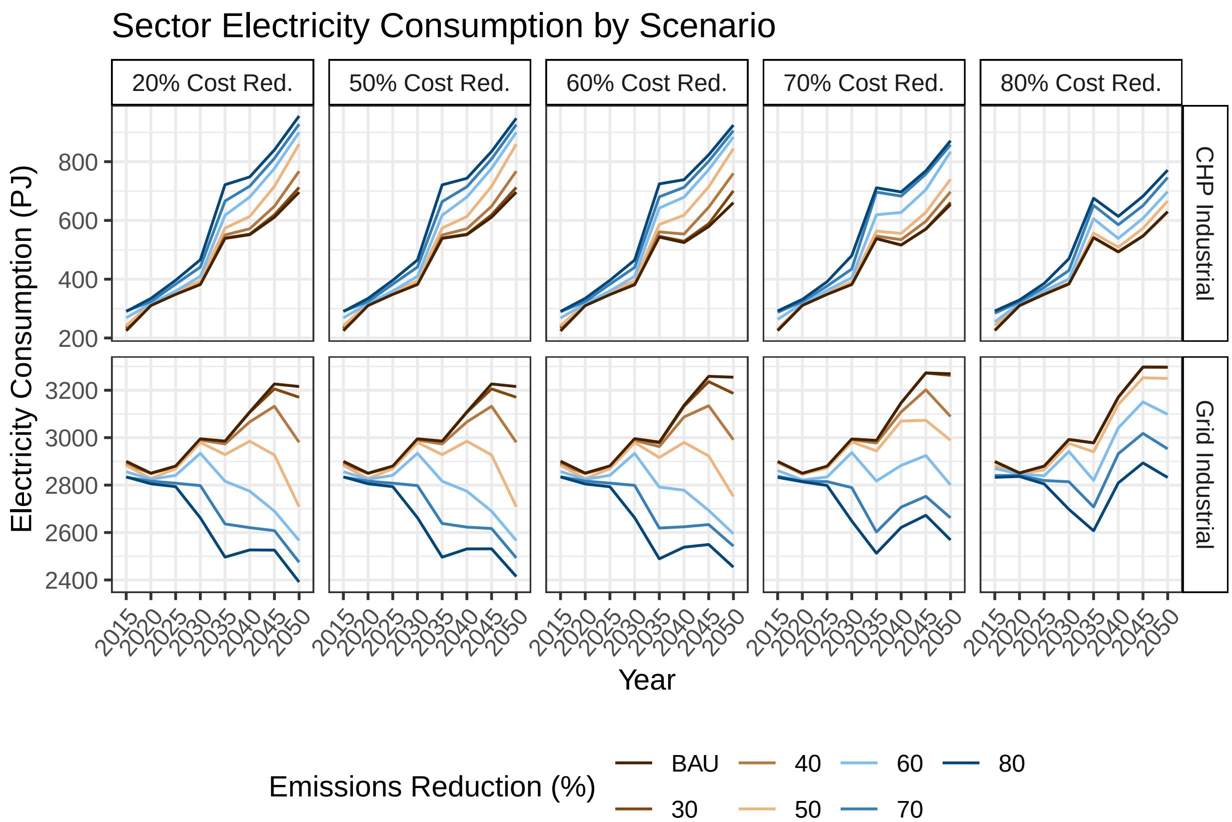




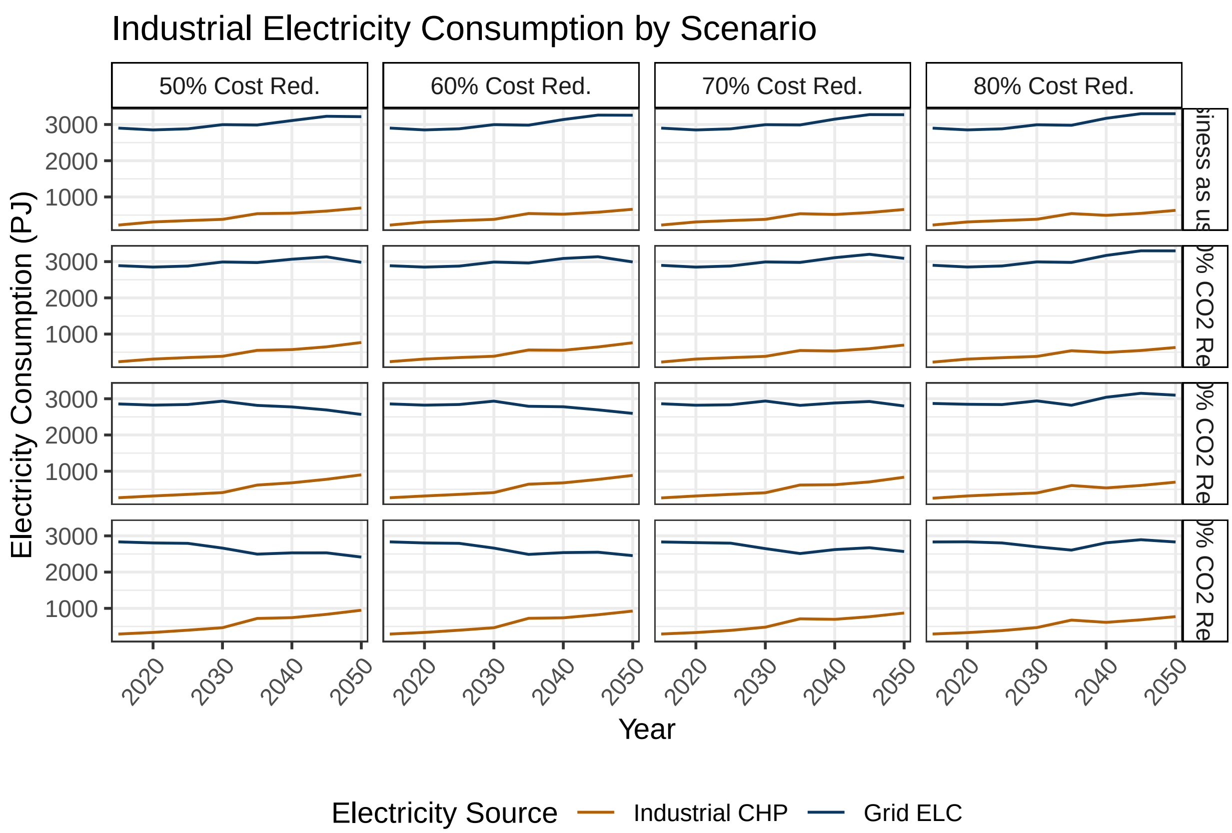
7 End Use ELC



Sector Electricity Consumption by Scenario
20% Cost Red.
50% Cost Red.
60% Cost Red.
70% Cost Red.
80% Cost Red.
Electricity Consumption (PJ)
Year
Emissions Reduction (%)
BAU
30
40
50
60
70
80

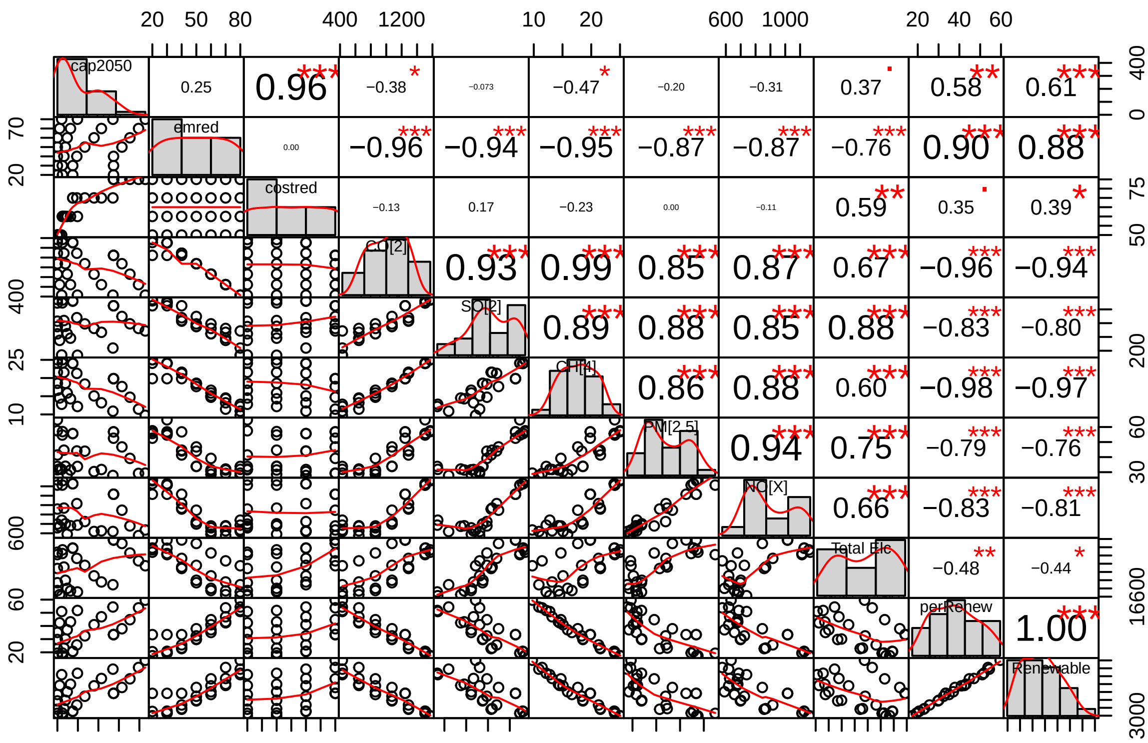


Sector Electricity Consumption by Scenario
20% Cost Red.
50% Cost Red.
60% Cost Red.
70% Cost Red.
80% Cost Red.
CHP Industrial
Grid Industrial
Electricity Consumption (PJ)
Year
Emissions Reduction (%)
BAU
30
40
50
60
70
80



Industrial Electricity Consumption by Scenario
50% Cost Red.
60% Cost Red.
70% Cost Red.
80% Cost Red.
3000
2000
1000
Electricity Consumption (PJ)
2020
2030
2040
2050
Year
Electricity Source
Industrial CHP
Grid ELC

8 Correlations



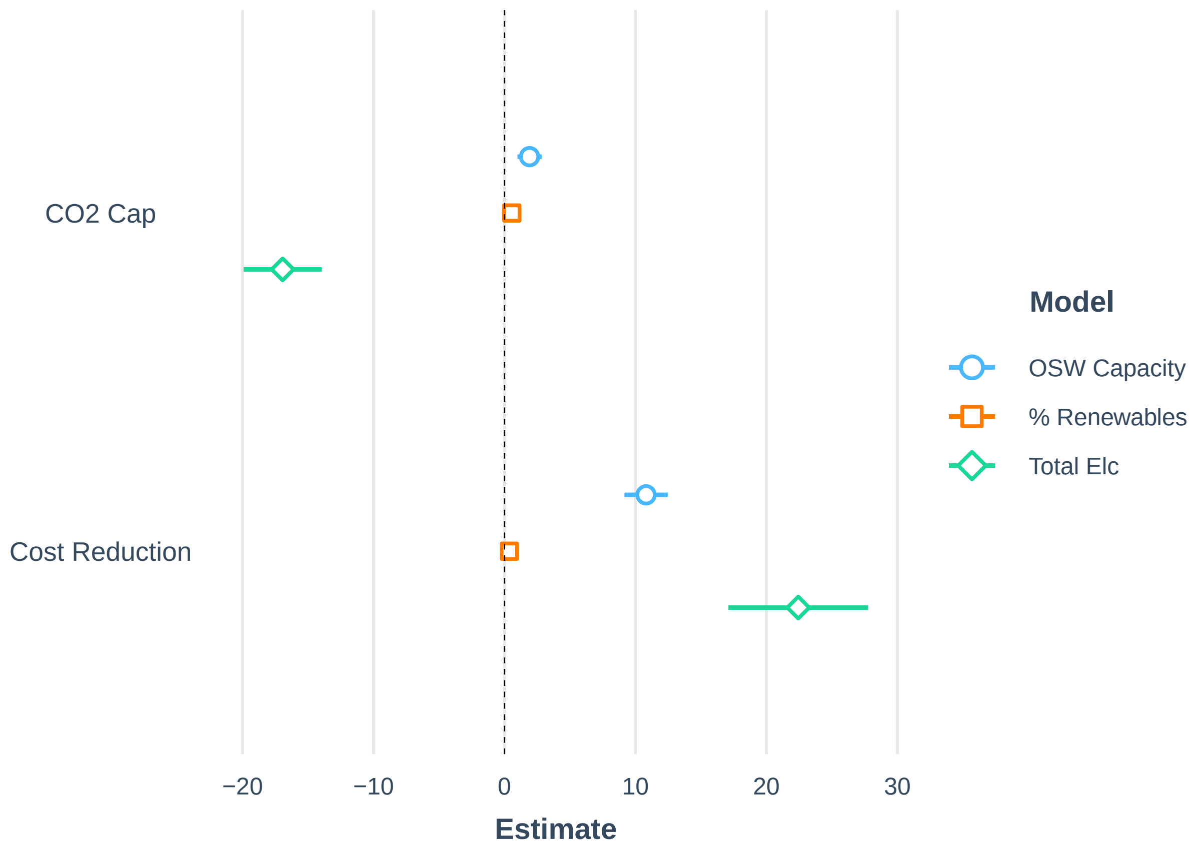
9 Regressions

9.1 Full set of models

OSW Capacity, % Renewables, and Total Elc Production Regressions

	OSW Capacity	% Renewables	Total Elc
CO2 Cap	1.91 ***	0.56 ***	-16.94 ***
	(0.45)	(0.03)	(1.45)
Cost Reduction	10.81 ***	0.37 ***	22.43 ***
	(0.80)	(0.06)	(2.59)
N	28	28	28
R2	0.89	0.93	0.89

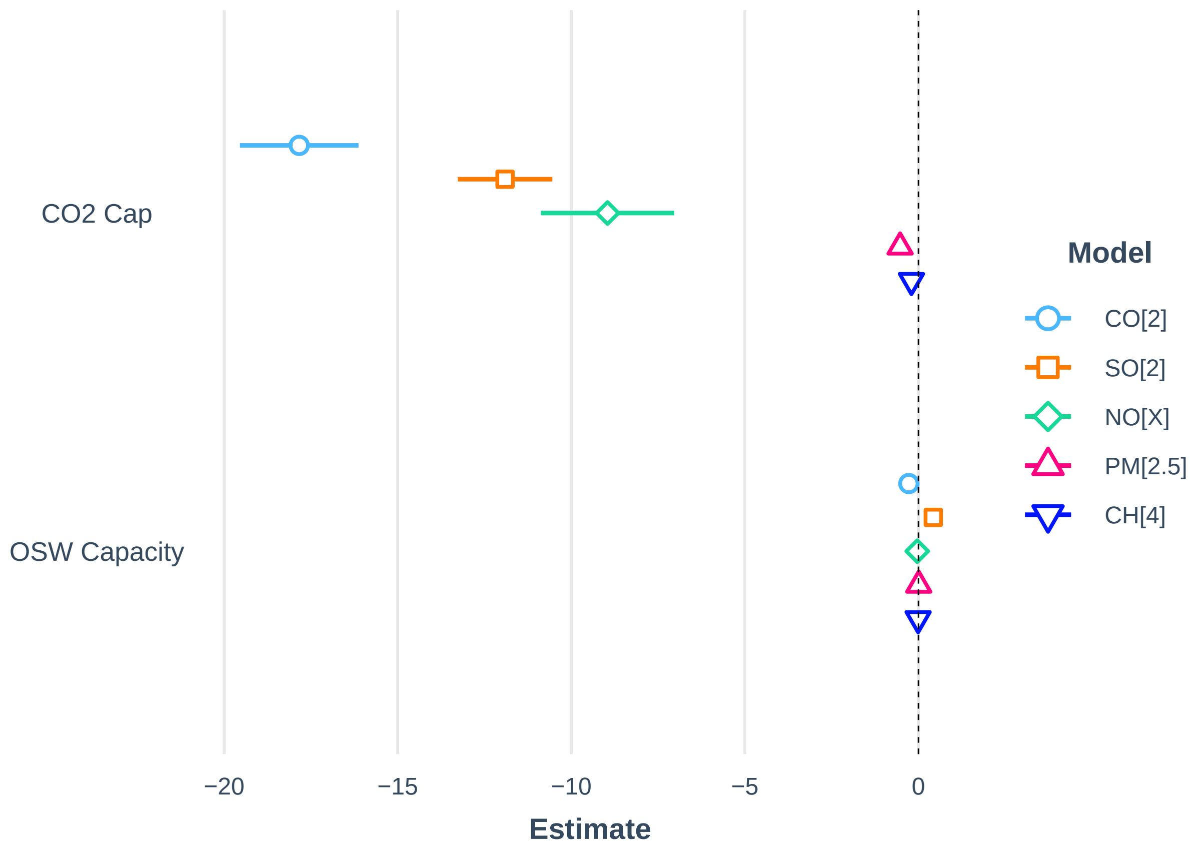
*** p < 0.001; ** p < 0.01; * p < 0.05.



Emissions Regressions

	CO[2]	SO[2]	NO[X]	PM[2.5]	CH[4]
CO2 Cap	-17.84 ***	-11.91 ***	-8.96 ***	-0.20 ***	-0.53 ***
	(0.83)	(0.66)	(0.93)	(0.01)	(0.05)
OSW Capacity	-0.28 *	0.43 ***	-0.03	-0.01 ***	0.01
	(0.12)	(0.10)	(0.14)	(0.00)	(0.01)
N	28	28	28	28	28
R2	0.96	0.93	0.80	0.96	0.80

*** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$.

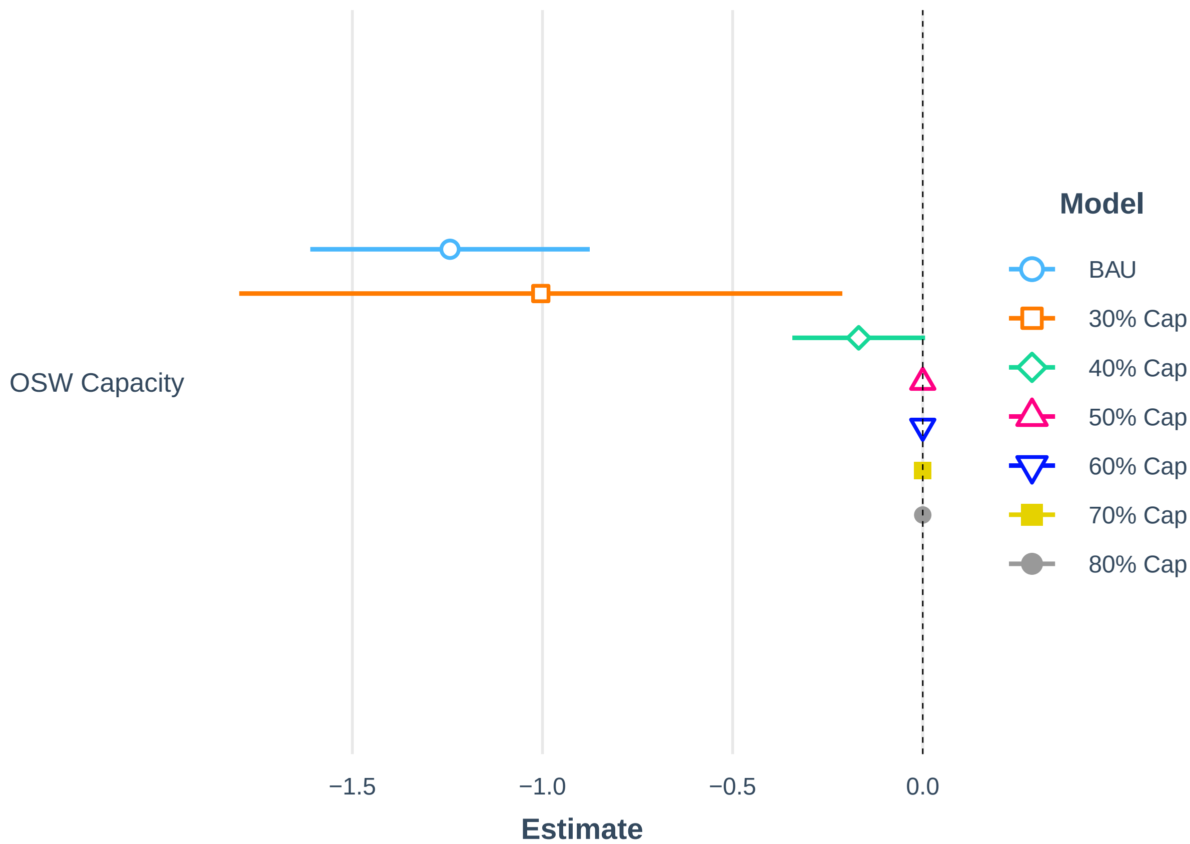


9.2 Emission-specific regressions by CO2 cap scenario

CO2

	BAU	30% Cap	40% Cap	50% Cap	60% Cap	70% Cap	80% Cap
OSW Capacity	-1.24 **	-1.00 *	-0.17	0.00	-0.00	-0.00	-0.00
	(0.09)	(0.18)	(0.04)	(0.00)	(0.00)	(0.00)	(0.00)
N	4	4	4	4	4	4	4
R2	0.99	0.94	0.90	0.84	0.20	0.00	0.83

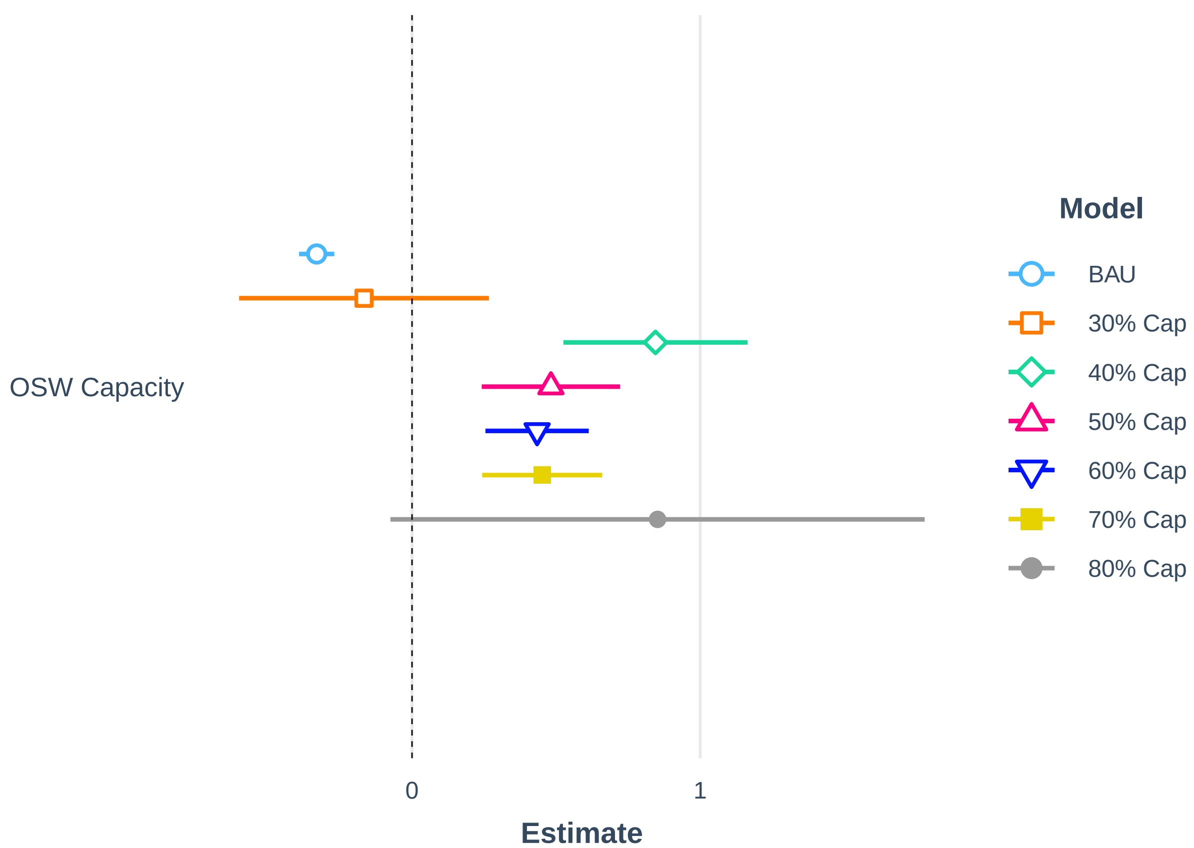
*** p < 0.001; ** p < 0.01; * p < 0.05.



SO2

	BAU	30% Cap	40% Cap	50% Cap	60% Cap	70% Cap	80% Cap
OSW Capacity	-0.33 **	-0.17	0.84 **	0.48 *	0.43 **	0.45 *	0.85
	(0.01)	(0.10)	(0.07)	(0.06)	(0.04)	(0.05)	(0.22)
N	4	4	4	4	4	4	4
R2	1.00	0.58	0.98	0.97	0.98	0.98	0.89

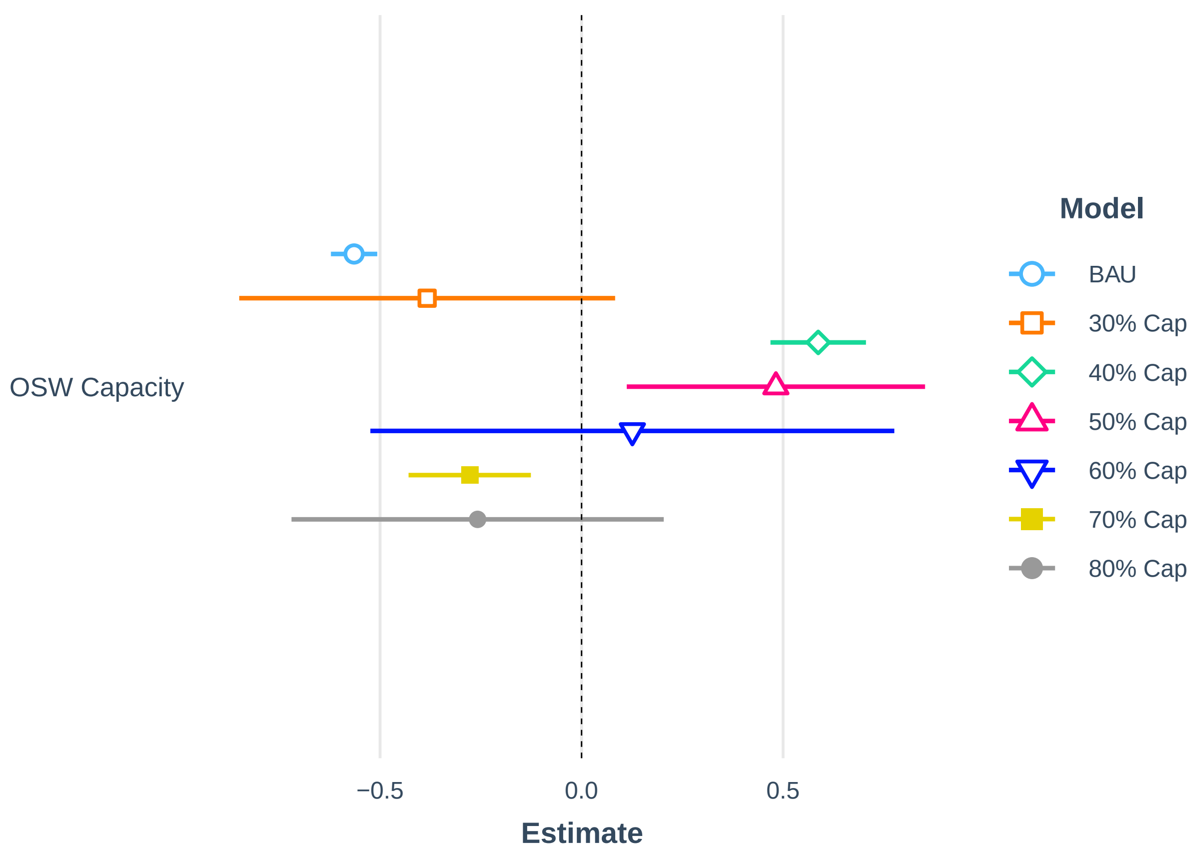
*** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$.



NOx

	BAU	30% Cap	40% Cap	50% Cap	60% Cap	70% Cap	80% Ca
OSW Capacity	-0.56 ***	-0.38	0.59 **	0.48 *	0.13	-0.28 *	-0.2
	(0.01)	(0.11)	(0.03)	(0.09)	(0.15)	(0.04)	(0.1
N	4	4	4	4	4	4	4
R2	1.00	0.86	1.00	0.94	0.26	0.97	0.7

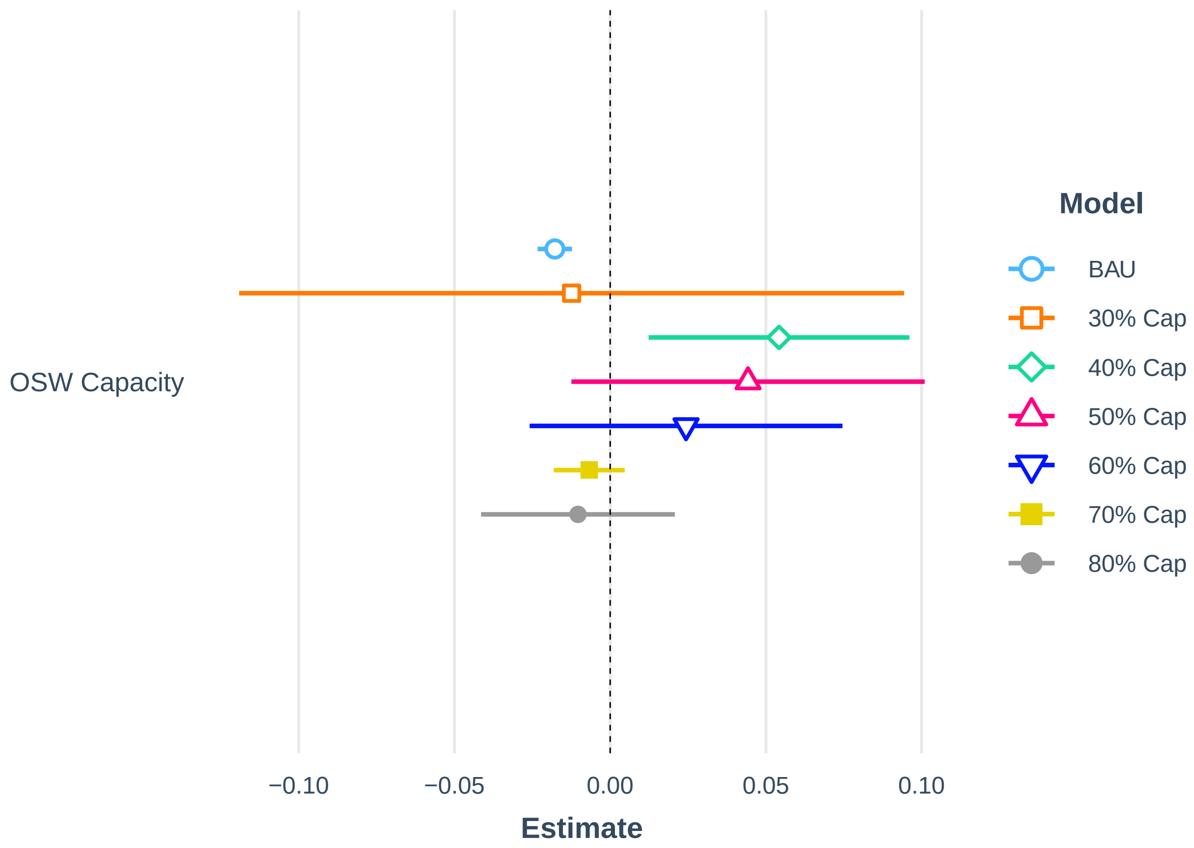
*** p < 0.001; ** p < 0.01; * p < 0.05.



PM 2.5

	BAU	30% Cap	40% Cap	50% Cap	60% Cap	70% Cap	80% Cap
OSW Capacity	-0.02 **	-0.01	0.05 *	0.04	0.02	-0.01	-0.01
	(0.00)	(0.02)	(0.01)	(0.01)	(0.01)	(0.00)	(0.01)
N	4	4	4	4	4	4	4
R2	0.99	0.11	0.94	0.85	0.69	0.76	0.51

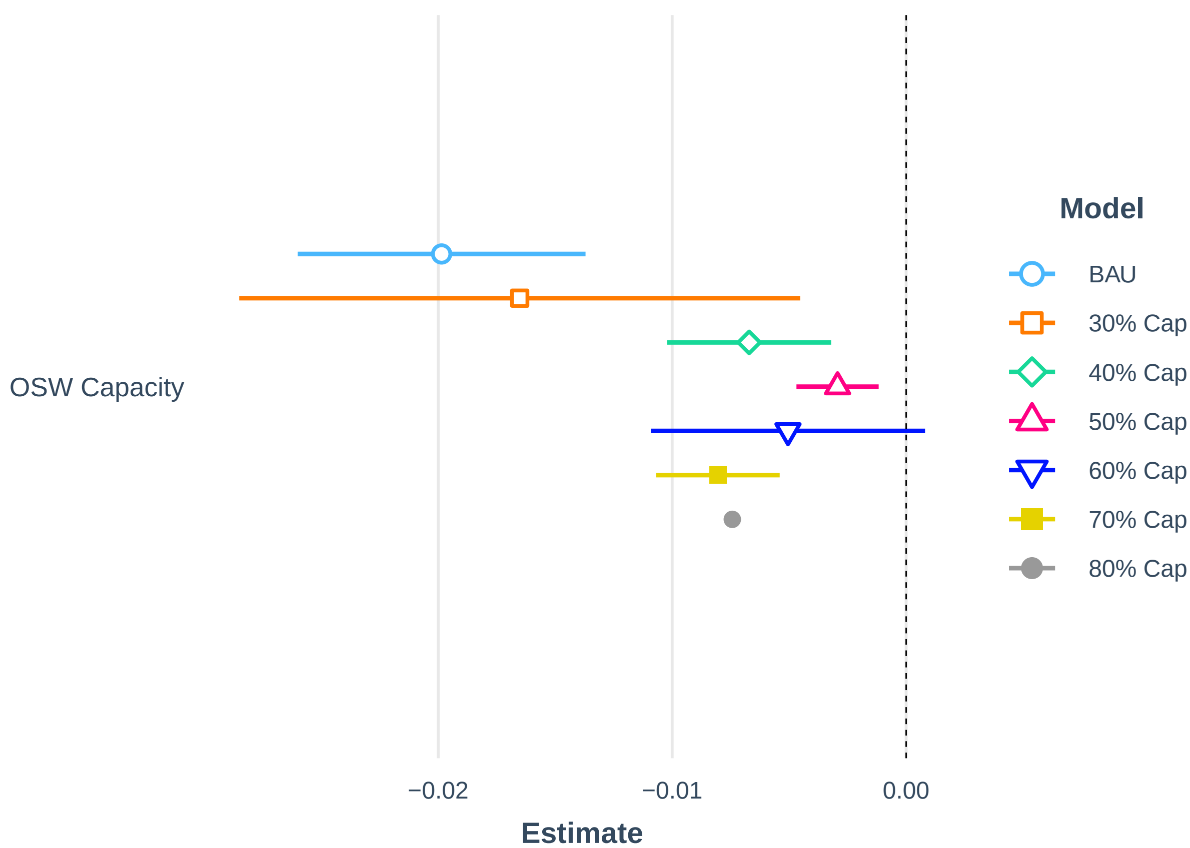
*** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$.



CH4

	BAU	30% Cap	40% Cap	50% Cap	60% Cap	70% Cap	80% Cap
OSW Capacity	-0.02 **	-0.02 *	-0.01 *	-0.00 *	-0.01	-0.01 **	-0.01 ***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
N	4	4	4	4	4	4	4
R2	0.99	0.95	0.97	0.96	0.87	0.99	1.00

*** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$.

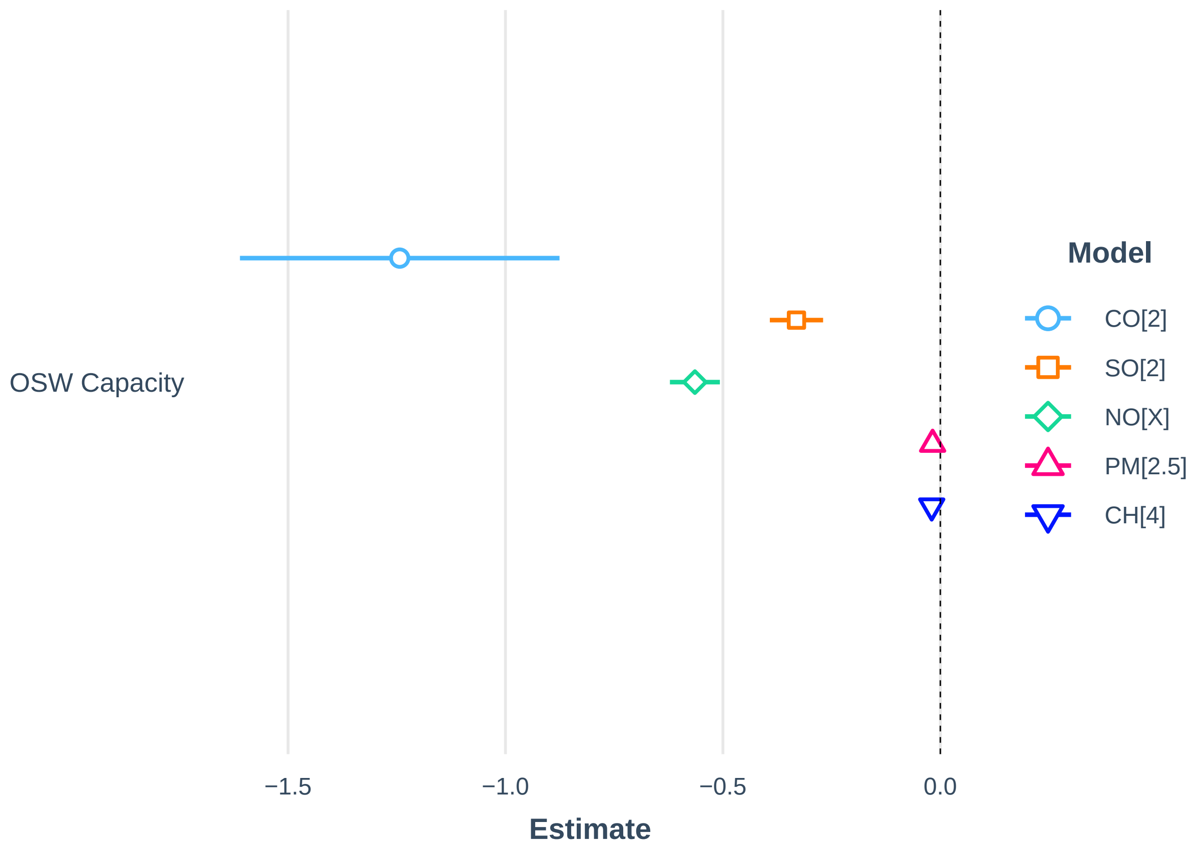


9.3 CO2 cap regressions by emissions type

BAU

	CO[2]	SO[2]	NO[X]	PM[2.5]	CH[4]
OSW Capacity	-1.24 **	-0.33 **	-0.56 ***	-0.02 **	-0.02 **
	(0.09)	(0.01)	(0.01)	(0.00)	(0.00)
N	4	4	4	4	4
R2	0.99	1.00	1.00	0.99	0.99

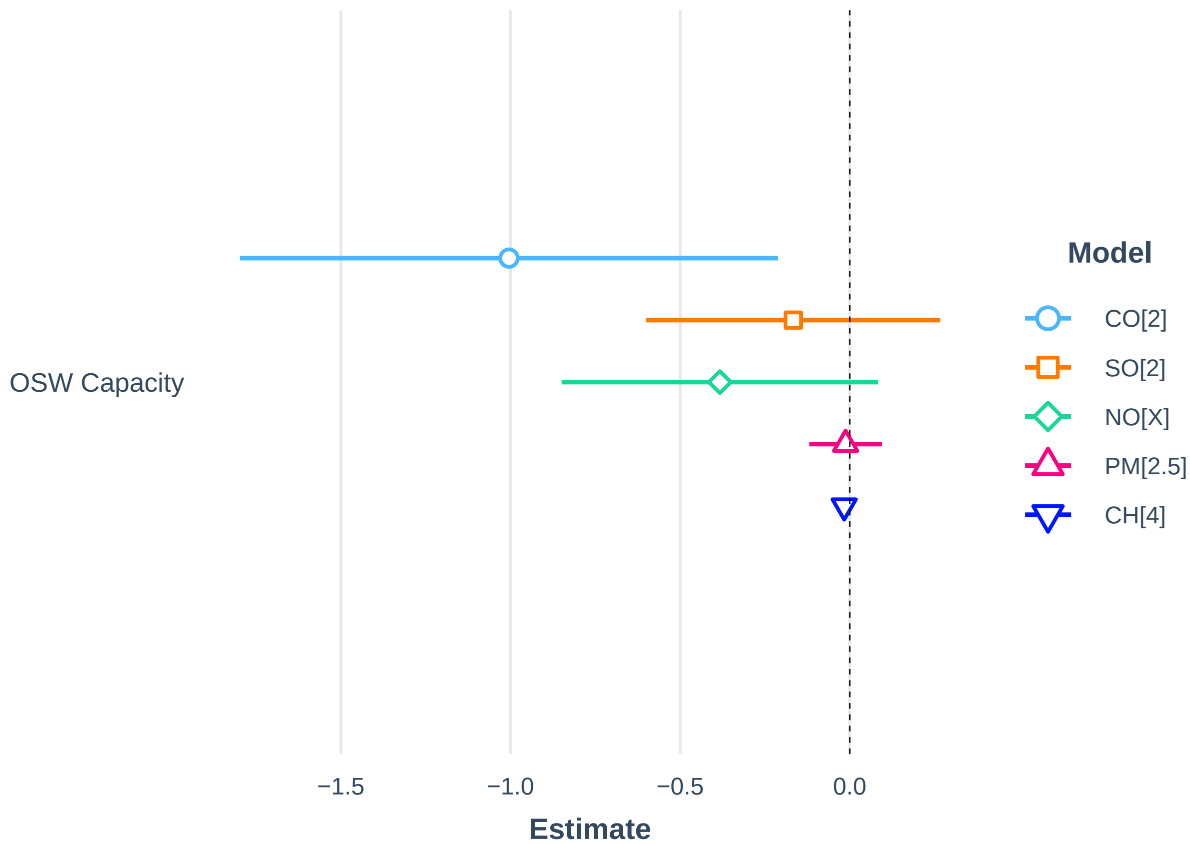
*** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$.



30% CO2 Cap

	CO[2]	SO[2]	NO[X]	PM[2.5]	CH[4]
OSW Capacity	-1.00 *	-0.17	-0.38	-0.01	-0.02 *
	(0.18)	(0.10)	(0.11)	(0.02)	(0.00)
N	4	4	4	4	4
R2	0.94	0.58	0.86	0.11	0.95

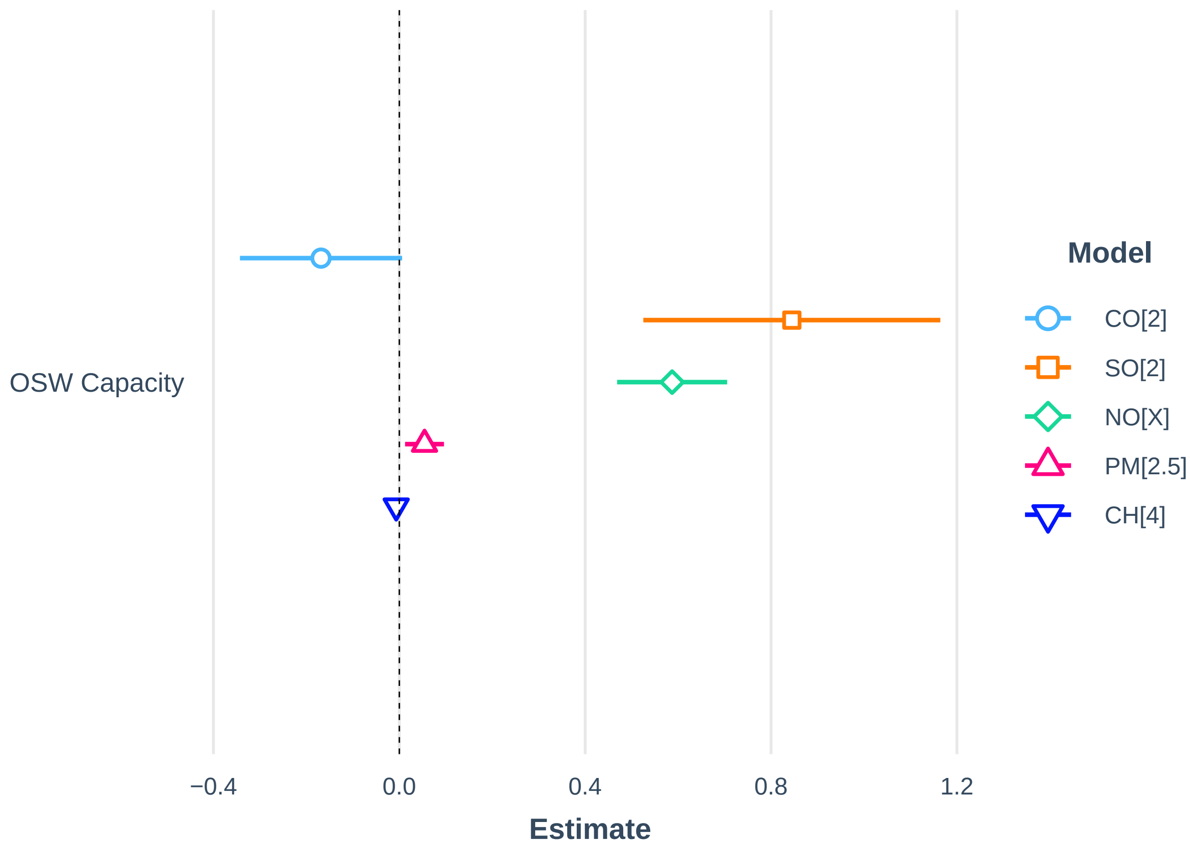
*** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$.



40% CO2 Cap

	CO[2]	SO[2]	NO[X]	PM[2.5]	CH[4]
OSW Capacity	-0.17	0.84 **	0.59 **	0.05 *	-0.01 *
	(0.04)	(0.07)	(0.03)	(0.01)	(0.00)
N	4	4	4	4	4
R2	0.90	0.98	1.00	0.94	0.97

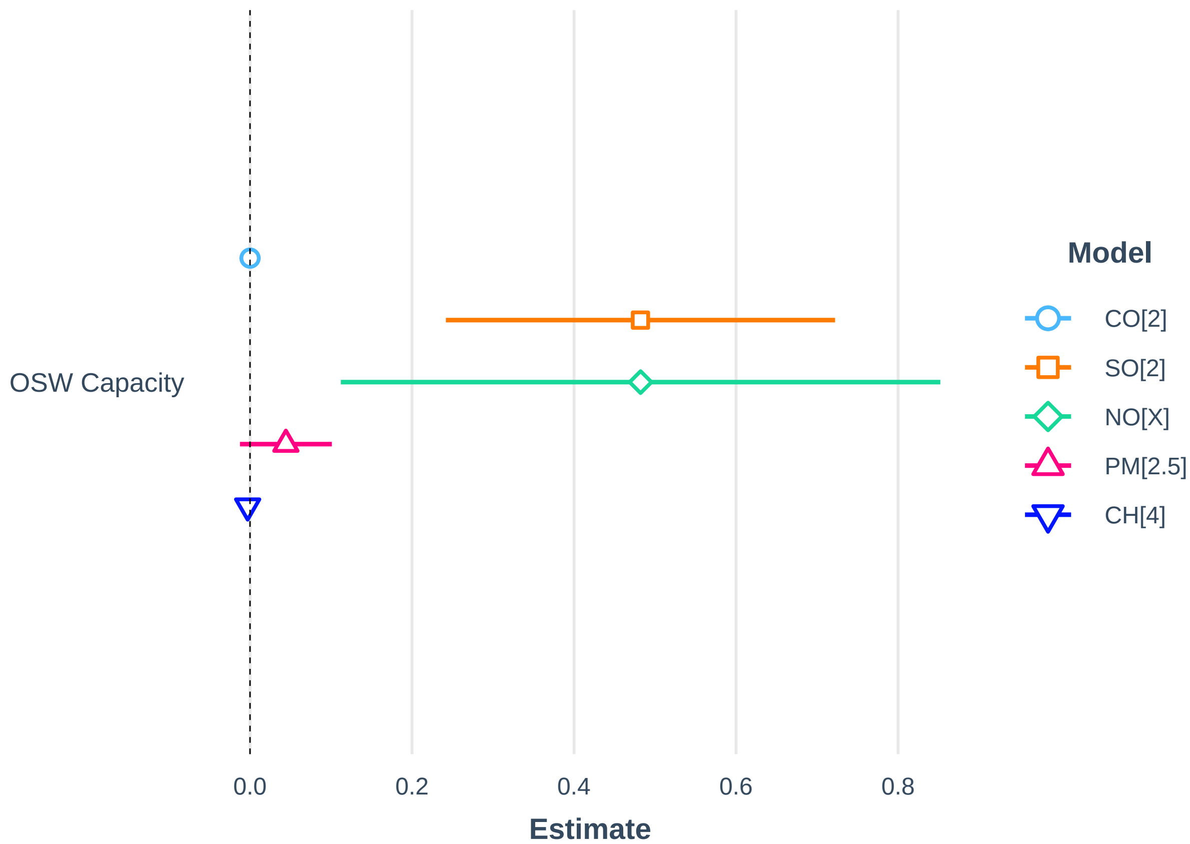
*** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$.



50% CO2 Cap

	CO[2]	SO[2]	NO[X]	PM[2.5]	CH[4]
OSW Capacity	0.00	0.48 *	0.48 *	0.04	-0.00 *
	(0.00)	(0.06)	(0.09)	(0.01)	(0.00)
N	4	4	4	4	4
R2	0.84	0.97	0.94	0.85	0.96

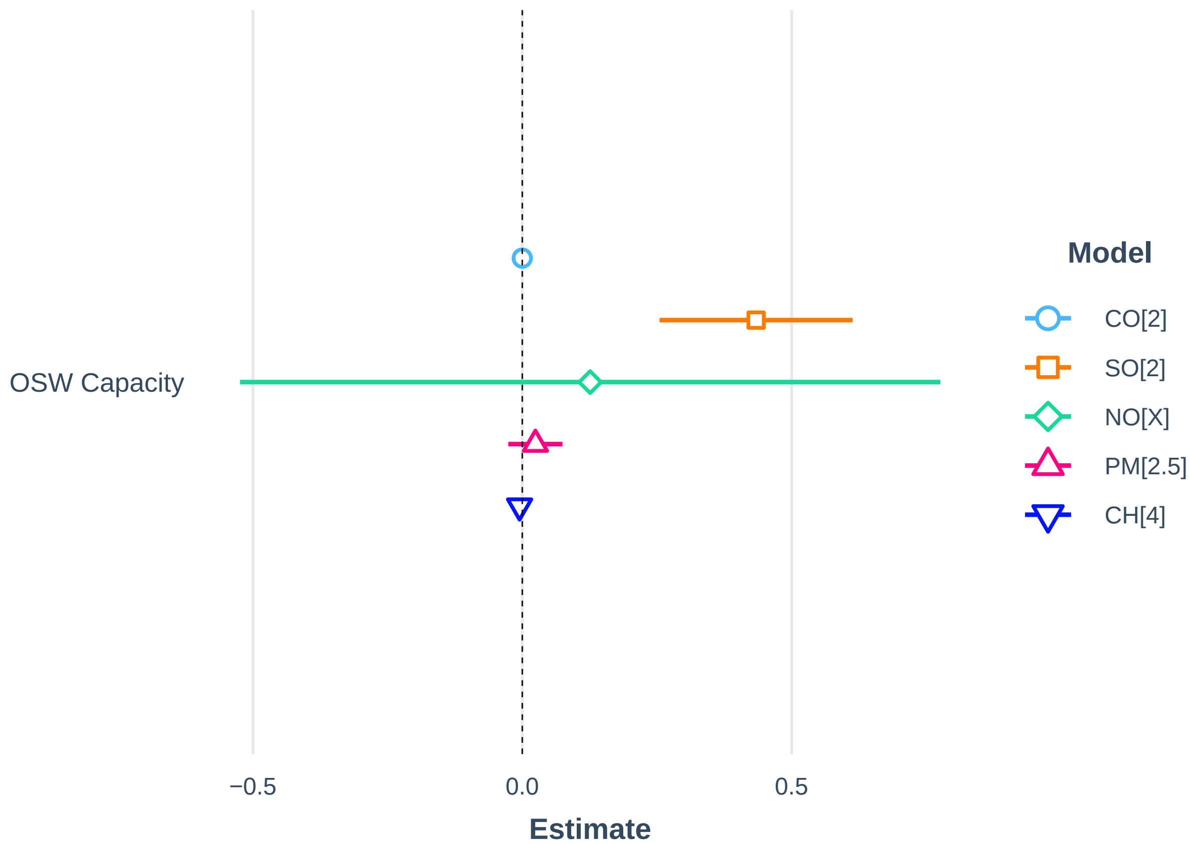
*** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$.



60% CO2 Cap

	CO[2]	SO[2]	NO[X]	PM[2.5]	CH[4]
OSW Capacity	-0.00	0.43 **	0.13	0.02	-0.01
	(0.00)	(0.04)	(0.15)	(0.01)	(0.00)
N	4	4	4	4	4
R2	0.20	0.98	0.26	0.69	0.87

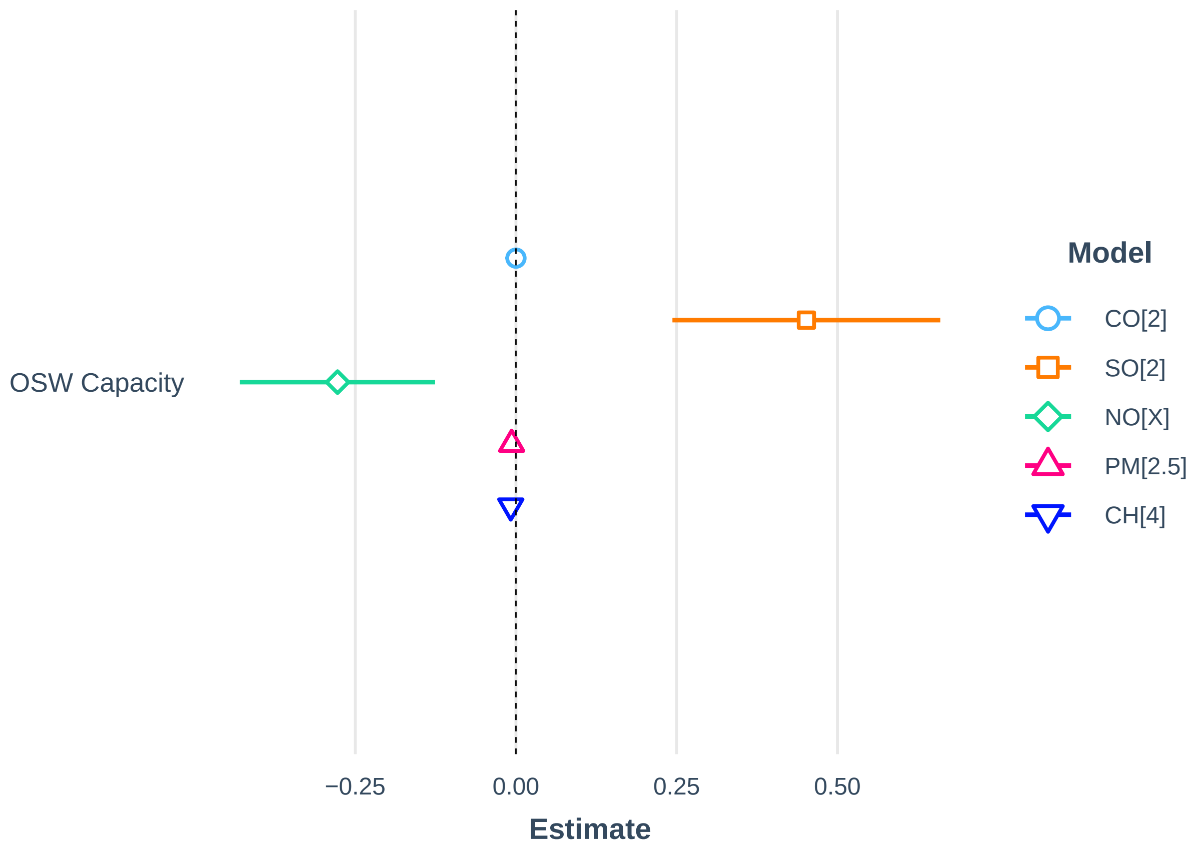
*** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$.



70% CO2 Cap

	CO[2]	SO[2]	NO[X]	PM[2.5]	CH[4]
OSW Capacity	-0.00	0.45 *	-0.28 *	-0.01	-0.01 **
	(0.00)	(0.05)	(0.04)	(0.00)	(0.00)
N	4	4	4	4	4
R2	0.00	0.98	0.97	0.76	0.99

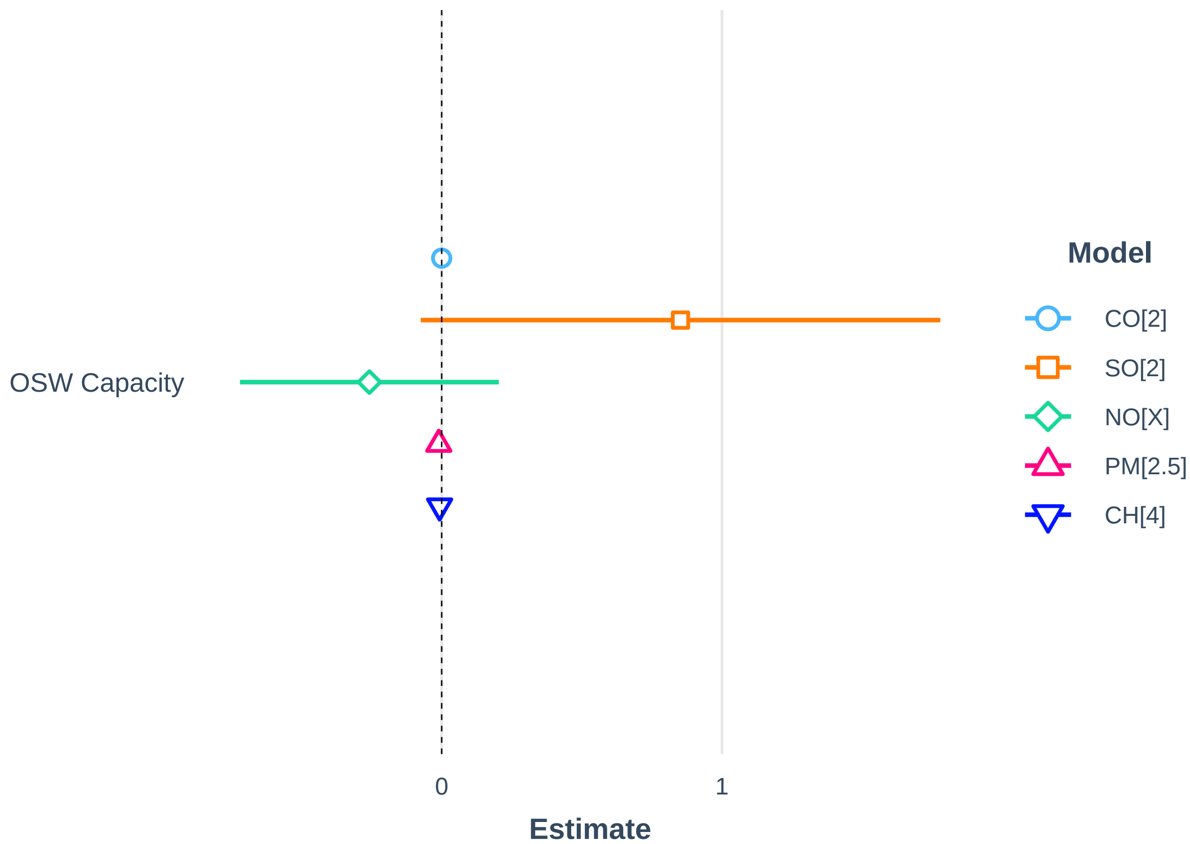
*** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$.



80% CO2 Cap

	CO[2]	SO[2]	NO[X]	PM[2.5]	CH[4]
OSW Capacity	-0.00	0.85	-0.26	-0.01	-0.01 ***
	(0.00)	(0.22)	(0.11)	(0.01)	(0.00)
N	4	4	4	4	4
R2	0.83	0.89	0.74	0.51	1.00

*** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$.



OSW Capacity
0
1
Estimate
Model
CO[2]
SO[2]
NO[X]
PM[2.5]
CH[4]