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

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Contents

1 Disclosure

This document functions as an all-inclusive working directory for synthesis and graphical analysis of the results from the offshore wind research of Morgan Browning, an ORISE Fellow at the U.S. Environmental Protection Agency's Office of Research and Development. This document and its contents are not finalized nor are intended for publication.

It is annotated primarily for ease of reproducability and a general understanding of the results.

2 Setup

Three scripts are loaded into this markdown document to allow for analysis of the data. The setup script loads the library, creates generalized functions, and creates global variables for color scales and factors. The data script loads an excel spreadsheet with all of the results data and performs the majority of data munging. The results script creates charts, graphs, and tables. This report functions as the annotated synthesis of the data and results.

Graphs are provided with many variations to meet criteria of different publication and presentation platforms. Formats may be chosen using the `colorcalls` toggles

3 Scenarios

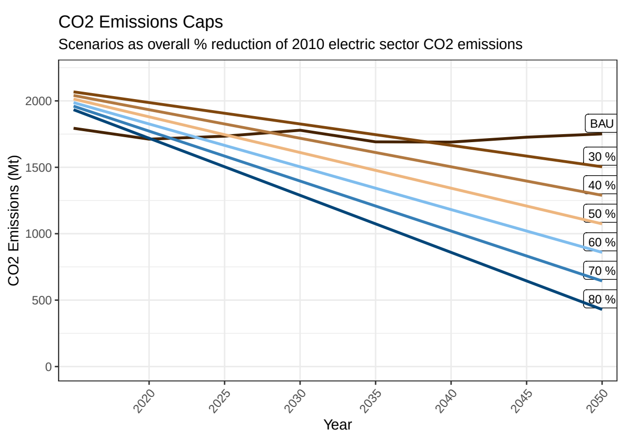
The nested parametric sensitivity analysis was built on combinations of two sets of scenarios:

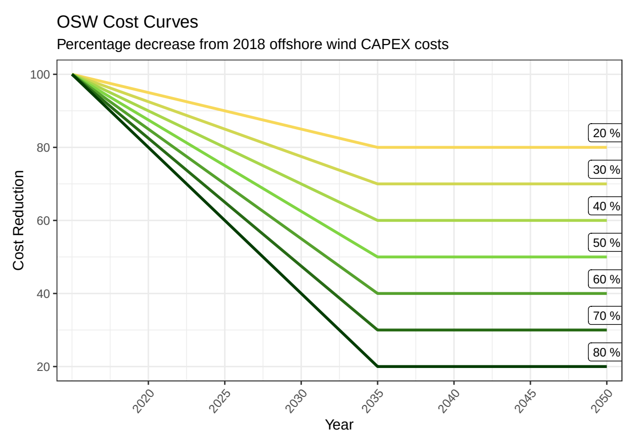
1. Electric sector CO_2 emissions caps, as a linear decrease to a given % decrease from 2010 emissions by 2050

- 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





4 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

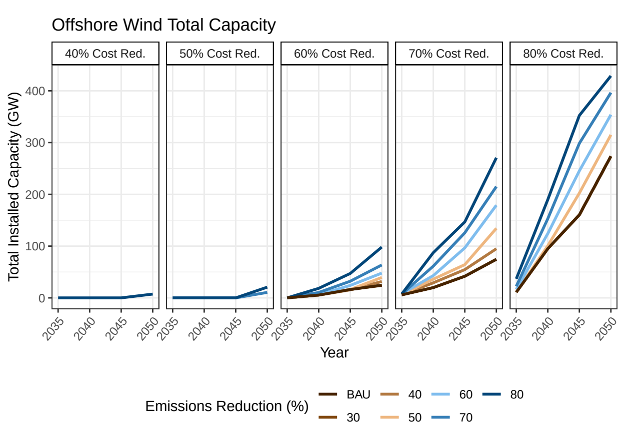
Note:
U.S. EIA Annual Energy Outlook 2019

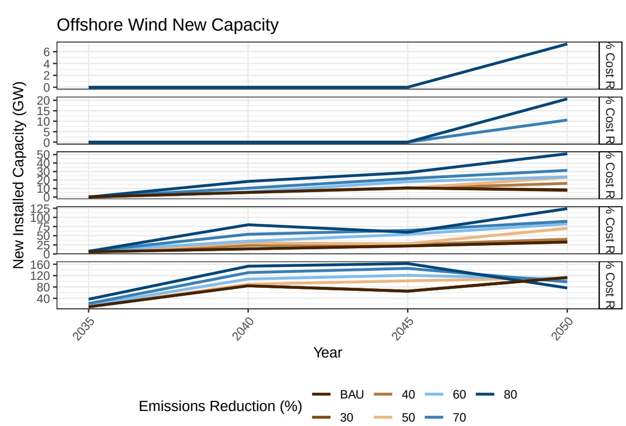
5 Offshore Wind

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.

5.1 Capacity Buildout

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





5.2 Total Capacity

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

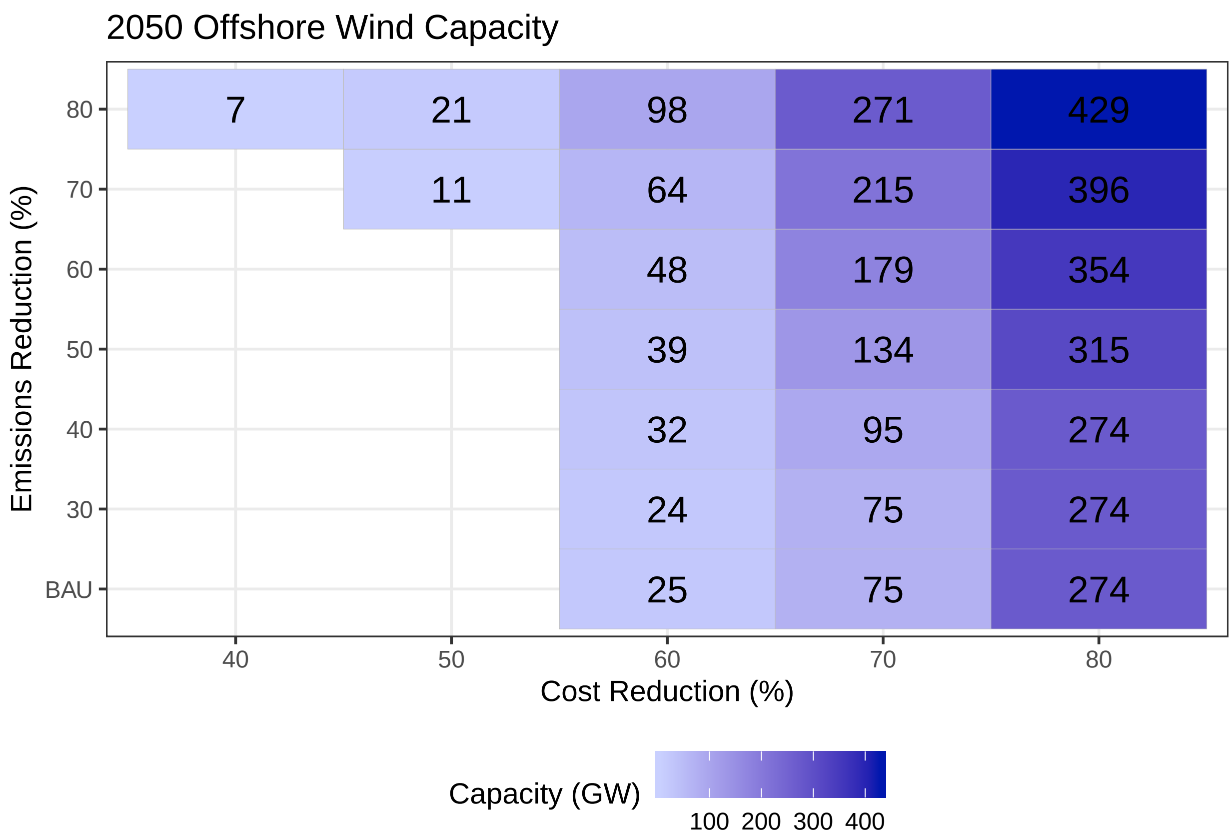


Table 2: Offshore Wind Total Installed Capacity (GW): 2050

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

5.3 Output

Total offshore wind electricity output across all nine census regions, by cost and emissions reduction scenario. Results show almost identical trajectories for total capacity and output due to the non-dispatchable quality of offshore wind. All generated electricity is utilized in the modeled scenarios.

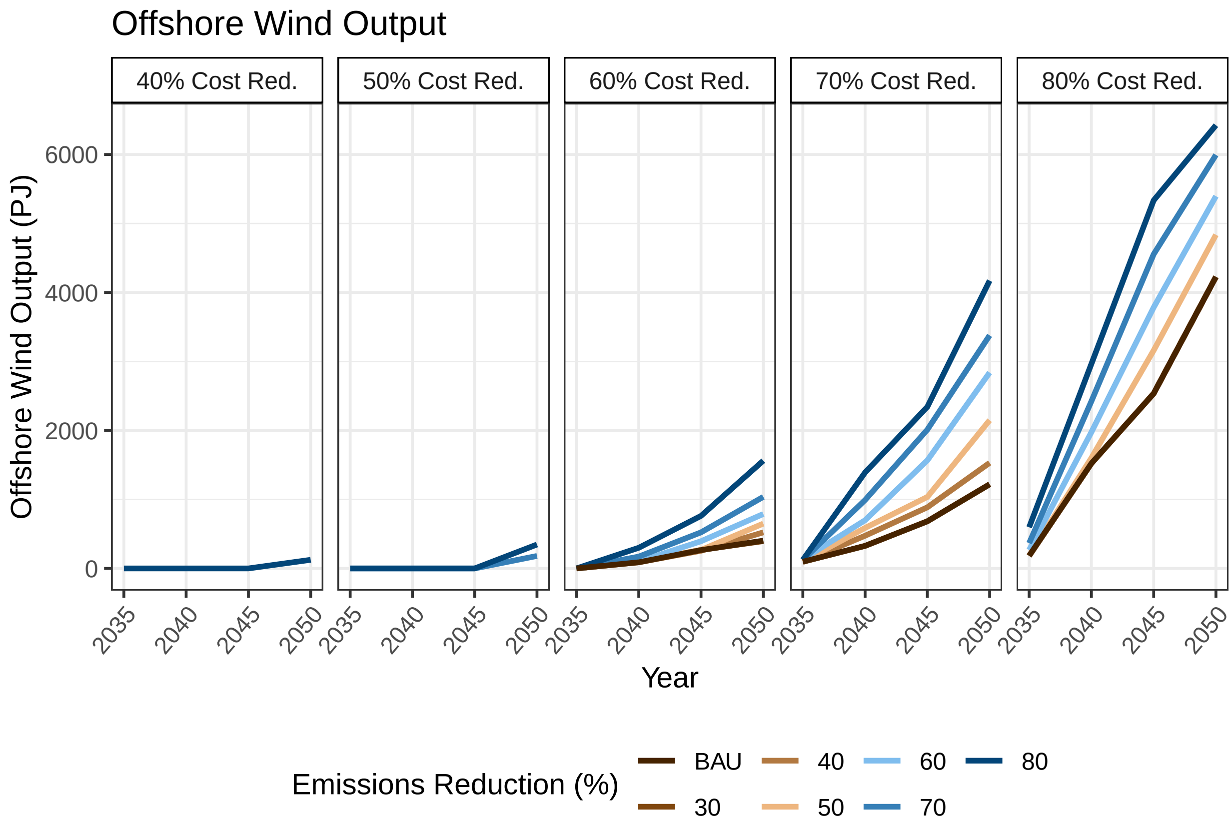
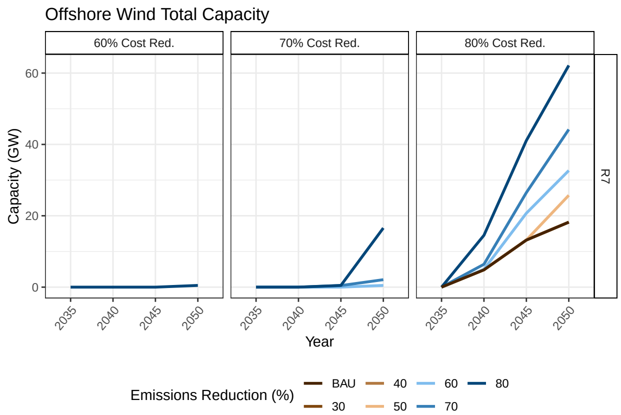


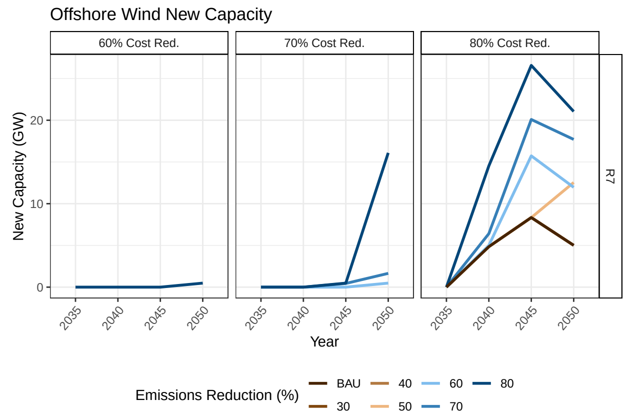
Table 3: Offshore Wind Total Output (PJ): 2050

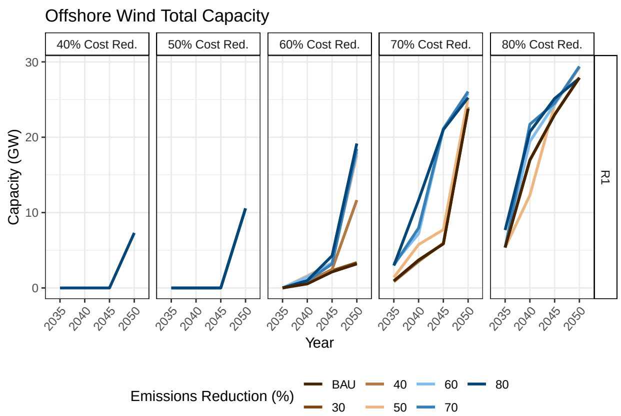
CO2 Emissions Reduction (%)	Cost Reduction (%)				
	40	50	60	70	80
BAU	-	-	403	1219	4226
30	-	-	396	1219	4226
40	-	-	523	1531	4226
50	-	-	650	2149	4836
60	-	-	789	2839	5396
70	-	181	1037	3378	5995
80	125	346	1562	4172	6424

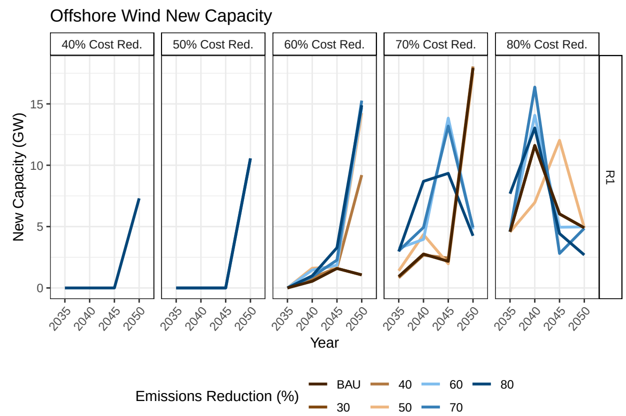
5.4 Regions

Cumulative and new addition offshore wind capacity by region. Regions are listed from least to highest electricity output.


Offshore Wind Total Capacity
60% Cost Red.
70% Cost Red.
80% Cost Red.
R7
Capacity (GW)
Year
Emissions Reduction (%)
BAU
30
40
50
60
70
80


Offshore Wind New Capacity
60% Cost Red.
70% Cost Red.
80% Cost Red.
R7
New Capacity (GW)
Year
Emissions Reduction (%)
BAU
30
40
50
60
70
80


Offshore Wind Total Capacity
40% Cost Red.
50% Cost Red.
60% Cost Red.
70% Cost Red.
80% Cost Red.
R1
Capacity (GW)
Year
Emissions Reduction (%)
BAU
30
40
50
60
70
80


Offshore Wind New Capacity
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50% Cost Red.
60% Cost Red.
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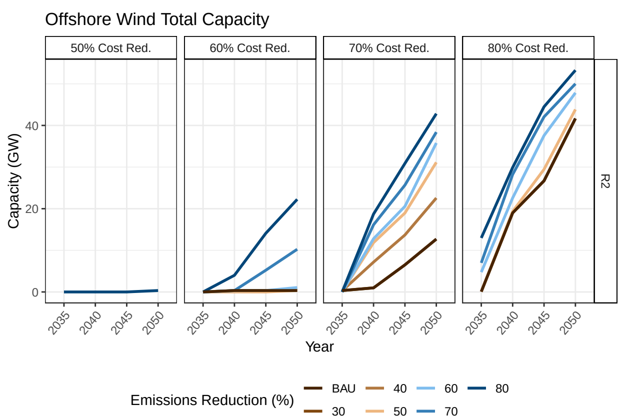
80% Cost Red.
R1
New Capacity (GW)
Year
Emissions Reduction (%)
BAU
30
40
50
60
70
80


Offshore Wind Total Capacity
50% Cost Red.
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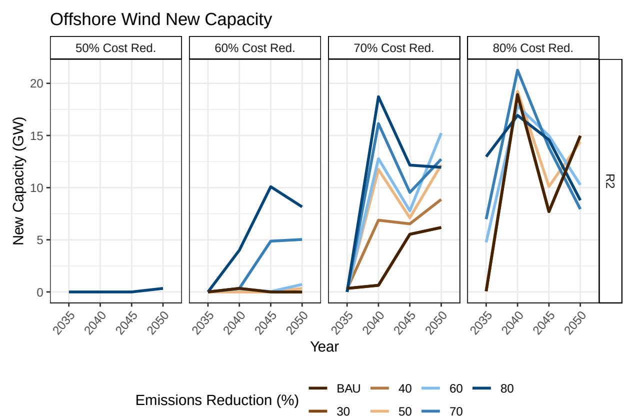
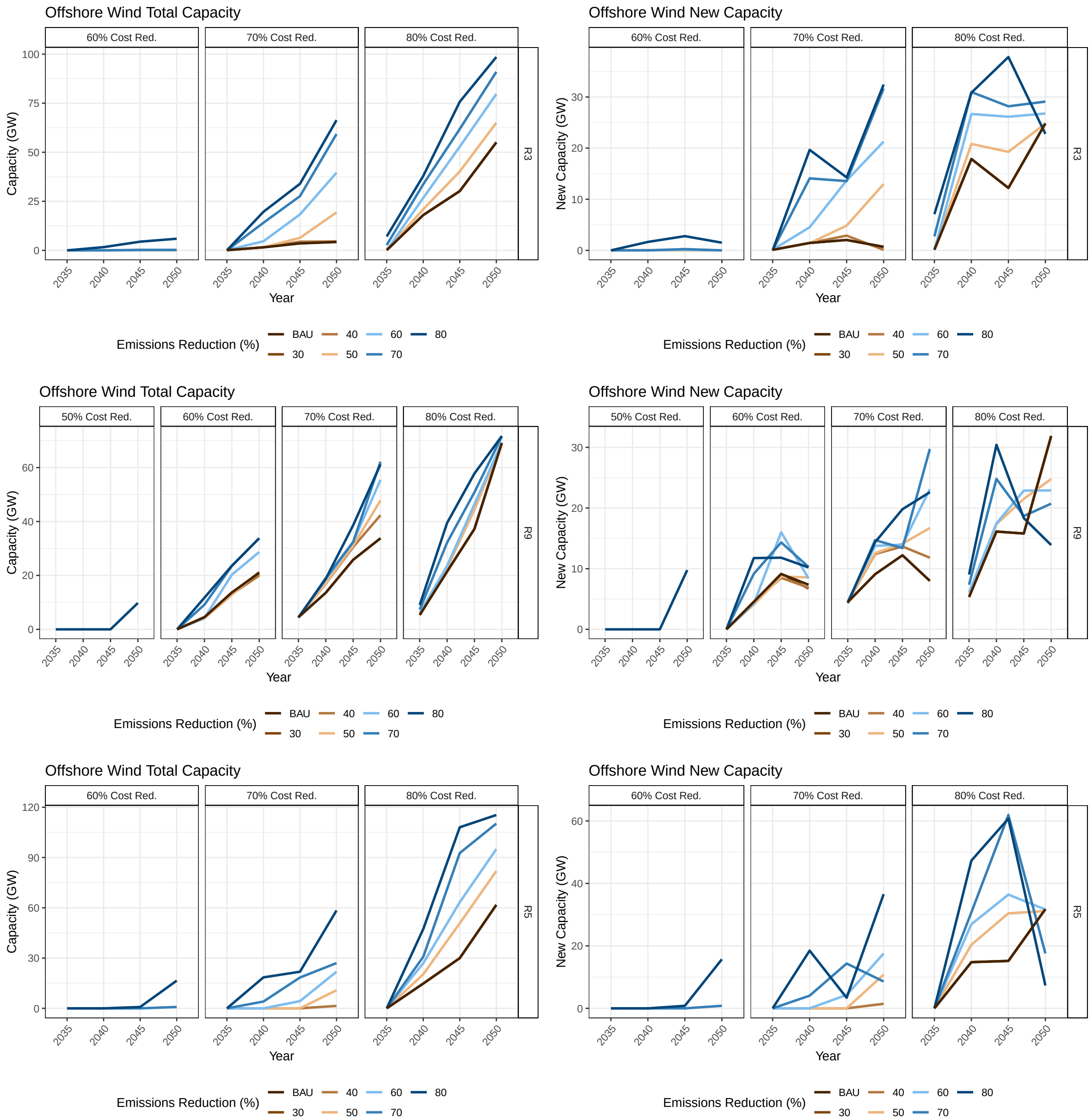
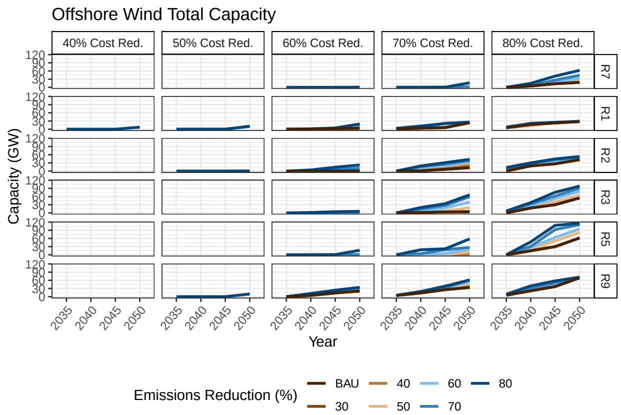
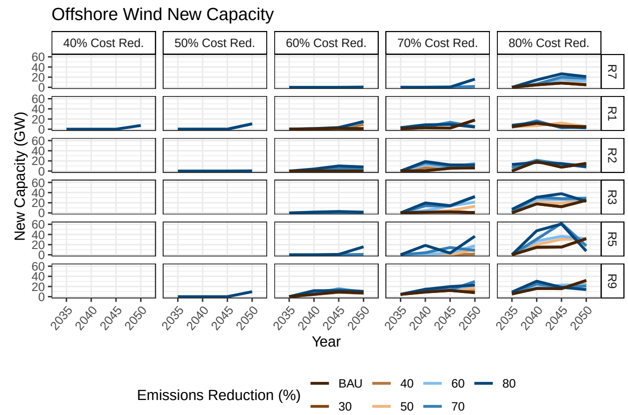
80% Cost Red.
R2
Capacity (GW)
Year
Emissions Reduction (%)
BAU
30
40
50
60
70
80

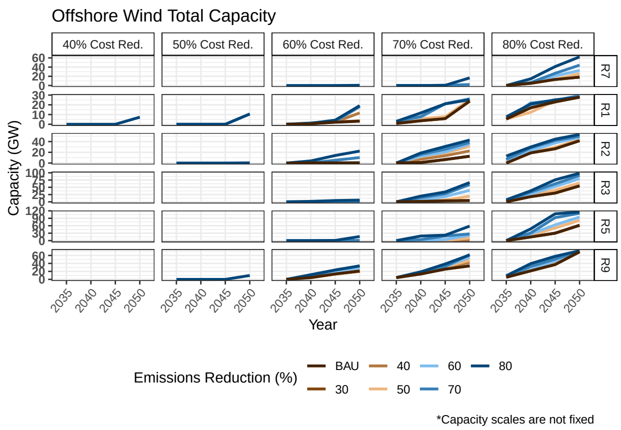

Offshore Wind New Capacity
50% Cost Red.
60% Cost Red.
70% Cost Red.
80% Cost Red.
R2
New Capacity (GW)
Year
Emissions Reduction (%)
BAU
30
40
50
60
70
80



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







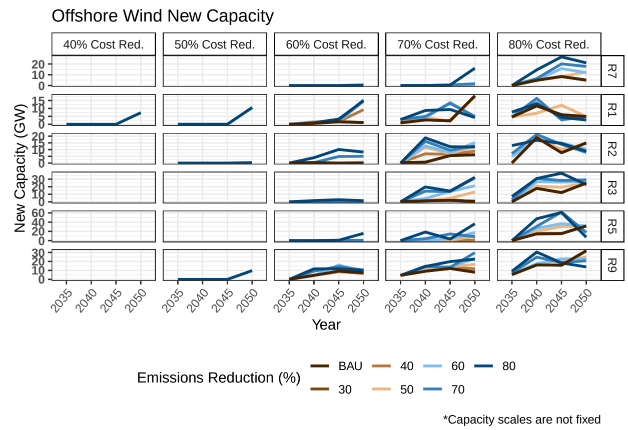


Table 4: Average Installed Capacity (GW)

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

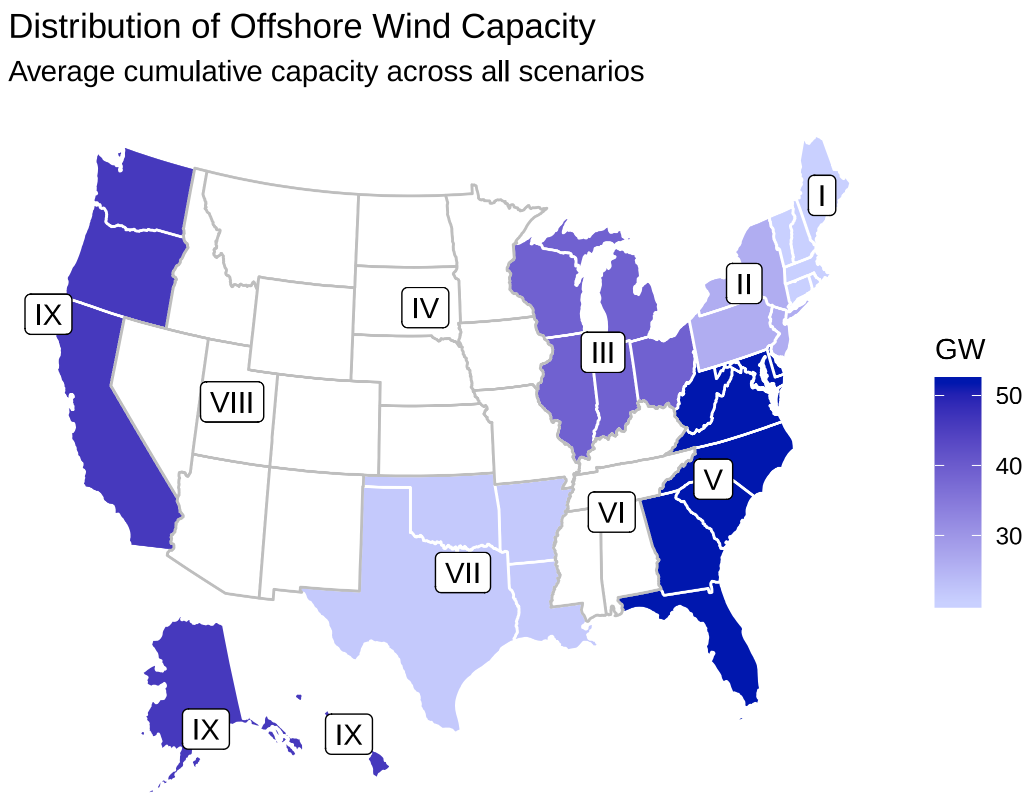
Note:
Average is across all scenarios

Table 5: Average Electricity Output (PJ)

Region	2050 Total
R1	96.6
R2	120.4
R7	128.7
R3	169.9
R9	208.7
R5	303.2

Note:
Average is across all scenarios

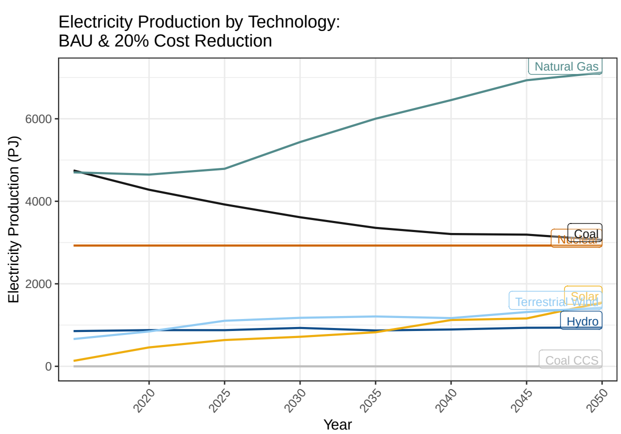
Map of average total capacity

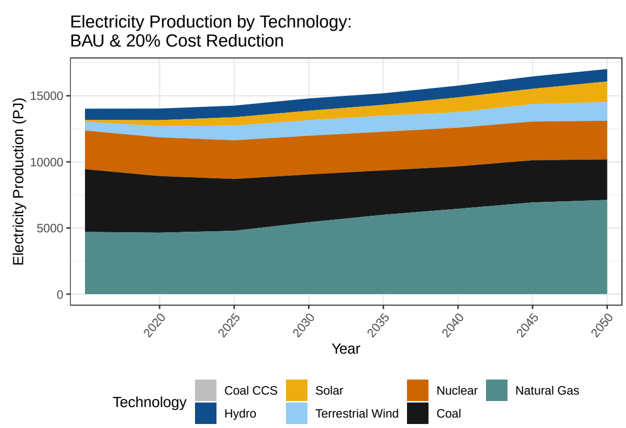


6 Grid Mix

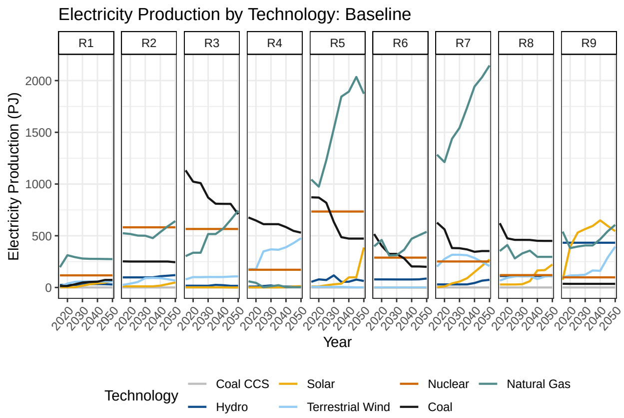
6.1 Baseline Production

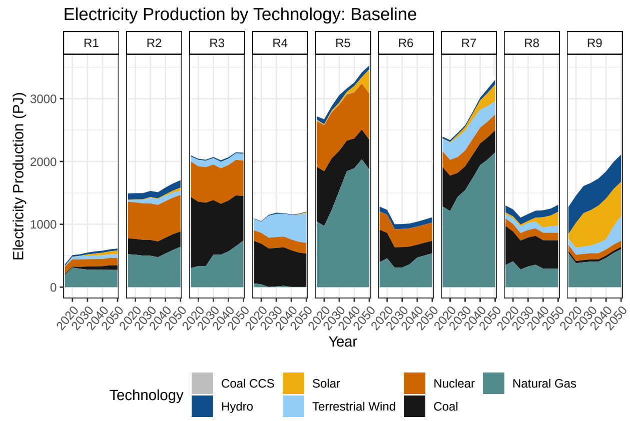
Grid mix without any offshore wind cost reduction or emissions cap.





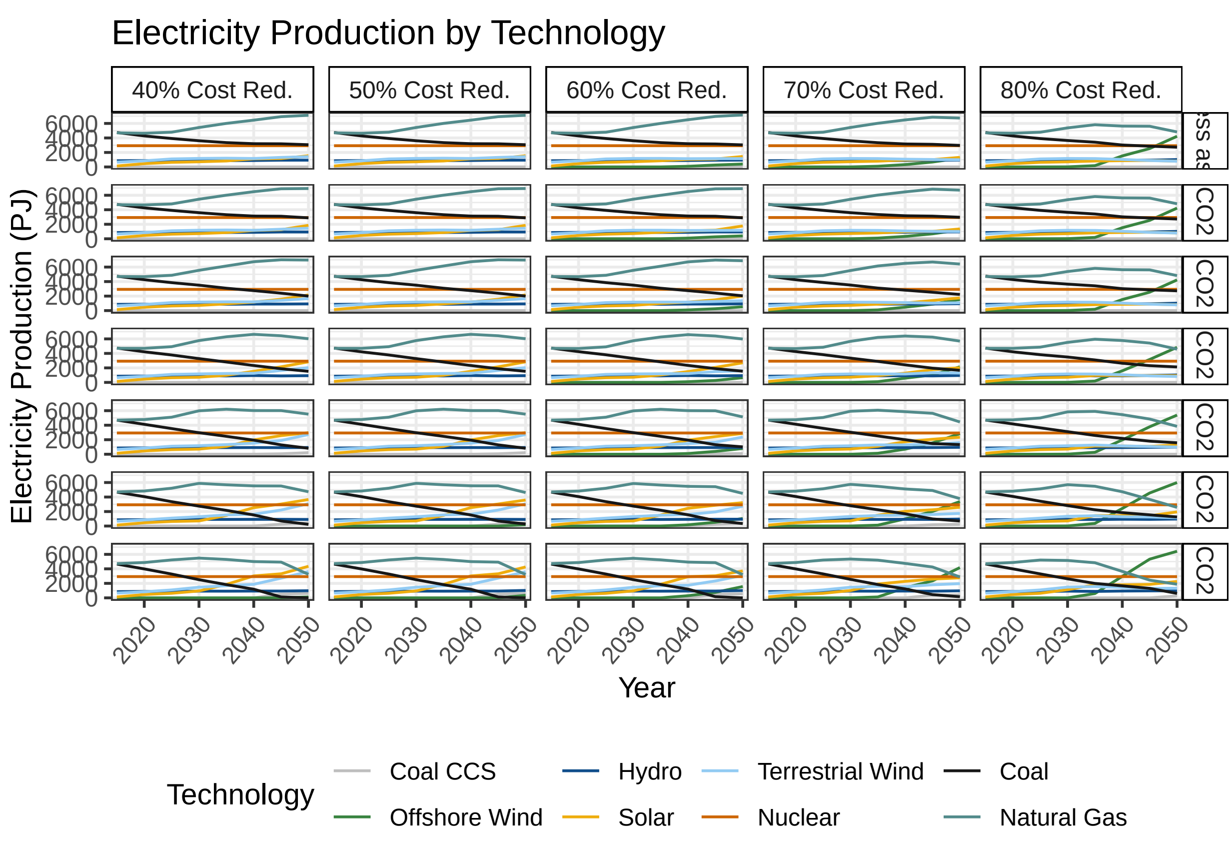
Regional baseline production



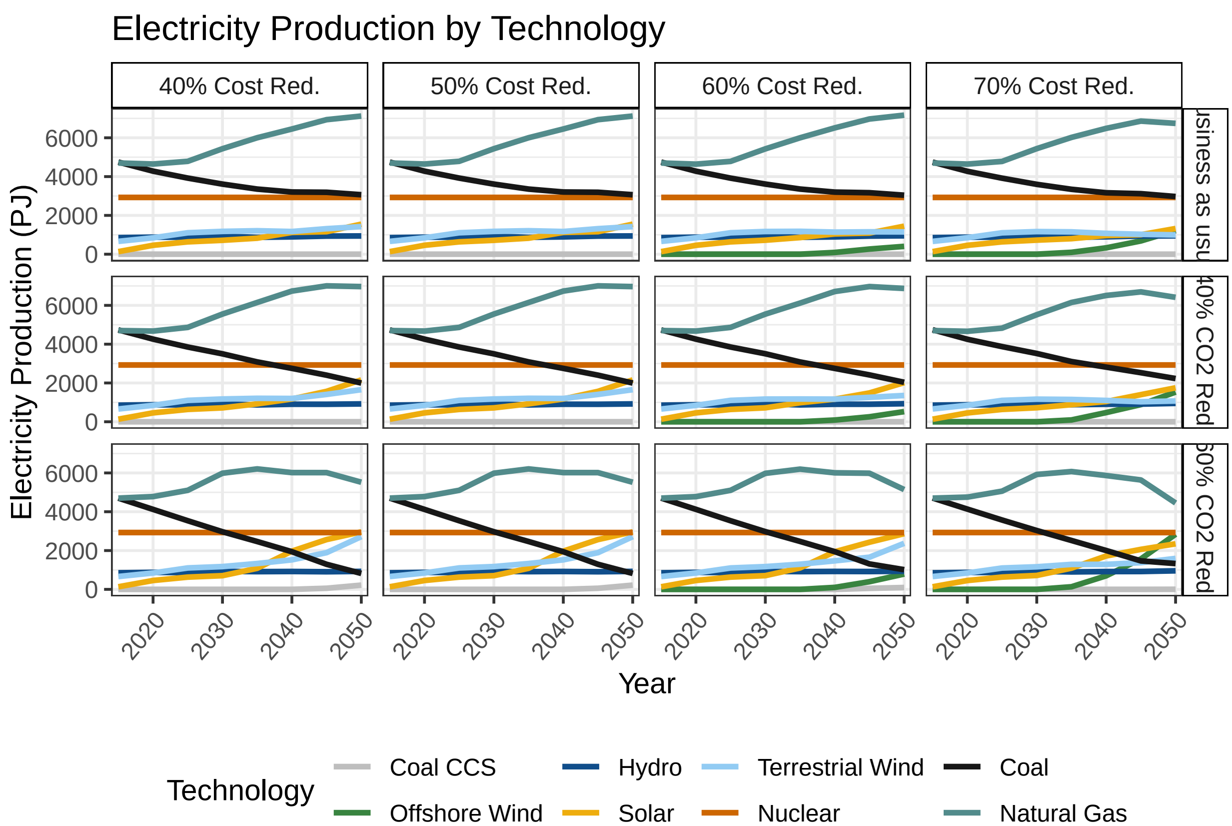


6.2 All Scenarios

Complete Set

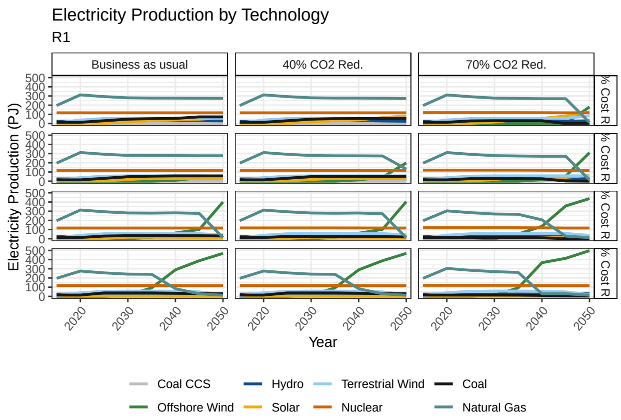


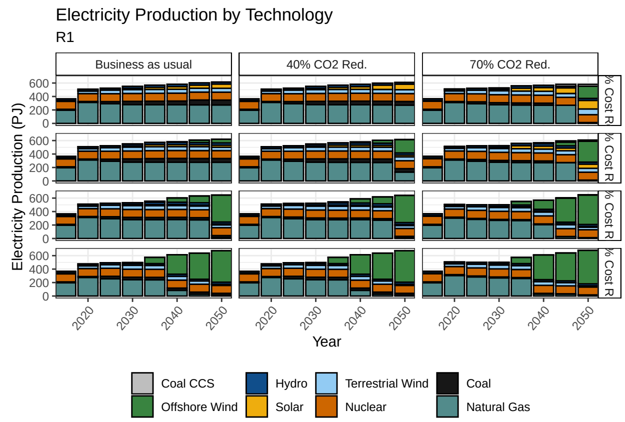
Parsed Set

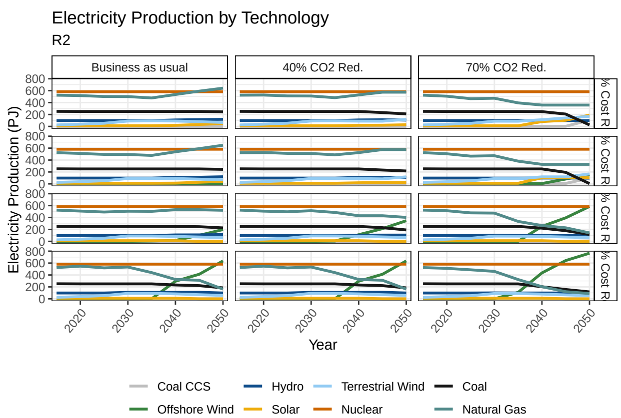


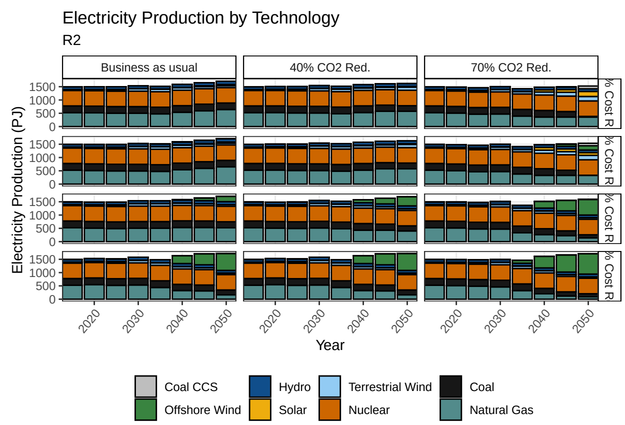
Electricity Production by Technology
40% Cost Red.
50% Cost Red.
60% Cost Red.
70% Cost Red.
usiness as usu
40% CO2 Red
50% CO2 Red
Electricity Production (PJ)
6000
4000
2000
0
2020
2030
2040
2050
Year
Technology
Coal CCS
Offshore Wind
Hydro
Solar
Terrestrial Wind
Nuclear
Coal
Natural Gas

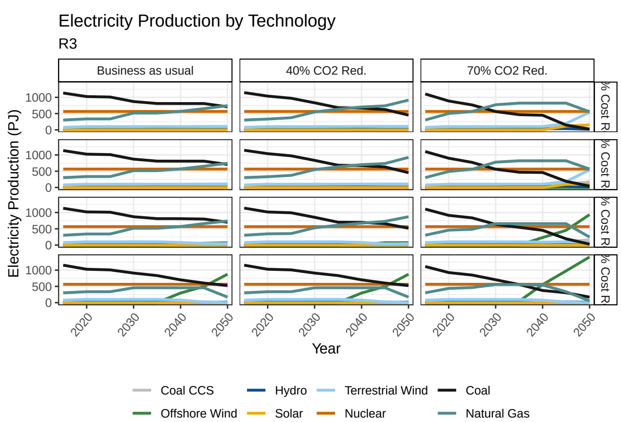
6.3 Regional Mix

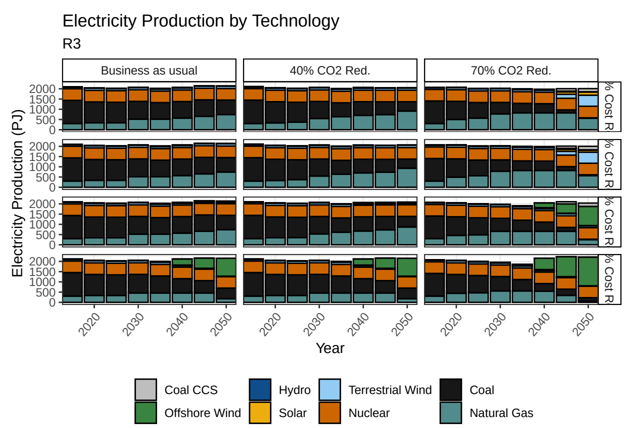


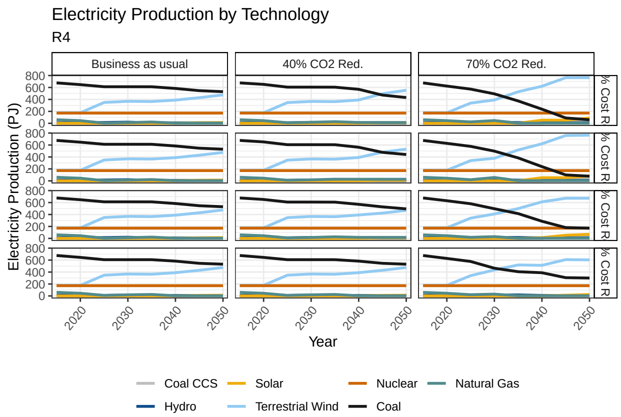


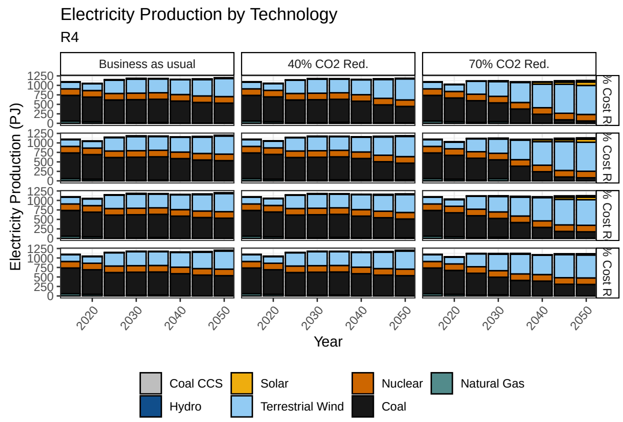


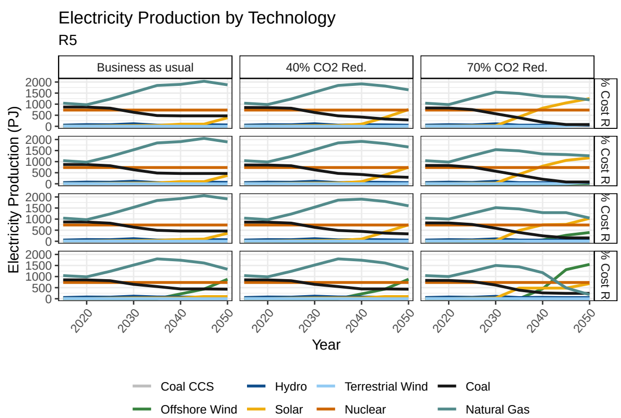







Electricity Production by Technology
R4
Business as usual
40% CO2 Red.
70% CO2 Red.
% Cost R
Electricity Production (PJ)
Year
Coal CCS
Solar
Nuclear
Natural Gas
Hydro
Terrestrial Wind
Coal


Electricity Production by Technology
R4
Business as usual
40% CO2 Red.
70% CO2 Red.
% Cost R
Electricity Production (PJ)
Year
Coal CCS
Solar
Nuclear
Natural Gas
Hydro
Terrestrial Wind
Coal


Electricity Production by Technology
R5
Business as usual
40% CO2 Red.
70% CO2 Red.
% Cost R
Electricity Production (PJ)
Year
Coal CCS
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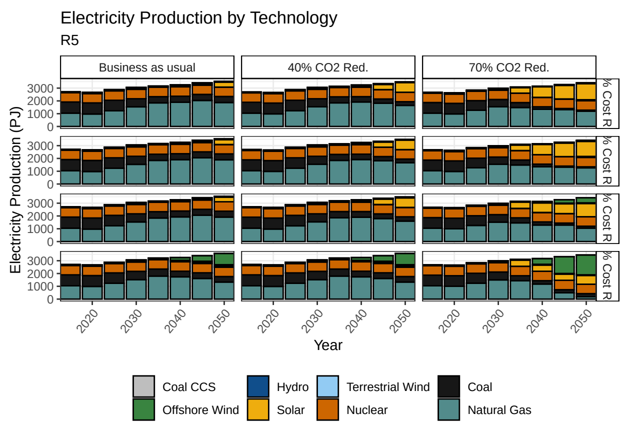
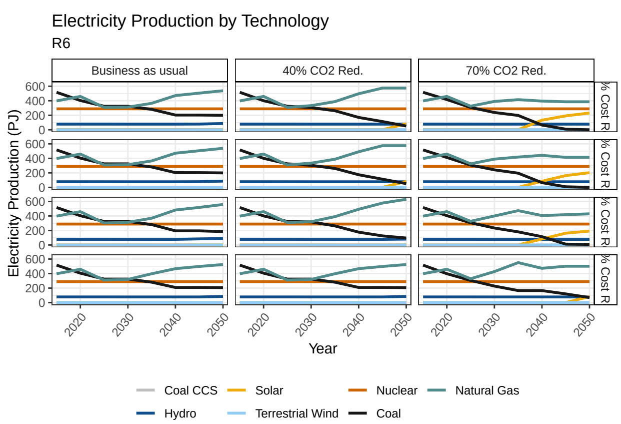
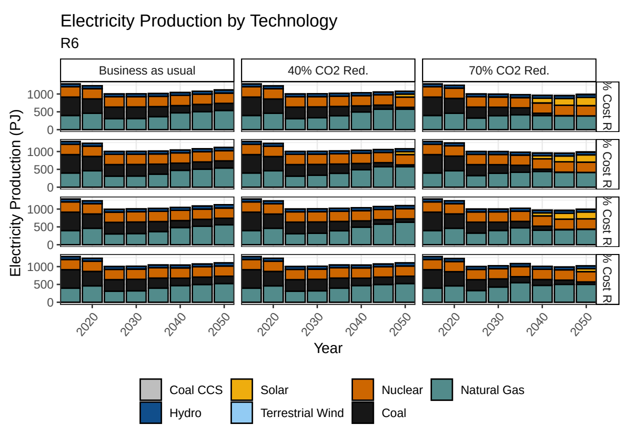
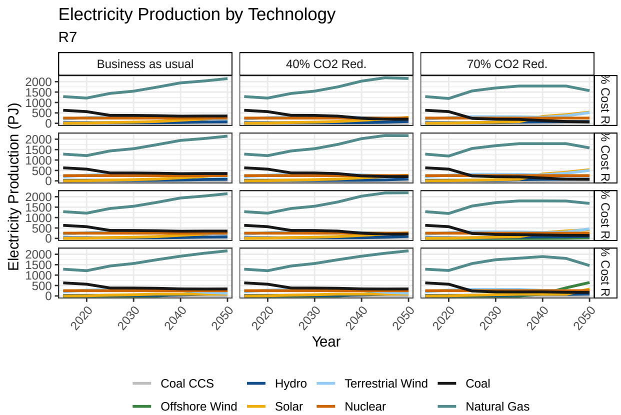
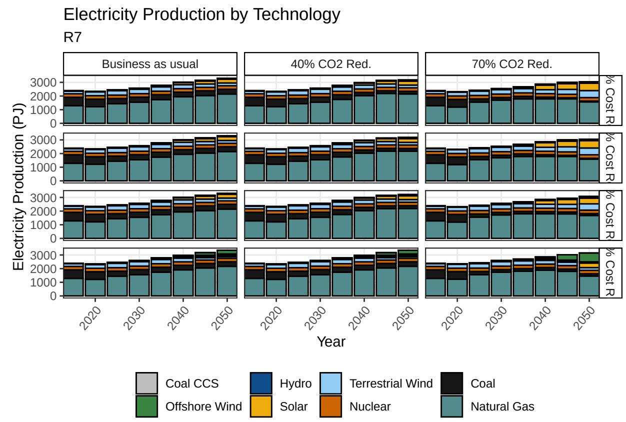
Terrestrial Wind
Coal
Offshore Wind
Solar
Nuclear
Natural Gas

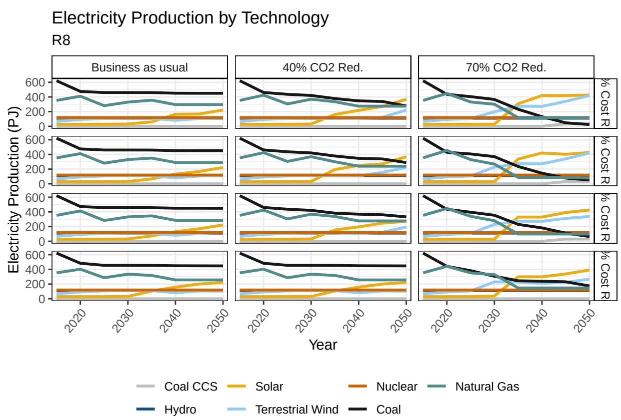

Electricity Production by Technology
R5
Business as usual
40% CO2 Red.
70% CO2 Red.
% Cost R
Electricity Production (PJ)
Year
Coal CCS
Hydro
Terrestrial Wind
Coal
Offshore Wind
Solar
Nuclear
Natural Gas

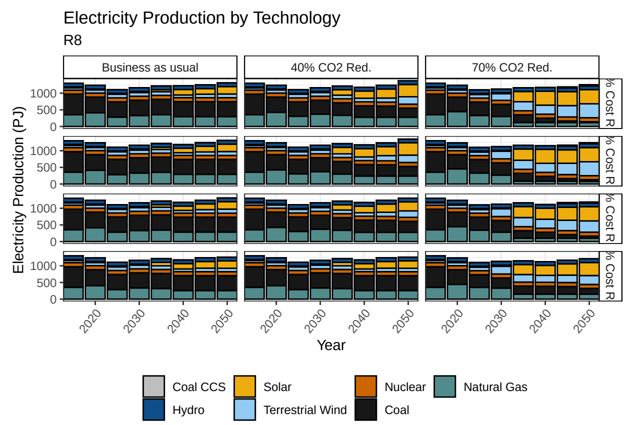

Electricity Production by Technology
R6
Business as usual
40% CO2 Red.
70% CO2 Red.
% Cost R
Electricity Production (PJ)
Year
Coal CCS
Solar
Nuclear
Natural Gas
Hydro
Terrestrial Wind
Coal

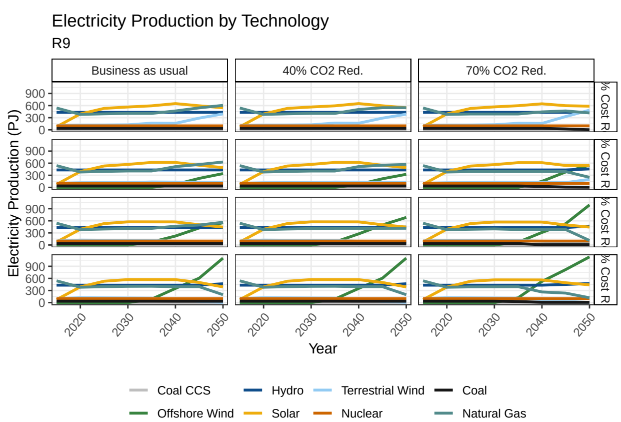

Electricity Production by Technology
R6
Business as usual
40% CO2 Red.
70% CO2 Red.
% Cost R
Electricity Production (PJ)
Year
Coal CCS
Solar
Nuclear
Natural Gas
Hydro
Terrestrial Wind
Coal

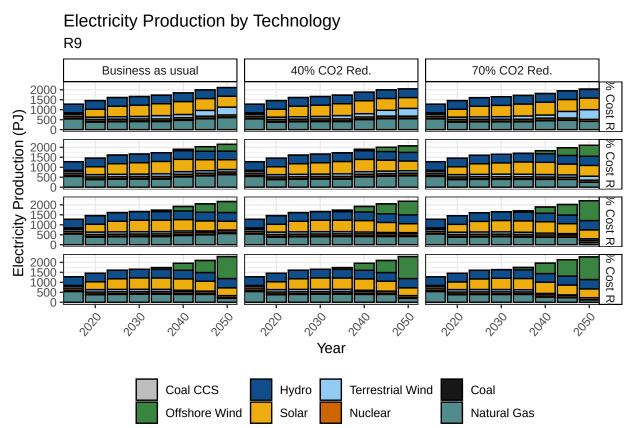






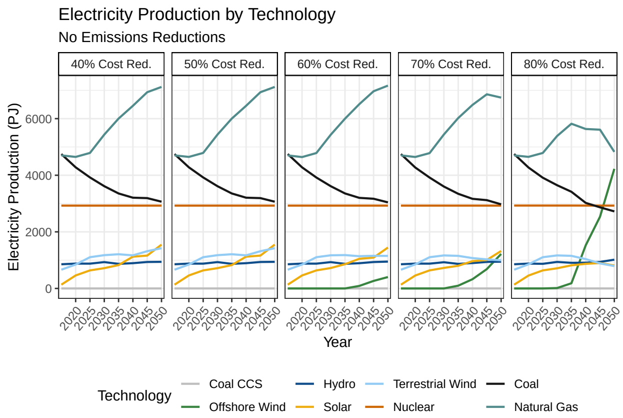


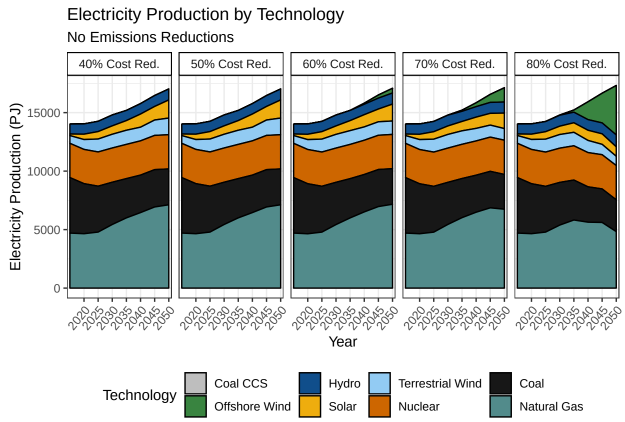




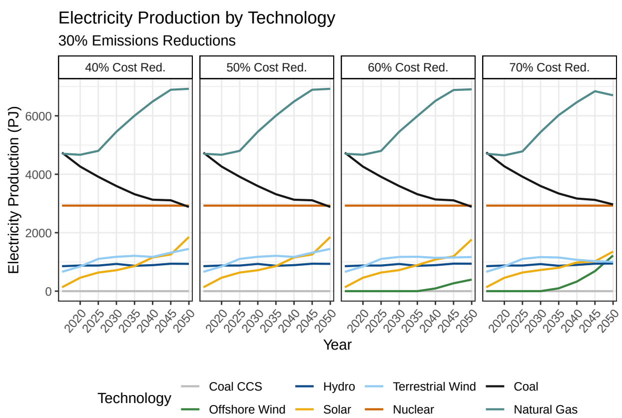
6.4 Emissions Cap

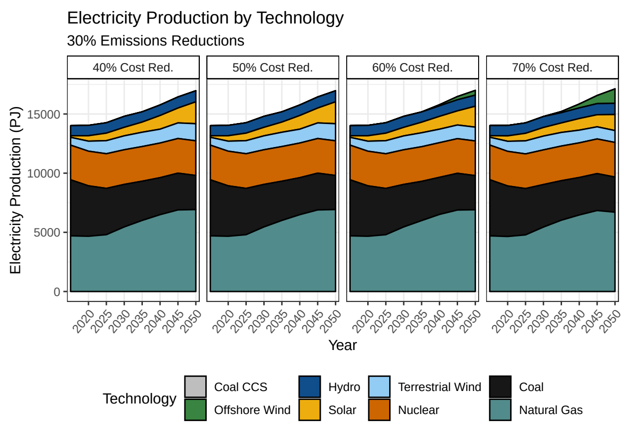
BAU emissions



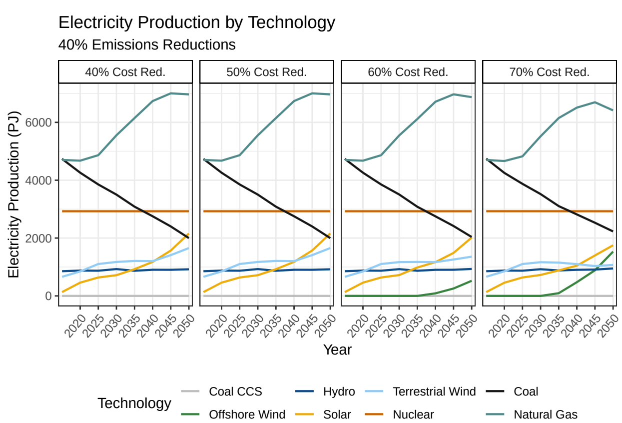


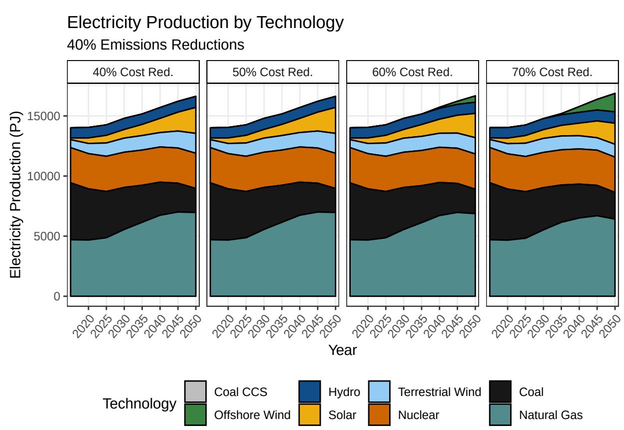
30% emissions reduction



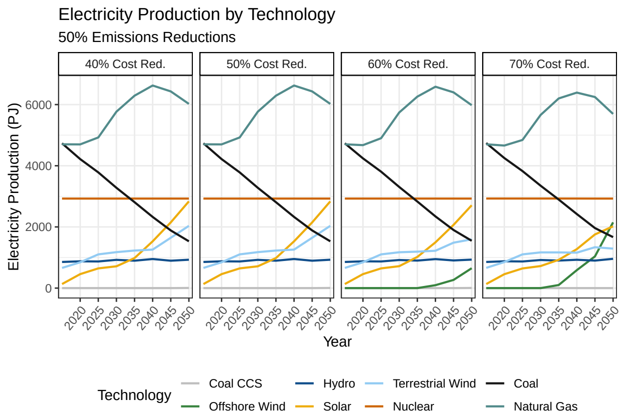


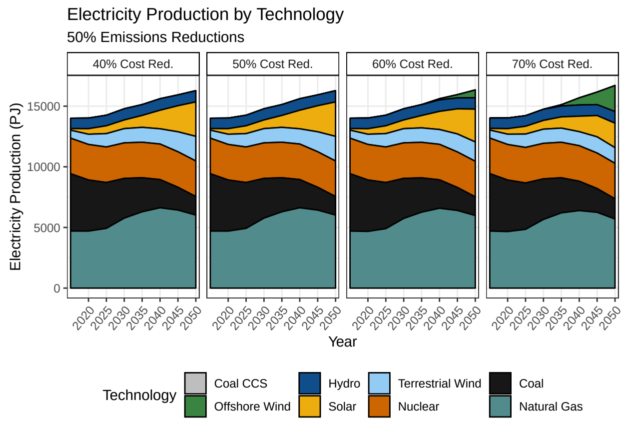
40% emissions reduction



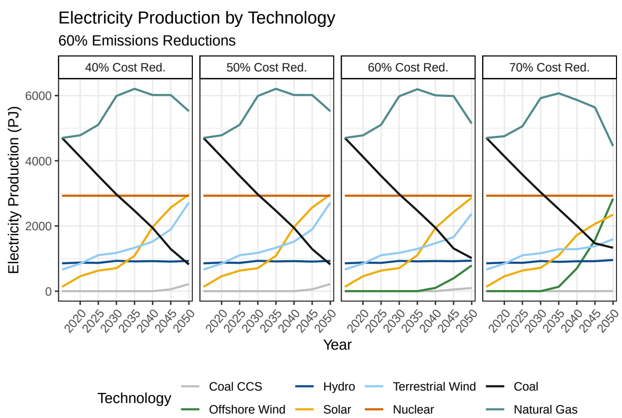


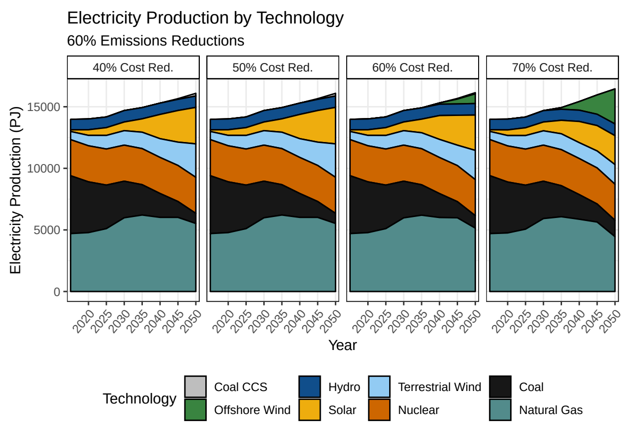
50% emissions reduction



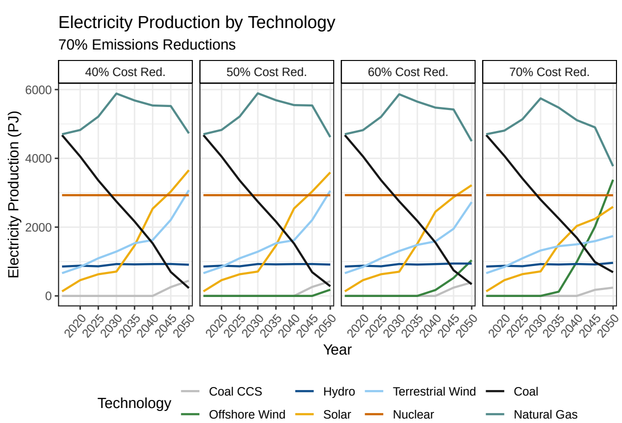


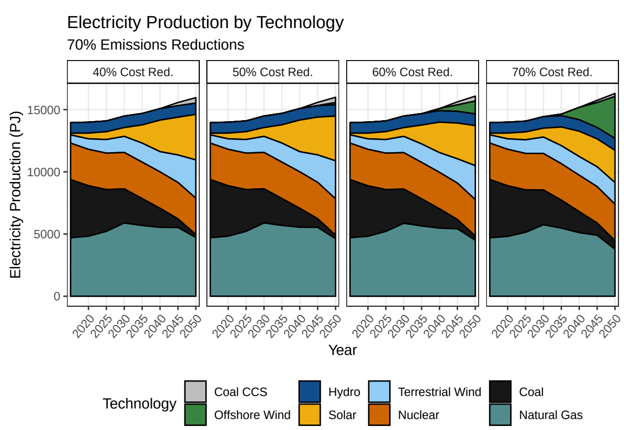
60% emissions reduction



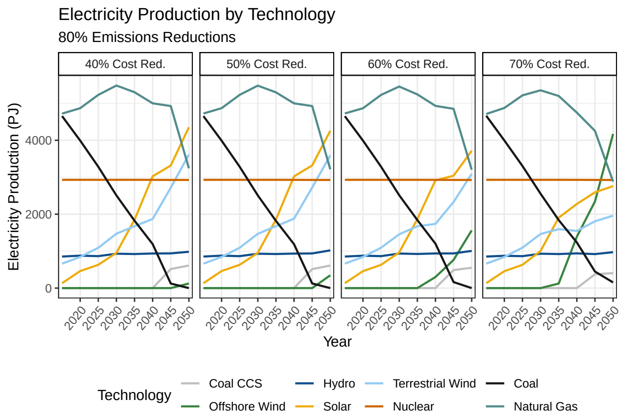


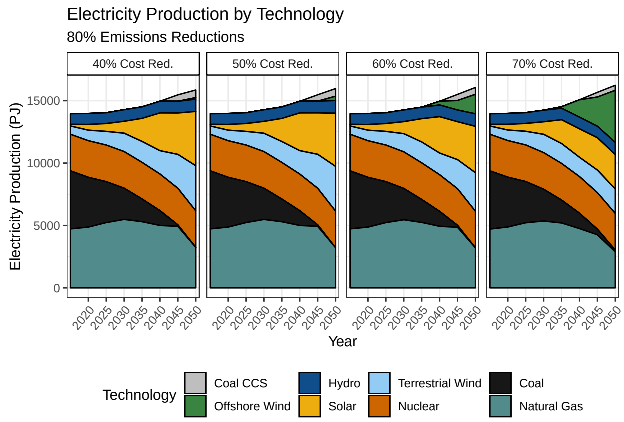
70% emissions reduction





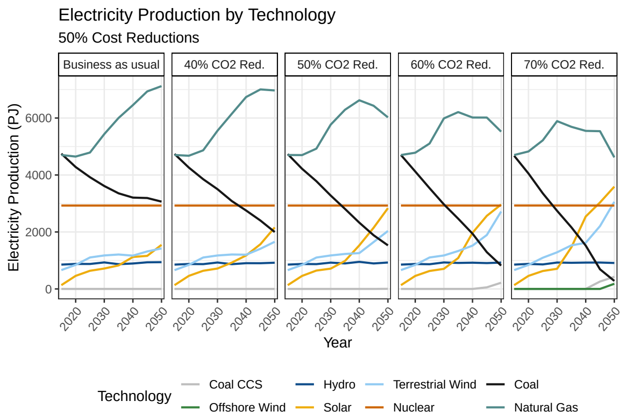
80% emissions reduction

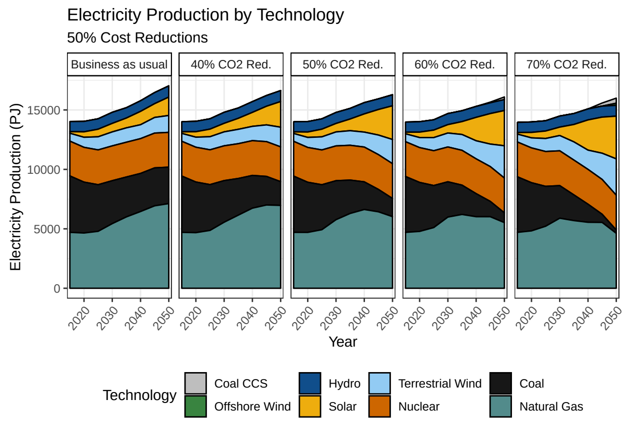




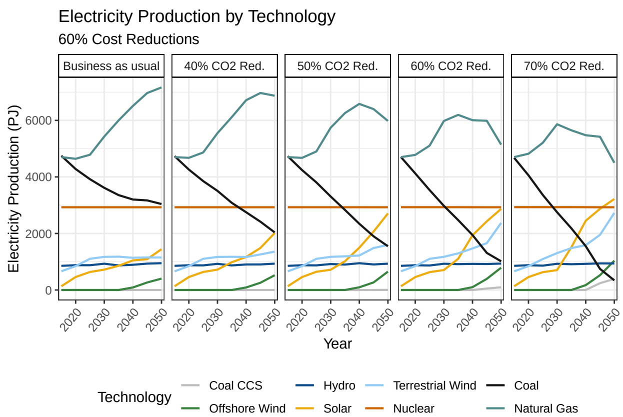
6.5 Cost Reductions

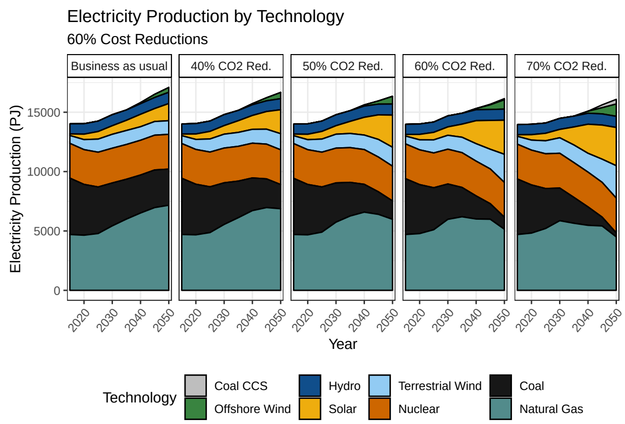
50% cost reduction



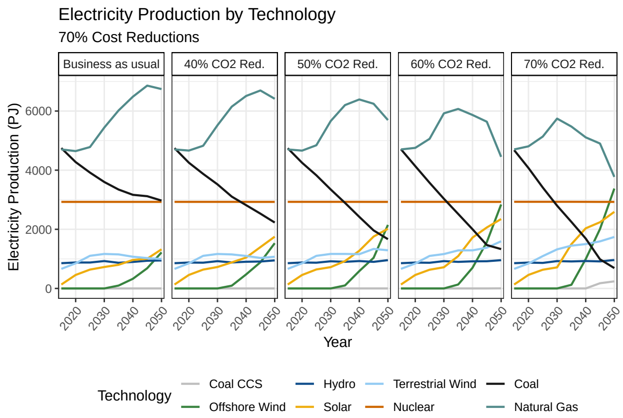


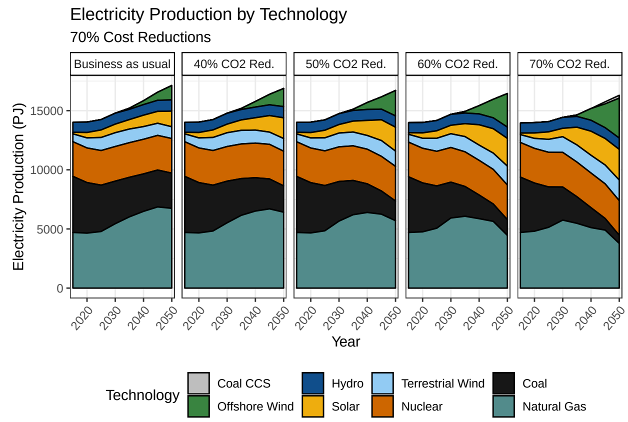
60% cost reduction



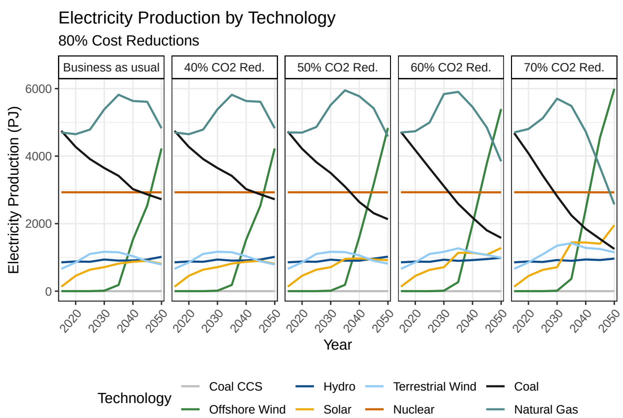


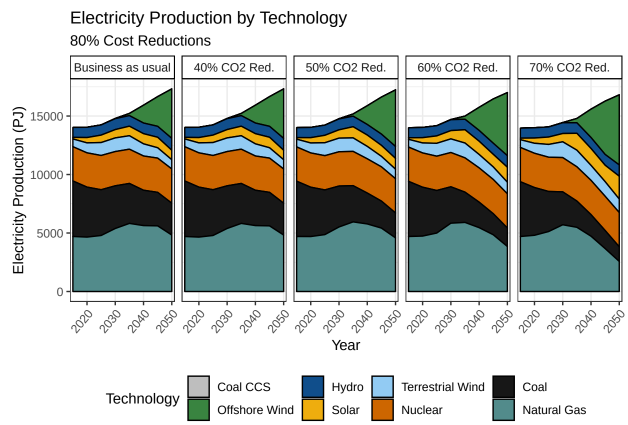
70% cost reduction



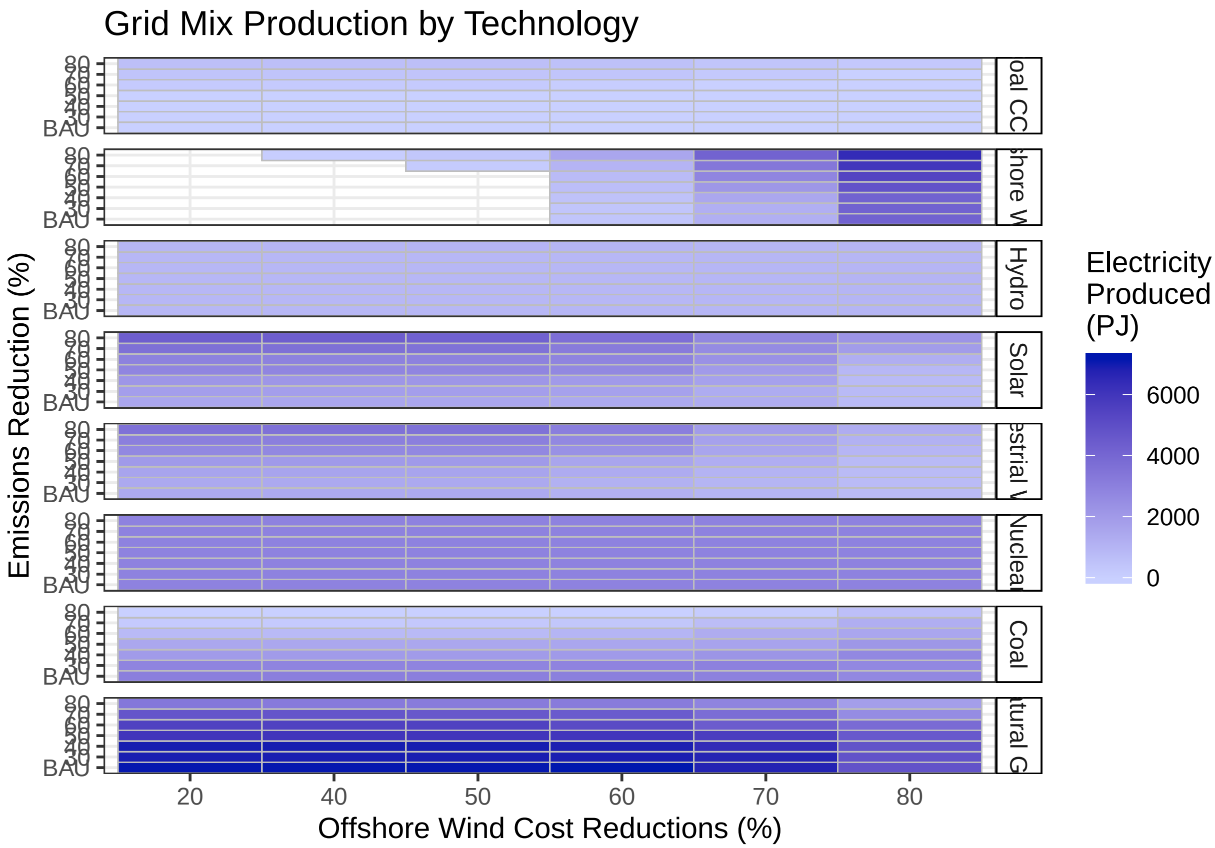


80% cost reduction

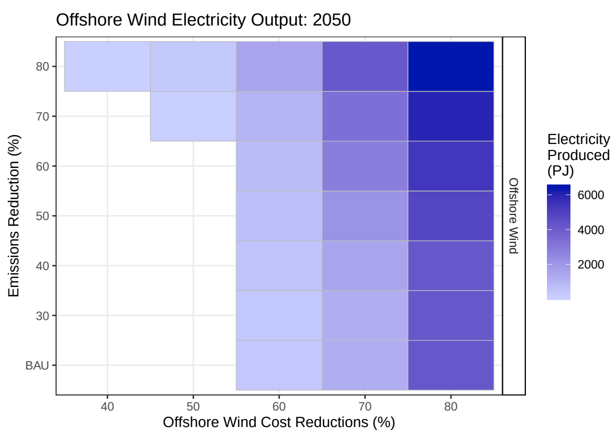




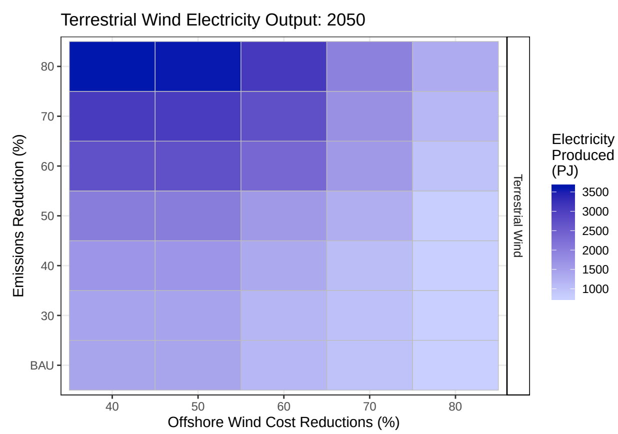
6.6 Heatmaps



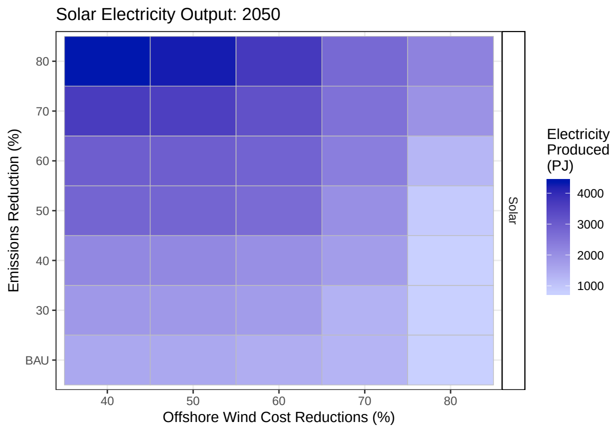
Grid Mix Production by Technology
Emissions Reduction (%)
Offshore Wind Cost Reductions (%)
20
40
50
60
70
80
Hydro
Solar
Coal
Electricity Produced (PJ)
6000
4000
2000
0

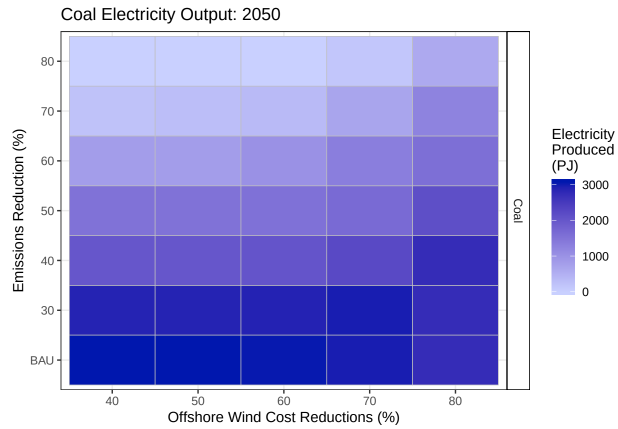


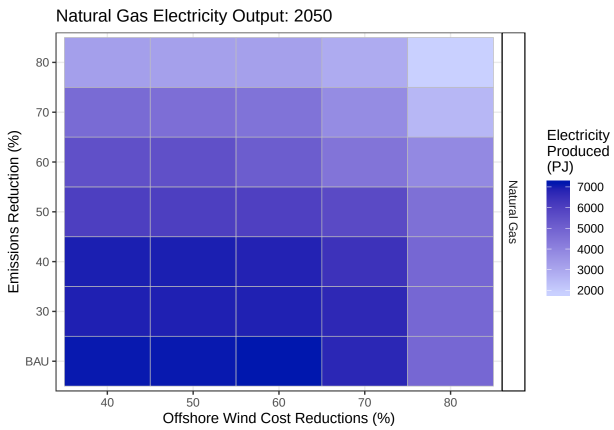
Offshore Wind Electricity Output: 2050
Emissions Reduction (%)
80
70
60
50
40
30
BAU
Offshore Wind Cost Reductions (%)
40
50
60
70
80
Offshore Wind
Electricity Produced (PJ)
6000
4000
2000

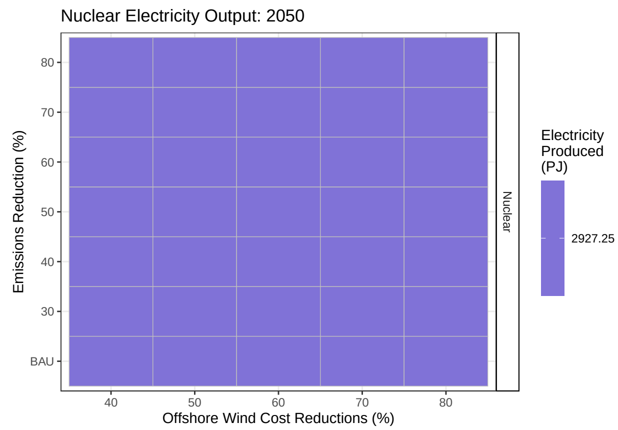


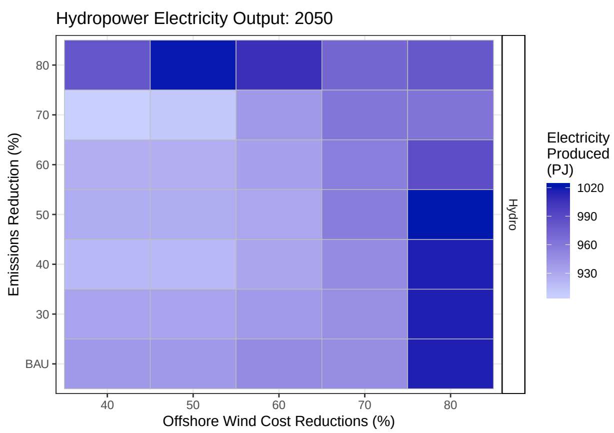
Terrestrial Wind Electricity Output: 2050
Emissions Reduction (%)
80
70
60
50
40
30
BAU
Offshore Wind Cost Reductions (%)
40
50
60
70
80
Terrestrial Wind
Electricity Produced (PJ)
3500
3000
2500
2000
1500
1000

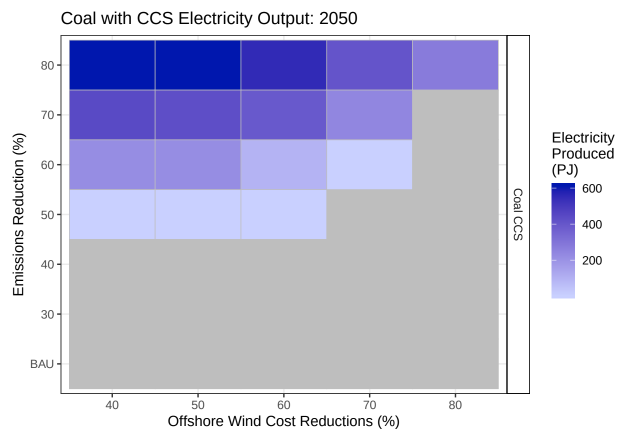












6.7 Market Share

```
## $Coal
##    Scenario           emred    costred  Technology           Year
##  Length:336           BAU:48   20:56   Length:336         Length:336
##  Class :character     30 :48   30: 0   Class :character   Class :character
##  Mode  :character     40 :48   40:56   Mode  :character   Mode  :character
##                       50 :48   50:56
##                       60 :48   60:56
##                       70 :48   70:56
##                       80 :48   80:56
##      Output           Total        MarketShare
```

```
##  Min.   :   0   Min.   :13945   Min.   : 0.00
##  1st Qu.:2327   1st Qu.:14040   1st Qu.:14.89
##  Median :3192   Median :14792   Median :20.35
##  Mean   :3049   Mean   :15002   Mean   :20.73
##  3rd Qu.:3940   3rd Qu.:15762   3rd Qu.:27.78
##  Max.   :4749   Max.   :17318   Max.   :33.86
##
##
## $`Coal CCS`
##    Scenario         emred    costred  Technology           Year
##  Length:336         BAU:48   20:56   Length:336         Length:336
##  Class :character   30 :48   30: 0   Class :character   Class :character
##  Mode  :character   40 :48   40:56   Mode  :character   Mode  :character
##                     50 :48   50:56
##                     60 :48   60:56
##                     70 :48   70:56
##                     80 :48   80:56
##      Output           Total        MarketShare
##  Min.   :  0.00   Min.   :13945   Min.   :0.0000
##  1st Qu.:  0.00   1st Qu.:14040   1st Qu.:0.0000
##  Median :  0.00   Median :14792   Median :0.0000
##  Mean   : 28.55   Mean   :15002   Mean   :0.1803
##  3rd Qu.:  0.00   3rd Qu.:15762   3rd Qu.:0.0000
##  Max.   :610.84   Max.   :17318   Max.   :3.8500
##
##
## $Hydro
##    Scenario         emred    costred  Technology           Year
##  Length:336         BAU:48   20:56   Length:336         Length:336
##  Class :character   30 :48   30: 0   Class :character   Class :character
##  Mode  :character   40 :48   40:56   Mode  :character   Mode  :character
##                     50 :48   50:56
##                     60 :48   60:56
##                     70 :48   70:56
##                     80 :48   80:56
##      Output           Total        MarketShare
##  Min.   : 854.0   Min.   :13945   Min.   :5.500
##  1st Qu.: 870.7   1st Qu.:14040   1st Qu.:5.768
##  Median : 903.0   Median :14792   Median :6.110
##  Mean   : 902.2   Mean   :15002   Mean   :6.026
##  3rd Qu.: 928.5   3rd Qu.:15762   3rd Qu.:6.250
##  Max.   :1021.6   Max.   :17318   Max.   :6.560
##
##
## $`Natural Gas`
##    Scenario         emred    costred  Technology           Year
##  Length:336         BAU:48   20:56   Length:336         Length:336
##  Class :character   30 :48   30: 0   Class :character   Class :character
##  Mode  :character   40 :48   40:56   Mode  :character   Mode  :character
##                     50 :48   50:56
##                     60 :48   60:56
##                     70 :48   70:56
##                     80 :48   80:56
##      Output         Total        MarketShare
```

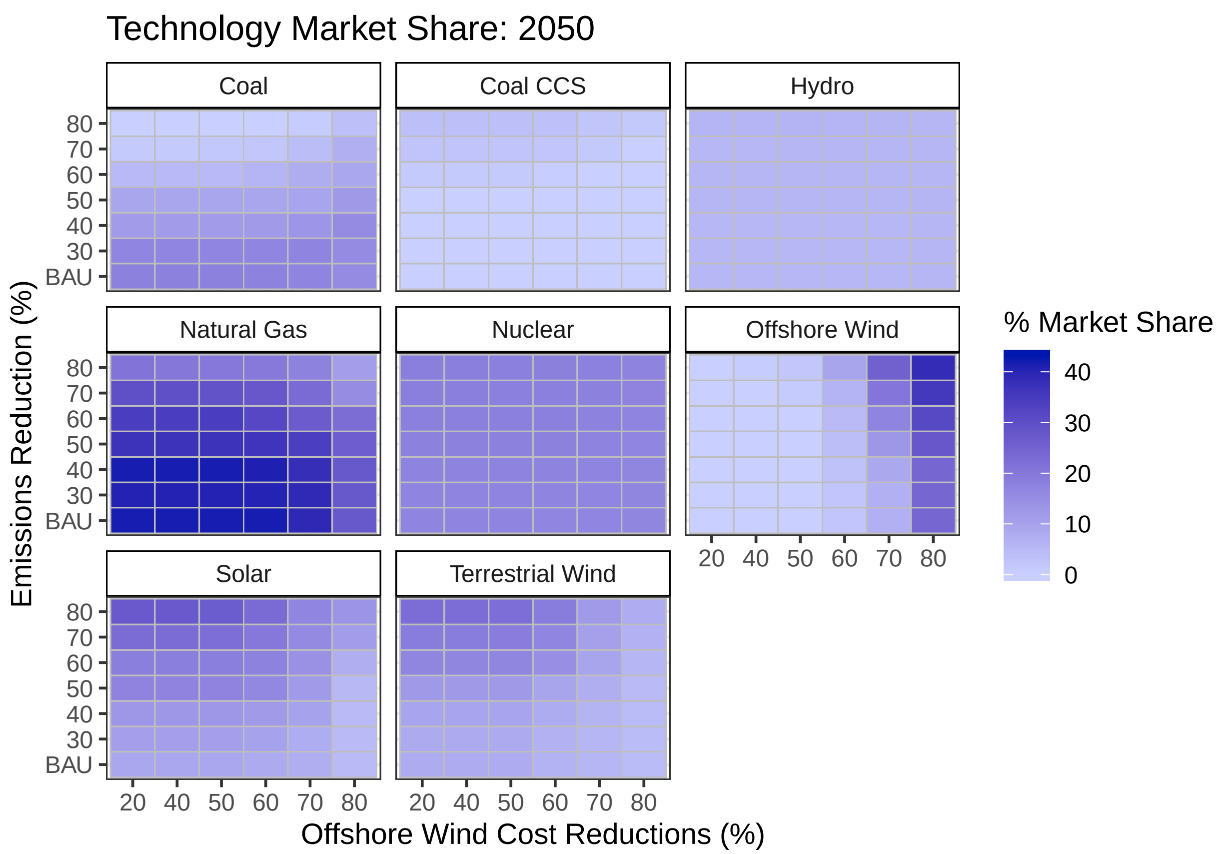
```
##  Min.   :1881   Min.   :13945   Min.   :11.27
##  1st Qu.:4727   1st Qu.:14040   1st Qu.:33.56
##  Median :5301   Median :14792   Median :36.02
##  Mean   :5393   Mean   :15002   Mean   :35.92
##  3rd Qu.:6004   3rd Qu.:15762   3rd Qu.:39.52
##  Max.   :7167   Max.   :17318   Max.   :43.20
##
##
## $Nuclear
##    Scenario          emred    costred  Technology            Year
##  Length:336         BAU:48   20:56   Length:336         Length:336
##  Class :character   30 :48   30: 0   Class :character   Class :character
##  Mode  :character   40 :48   40:56   Mode  :character   Mode  :character
##                     50 :48   50:56
##                     60 :48   60:56
##                     70 :48   70:56
##                     80 :48   80:56
##      Output         Total         MarketShare
##  Min.   :2927   Min.   :13945   Min.   :16.90
##  1st Qu.:2927   1st Qu.:14040   1st Qu.:18.57
##  Median :2927   Median :14792   Median :19.80
##  Mean   :2928   Mean   :15002   Mean   :19.59
##  3rd Qu.:2929   3rd Qu.:15762   3rd Qu.:20.85
##  Max.   :2930   Max.   :17318   Max.   :21.01
##
##
## $`Offshore Wind`
##    Scenario          emred    costred  Technology            Year
##  Length:336         BAU:48   20:56   Length:336         Length:336
##  Class :character   30 :48   30: 0   Class :character   Class :character
##  Mode  :character   40 :48   40:56   Mode  :character   Mode  :character
##                     50 :48   50:56
##                     60 :48   60:56
##                     70 :48   70:56
##                     80 :48   80:56
##      Output            Total         MarketShare
##  Min.   :   0.00   Min.   :13945   Min.   : 0.000
##  1st Qu.:   0.00   1st Qu.:14040   1st Qu.: 0.000
##  Median :   0.00   Median :14792   Median : 0.000
##  Mean   : 346.17   Mean   :15002   Mean   : 2.113
##  3rd Qu.:  13.46   3rd Qu.:15762   3rd Qu.: 0.090
##  Max.   :6424.29   Max.   :17318   Max.   :38.480
##
##
## $Solar
##    Scenario          emred    costred  Technology            Year
##  Length:336         BAU:48   20:56   Length:336         Length:336
##  Class :character   30 :48   30: 0   Class :character   Class :character
##  Mode  :character   40 :48   40:56   Mode  :character   Mode  :character
##                     50 :48   50:56
##                     60 :48   60:56
##                     70 :48   70:56
##                     80 :48   80:56
##      Output           Total         MarketShare
```

```
##  Min.   : 132.3   Min.   :13945   Min.   : 0.940
##  1st Qu.: 587.4   1st Qu.:14040   1st Qu.: 4.162
##  Median : 816.2   Median :14792   Median : 5.350
##  Mean   :1121.7   Mean   :15002   Mean   : 7.276
##  3rd Qu.:1501.6   3rd Qu.:15762   3rd Qu.: 9.670
##  Max.   :4352.6   Max.   :17318   Max.   :27.470
##
##
## $`Terrestrial Wind`
##    Scenario          emred    costred  Technology            Year
##  Length:336         BAU:48   20:56   Length:336         Length:336
##  Class :character   30 :48   30: 0   Class :character   Class :character
##  Mode  :character   40 :48   40:56   Mode  :character   Mode  :character
##                     50 :48   50:56
##                     60 :48   60:56
##                     70 :48   70:56
##                     80 :48   80:56
##      Output           Total        MarketShare
##  Min.   : 659.8   Min.   :13945   Min.   : 4.560
##  1st Qu.: 852.2   1st Qu.:14040   1st Qu.: 6.055
##  Median :1166.2   Median :14792   Median : 7.770
##  Mean   :1234.2   Mean   :15002   Mean   : 8.160
##  3rd Qu.:1350.4   3rd Qu.:15762   3rd Qu.: 8.700
##  Max.   :3614.8   Max.   :17318   Max.   :22.810
##
```

Table 6: 2050 Percent Market Share by Technology

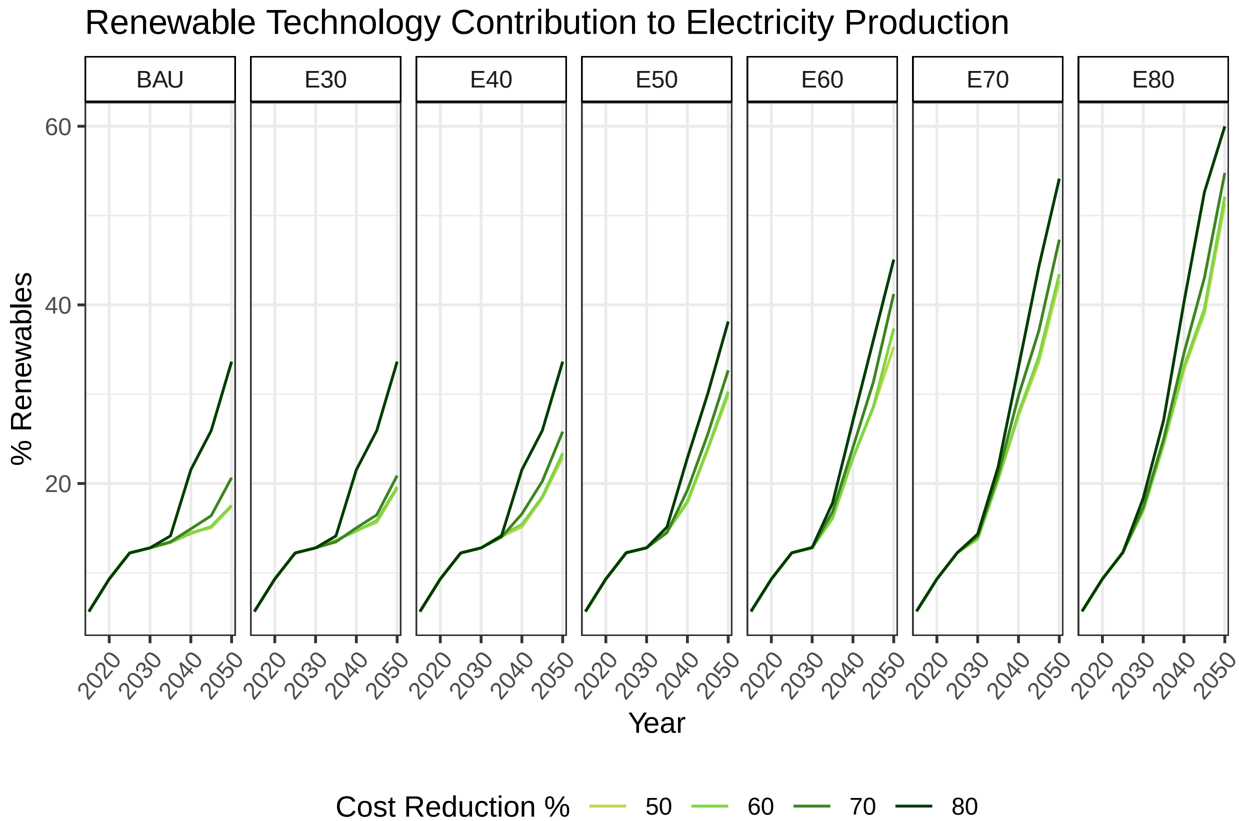
		Cost Reduction (%)					
Technology	CO2 Cap	20	40	50	60	70	80
Coal	BAU	18.0	18.0	18.0	17.8	17.4	15.7
	30	17.0	17.0	17.0	17.0	17.3	15.7
	40	12.0	12.0	12.0	12.2	13.2	15.7
	50	9.4	9.4	9.4	9.5	10.0	12.4
	60	5.1	5.1	5.1	6.3	8.1	9.3
	70	1.4	1.4	1.8	2.1	4.2	7.4
	80	0.0	0.0	0.0	0.0	0.9	3.7
Coal CCS	BAU	0.0	0.0	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	1.4	1.4	1.4	0.6	0.0	0.0
	70	2.8	2.8	2.7	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	5.9
	30	5.5	5.5	5.5	5.5	5.5	5.9
	40	5.5	5.5	5.5	5.6	5.6	5.9
	50	5.7	5.7	5.7	5.7	5.7	5.9
	60	5.8	5.8	5.8	5.8	5.8	5.8
	70	5.7	5.7	5.7	5.8	5.9	5.7
	80	6.2	6.2	6.4	6.3	6.0	5.9
	BAU	41.8	41.8	41.8	42.0	39.4	27.9

Natural Gas	30	40.8	40.8	40.8	40.6	39.1	27.9
	40	41.9	41.9	41.9	41.2	38.0	27.9
	50	37.0	37.0	37.0	36.6	34.1	26.6
	60	34.3	34.3	34.3	31.9	27.1	22.6
	70	29.6	29.6	28.9	28.0	23.1	15.3
	80	21.2	20.4	20.1	19.9	17.8	11.3
Nuclear	BAU	17.2	17.2	17.2	17.1	17.1	16.9
	30	17.2	17.2	17.2	17.2	17.1	16.9
	40	17.6	17.6	17.6	17.6	17.4	16.9
	50	18.0	18.0	18.0	17.9	17.5	17.0
	60	18.2	18.2	18.2	18.1	17.8	17.2
	70	18.3	18.3	18.3	18.2	18.0	17.4
	80	18.5	18.5	18.3	18.2	18.0	17.5
Offshore Wind	BAU	0.0	0.0	0.0	2.4	7.1	24.4
	30	0.0	0.0	0.0	2.3	7.1	24.4
	40	0.0	0.0	0.0	3.1	9.1	24.4
	50	0.0	0.0	0.0	4.0	12.9	28.1
	60	0.0	0.0	0.0	4.9	17.3	31.7
	70	0.0	0.0	1.1	6.5	20.7	35.7
	80	0.0	0.8	2.2	9.7	25.7	38.5
Solar	BAU	9.1	9.1	9.1	8.5	7.7	4.7
	30	10.9	10.9	10.9	10.4	7.9	4.7
	40	13.0	13.0	13.0	12.1	10.4	4.7
	50	17.4	17.4	17.4	16.6	12.1	5.3
	60	18.4	18.4	18.4	17.8	14.3	7.5
	70	22.9	22.9	22.4	20.0	15.9	11.6
	80	27.5	27.4	26.7	23.1	17.0	13.6
Terrestrial Wind	BAU	8.3	8.3	8.3	6.7	5.8	4.6
	30	8.5	8.5	8.5	6.9	5.9	4.6
	40	9.9	9.9	9.9	8.1	6.3	4.6
	50	12.5	12.5	12.5	9.8	7.7	4.7
	60	16.9	16.9	16.9	14.7	9.7	5.8
	70	19.3	19.3	19.1	17.0	10.7	6.8
	80	22.8	22.8	22.5	19.3	12.1	8.0



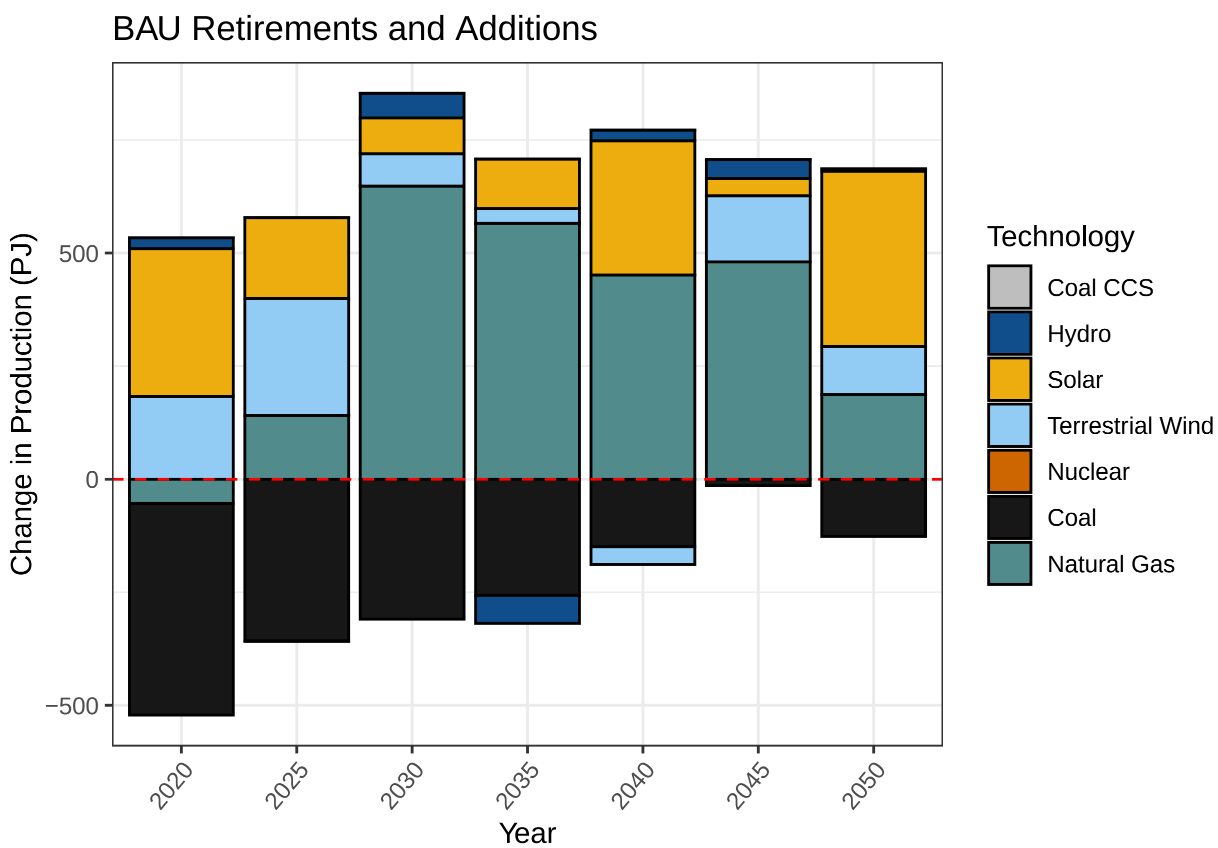
Technology Market Share: 2050
Coal
Coal CCS
Hydro
Natural Gas
Nuclear
Offshore Wind
Solar
Terrestrial Wind
Emissions Reduction (%)
80
70
60
50
40
30
BAU
20
40
50
60
70
80
Offshore Wind Cost Reductions (%)
% Market Share
40
30
20
10
0

6.8 Renewable Contributions



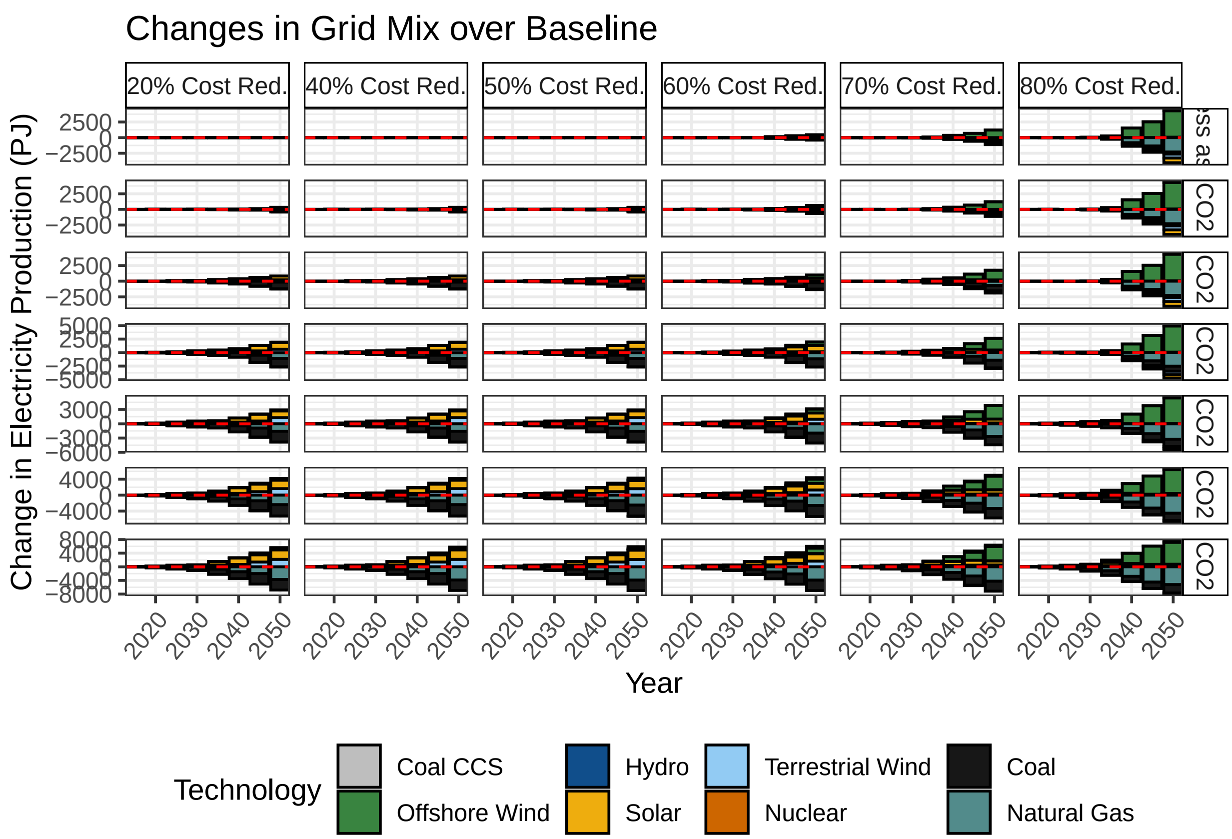
6.9 Retirements and Additions

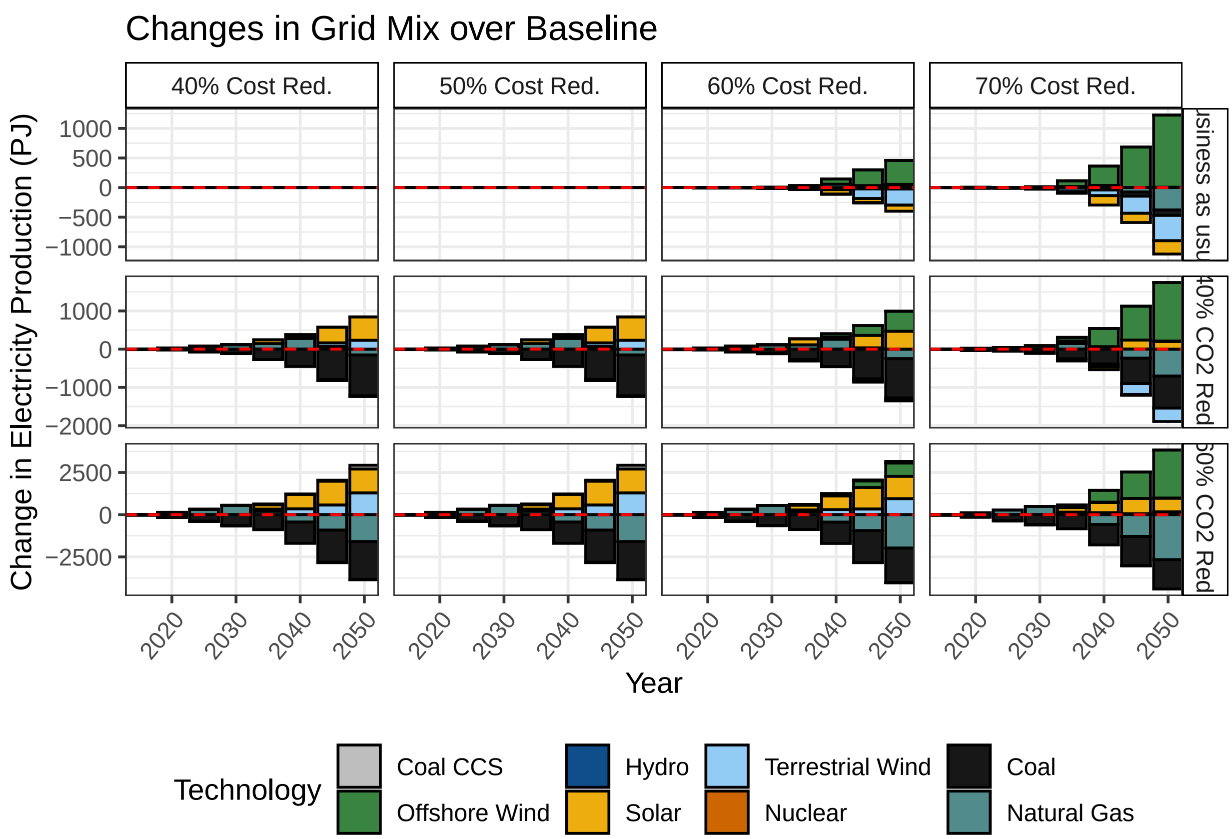
Basecase year-on-year changes in the grid mix. Shows the modeled fluctuations in generation. All following quantifications of grid mix changes are as compared to these changes in the basecase.



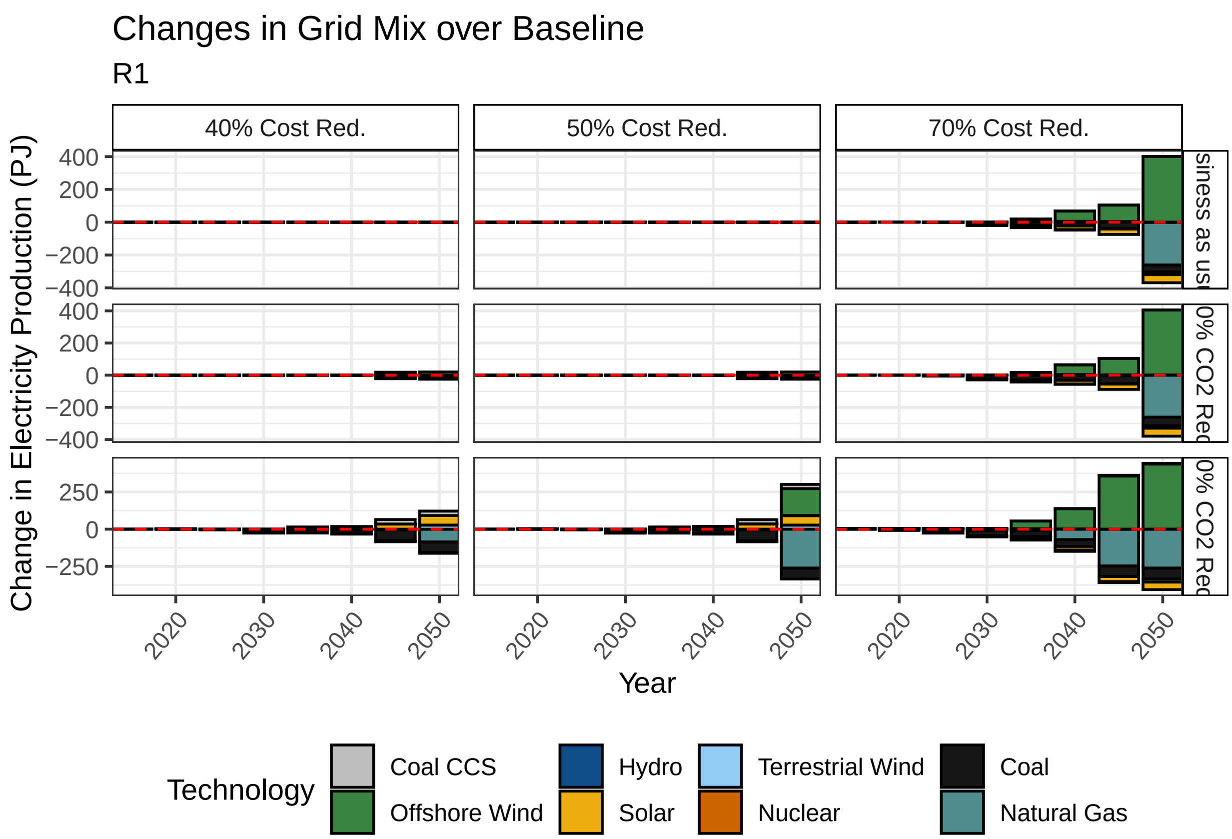
6.10 Changes Over Baseline

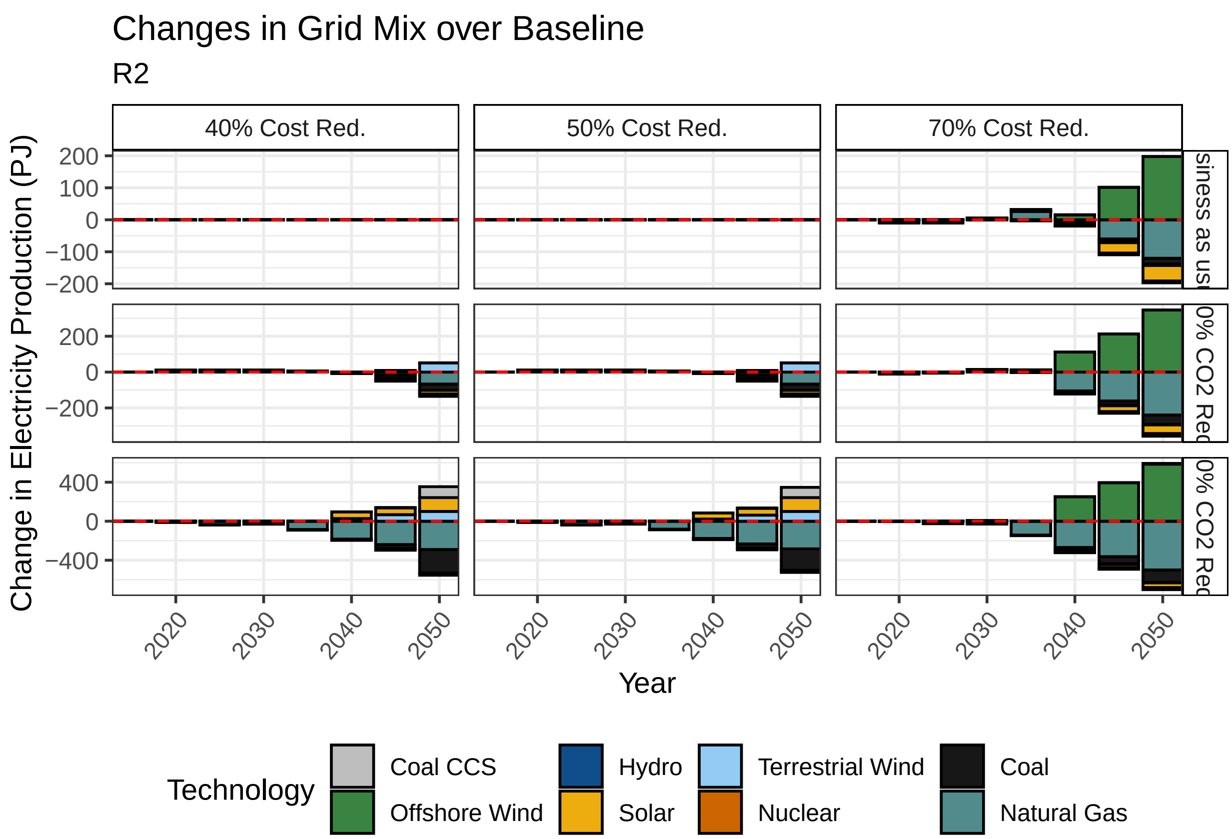
Summary Graph


Changes in Grid Mix over Baseline
20% Cost Red.
40% Cost Red.
50% Cost Red.
60% Cost Red.
70% Cost Red.
80% Cost Red.
Change in Electricity Production (PJ)
Year
CO2
Technology
Coal CCS
Hydro
Terrestrial Wind
Coal
Offshore Wind
Solar
Nuclear
Natural Gas

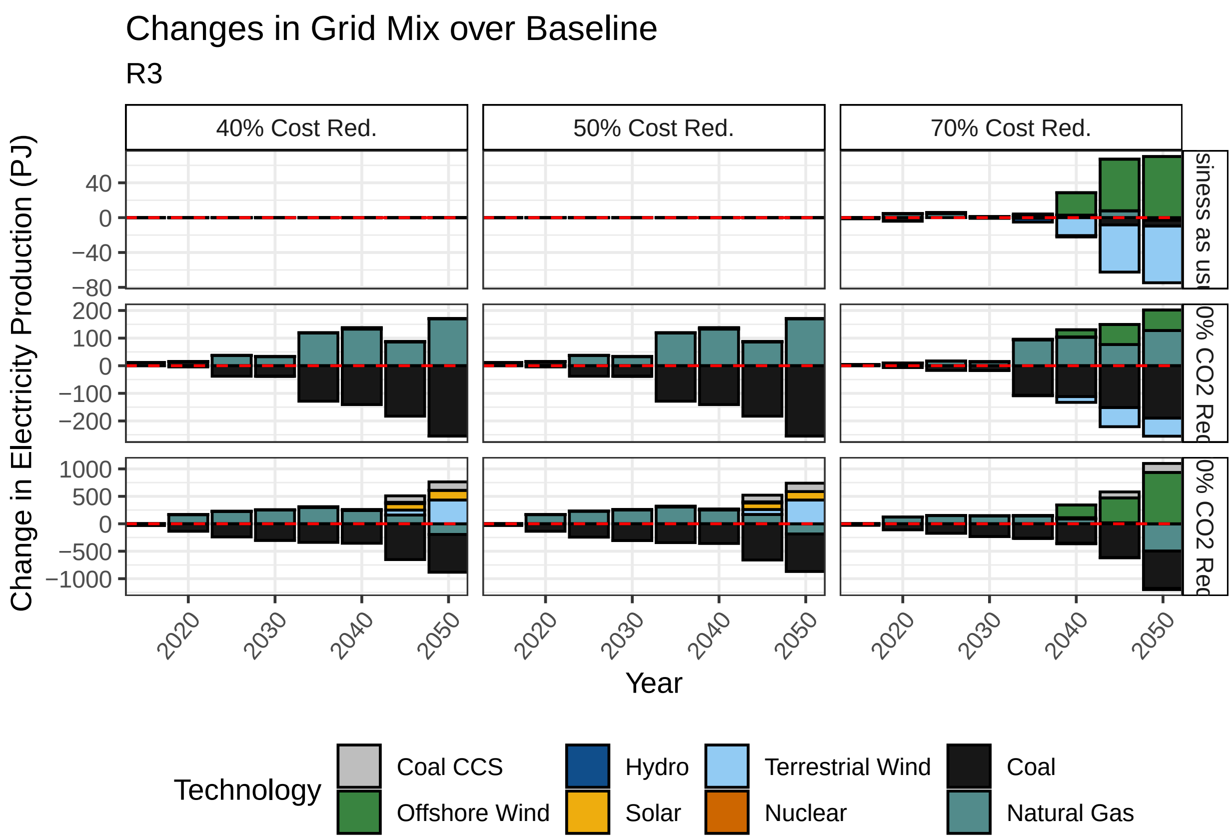


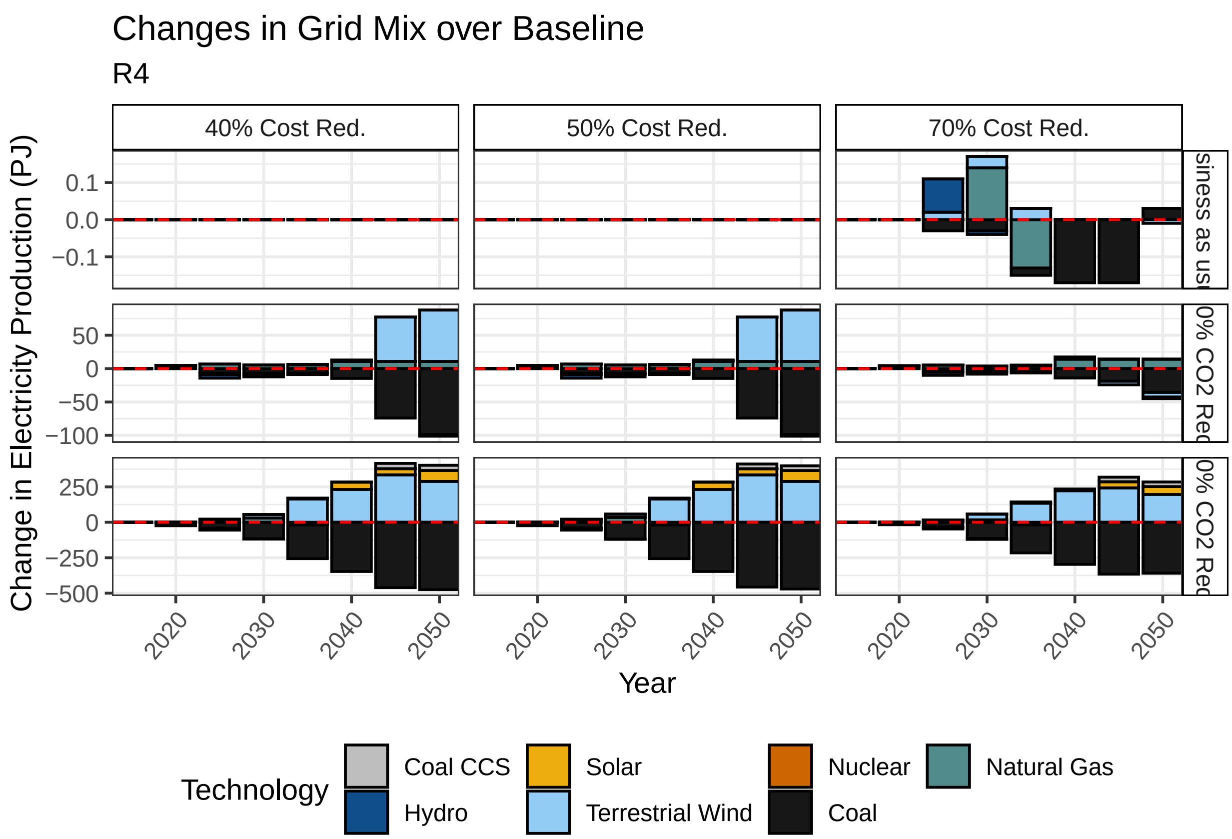
Regional Summary Graphs


Changes in Grid Mix over Baseline
R1
40% Cost Red.
50% Cost Red.
70% Cost Red.
siness as us
0% CO2 Red
0% CO2 Red
Change in Electricity Production (PJ)
400
200
0
−200
−400
250
−250
2020
2030
2040
2050
Year
Technology
Coal CCS
Offshore Wind
Hydro
Solar
Terrestrial Wind
Nuclear
Coal
Natural Gas

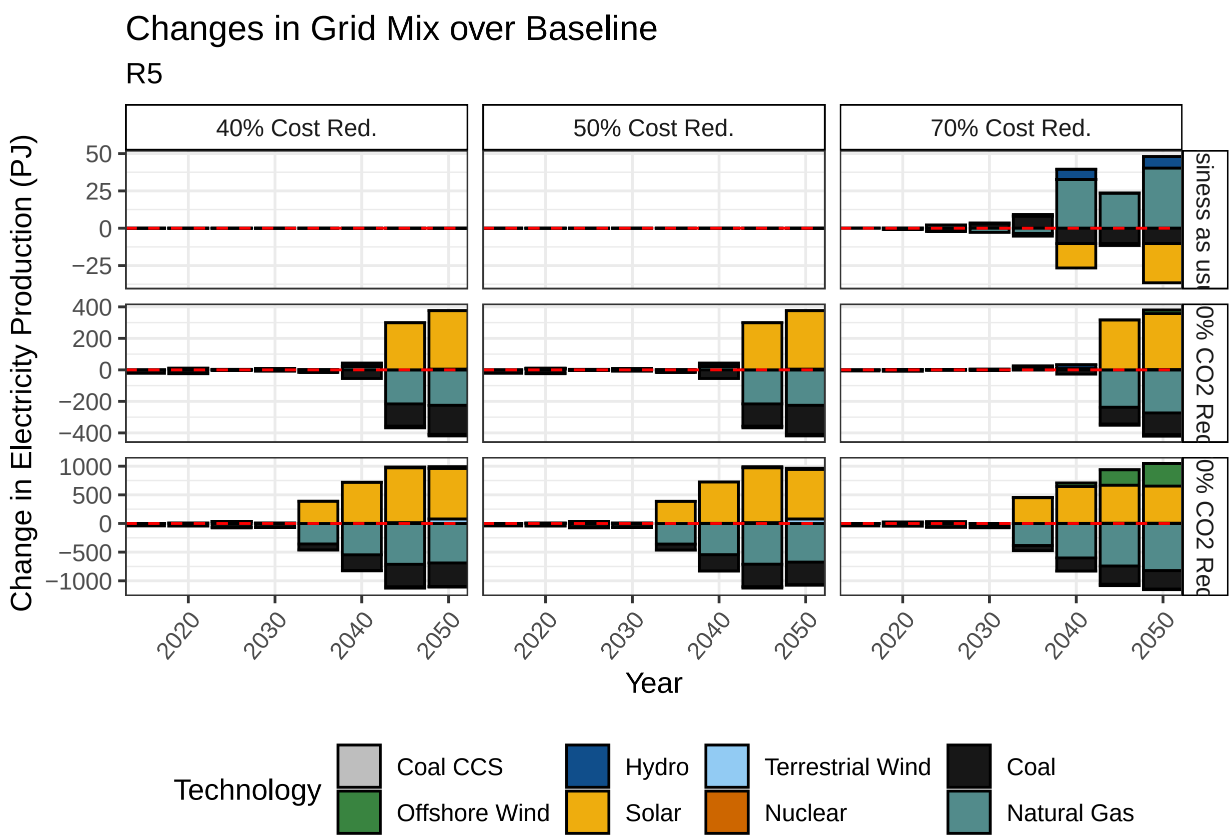


Changes in Grid Mix over Baseline
R2
40% Cost Red.
50% Cost Red.
70% Cost Red.
siness as usu
0% CO2 Red
0% CO2 Red
Change in Electricity Production (PJ)
200
100
0
−100
−200
400
−400
2020
2030
2040
2050
Year
Technology
Coal CCS
Offshore Wind
Hydro
Solar
Terrestrial Wind
Nuclear
Coal
Natural Gas

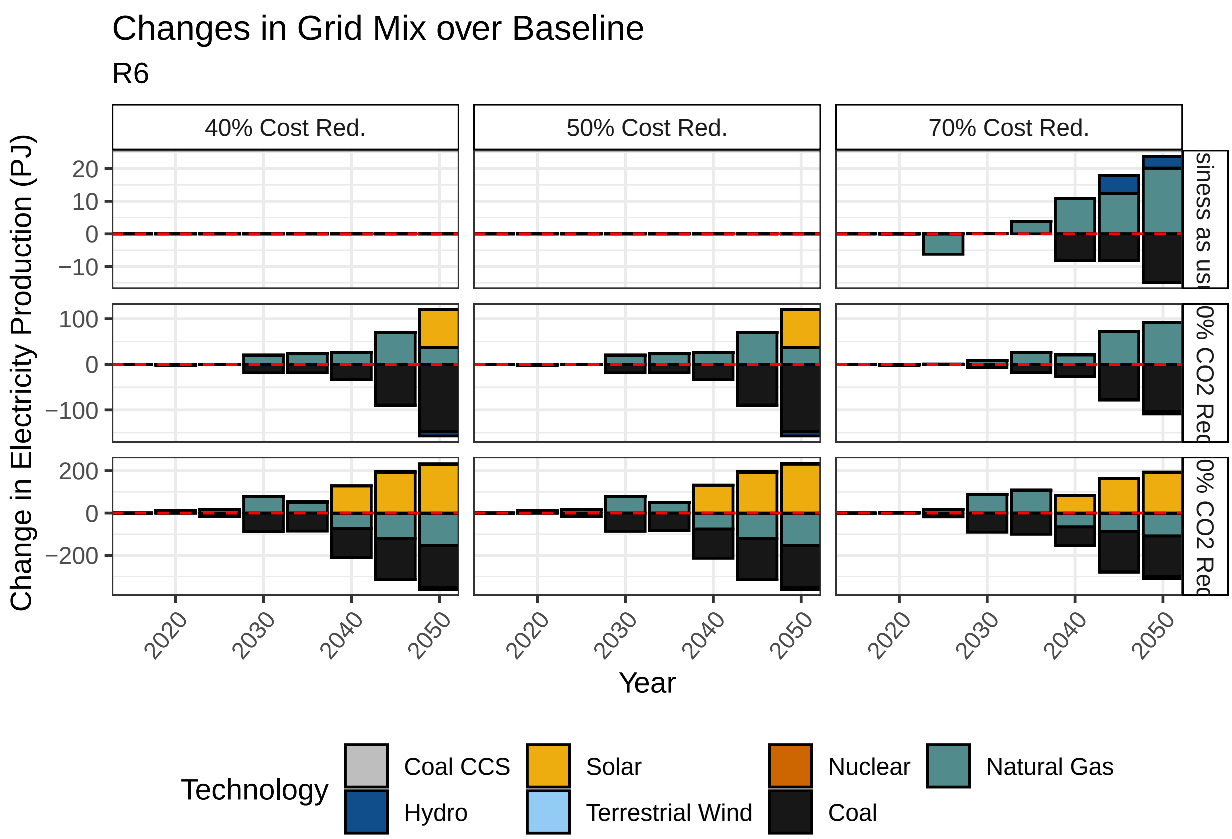

Changes in Grid Mix over Baseline
R3
40% Cost Red.
50% Cost Red.
70% Cost Red.
siness as usu
0% CO2 Red
0% CO2 Red
Change in Electricity Production (PJ)
40
0
−40
−80
200
100
0
−100
−200
1000
500
0
−500
−1000
2020
2030
2040
2050
Year
Technology
Coal CCS
Offshore Wind
Hydro
Solar
Terrestrial Wind
Nuclear
Coal
Natural Gas

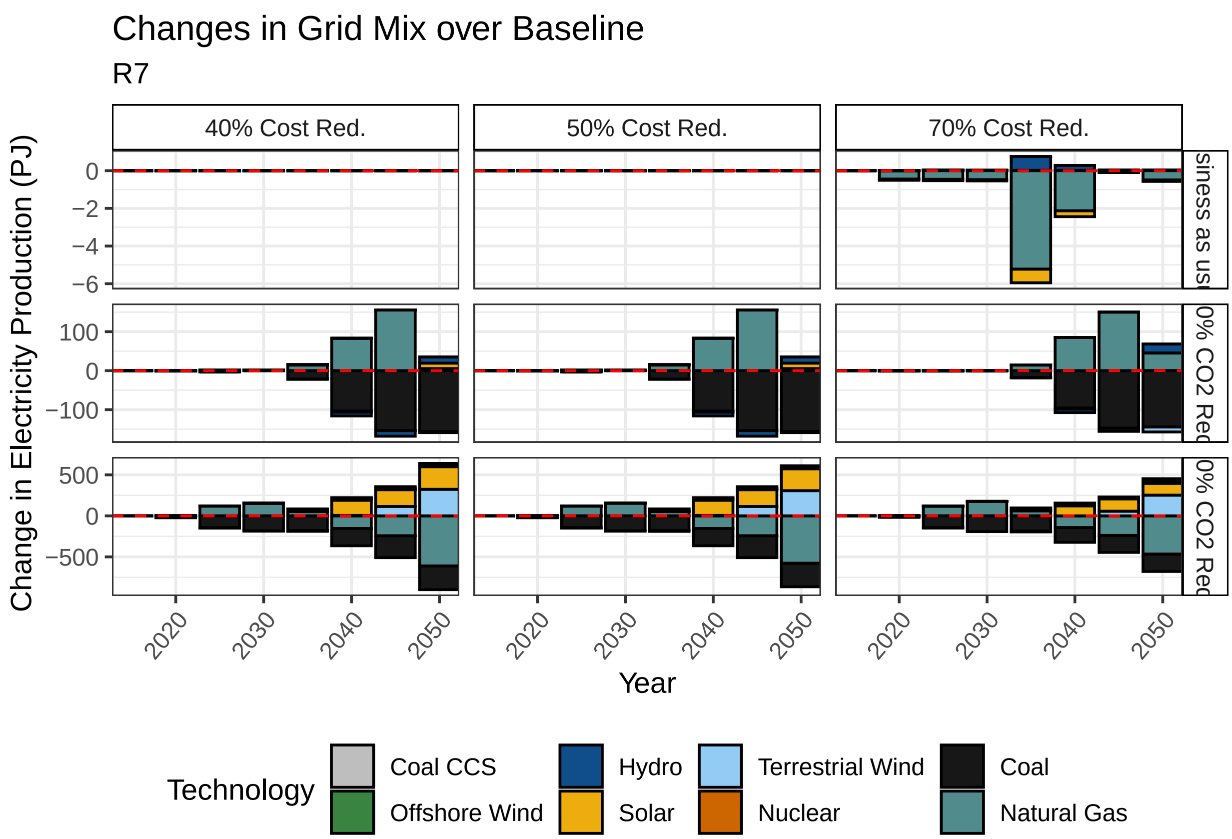


Changes in Grid Mix over Baseline
R4
40% Cost Red.
50% Cost Red.
70% Cost Red.
siness as us
0% CO2 Red
0% CO2 Red
0.1
0.0
−0.1
50
0
−50
−100
250
0
−250
−500
Change in Electricity Production (PJ)
2020
2030
2040
2050
Year
Technology
Coal CCS
Hydro
Solar
Terrestrial Wind
Nuclear
Coal
Natural Gas

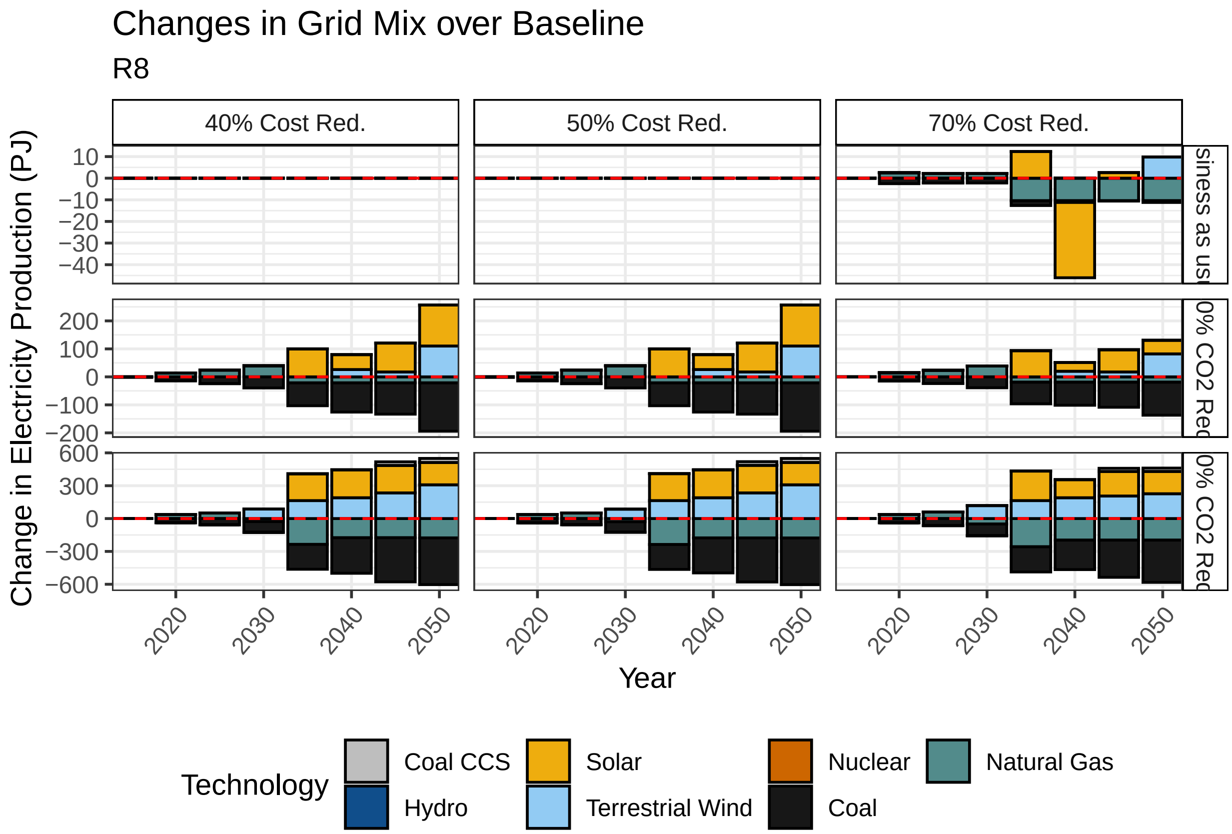


Changes in Grid Mix over Baseline
R5
40% Cost Red.
50% Cost Red.
70% Cost Red.
Change in Electricity Production (PJ)
Year
Technology
Coal CCS
Offshore Wind
Hydro
Solar
Terrestrial Wind
Nuclear
Coal
Natural Gas

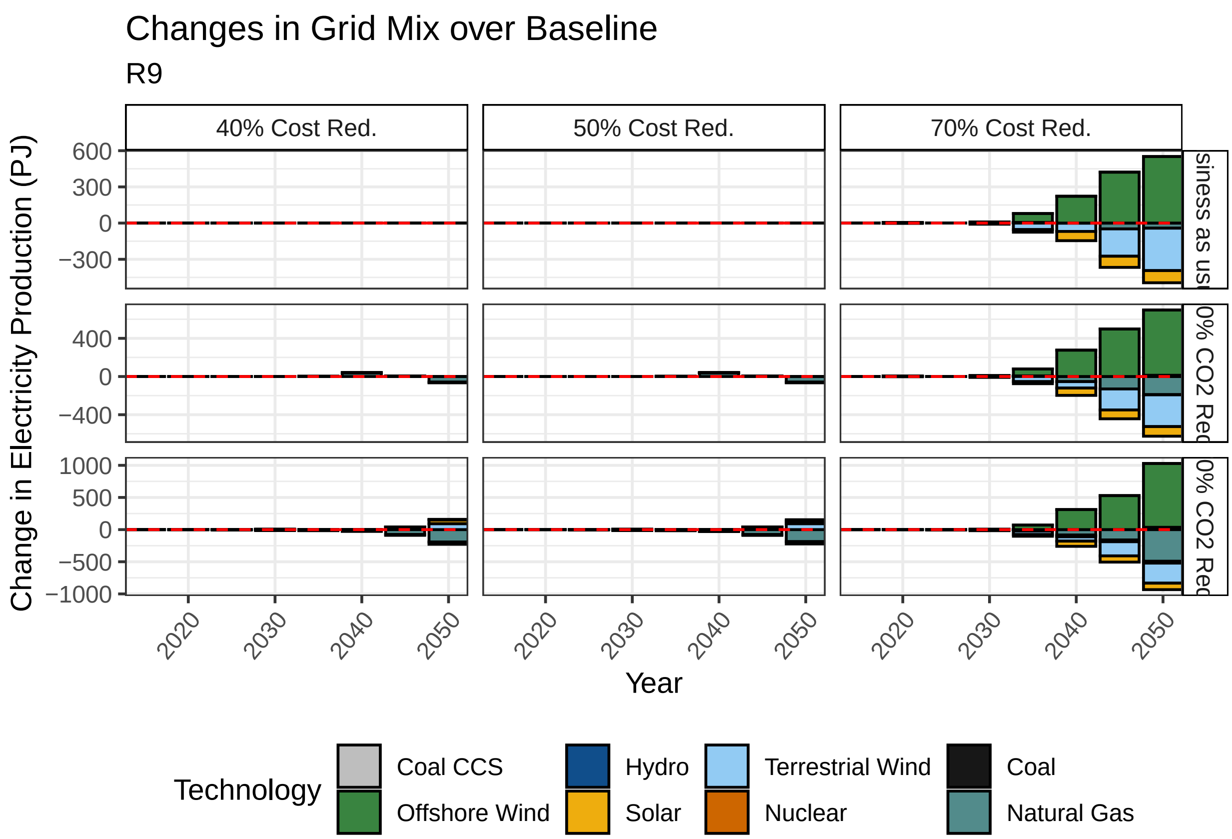

Changes in Grid Mix over Baseline
R6
40% Cost Red.
50% Cost Red.
70% Cost Red.
Change in Electricity Production (PJ)
Year
Technology
Coal CCS
Hydro
Solar
Terrestrial Wind
Nuclear
Coal
Natural Gas



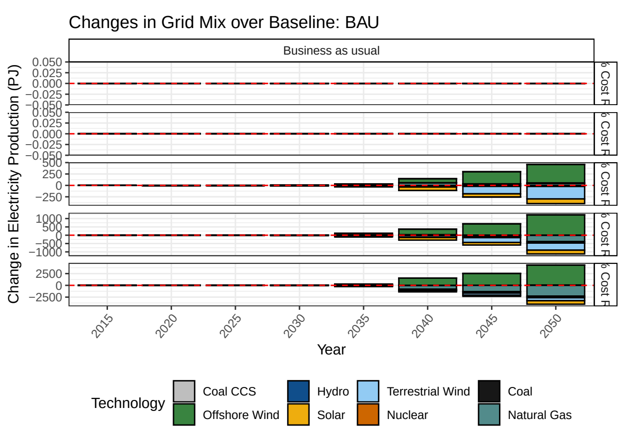
Changes in Grid Mix over Baseline
R7
40% Cost Red.
50% Cost Red.
70% Cost Red.
siness as us
0% CO2 Red
0% CO2 Red
Change in Electricity Production (PJ)
0
−2
−4
−6
100
0
−100
500
0
−500
2020
2030
2040
2050
Year
Technology
Coal CCS
Offshore Wind
Hydro
Solar
Terrestrial Wind
Nuclear
Coal
Natural Gas

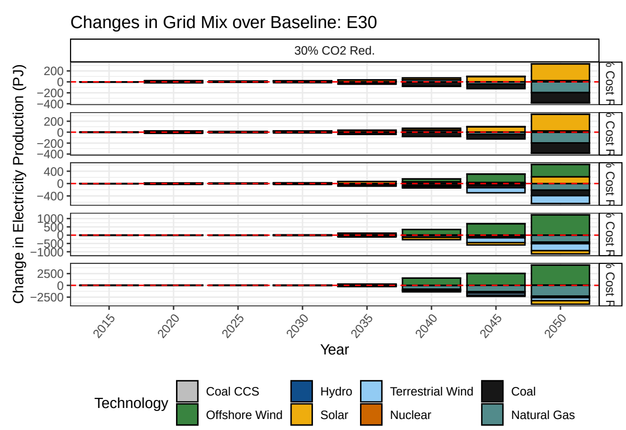


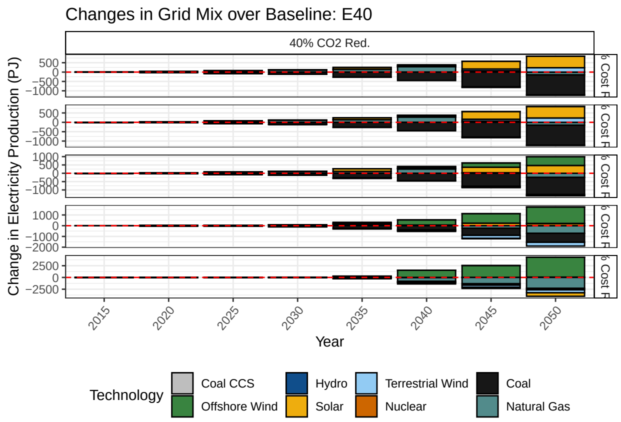
Changes in Grid Mix over Baseline
R8
40% Cost Red.
50% Cost Red.
70% Cost Red.
Change in Electricity Production (PJ)
Year
Technology
Coal CCS
Hydro
Solar
Terrestrial Wind
Nuclear
Coal
Natural Gas

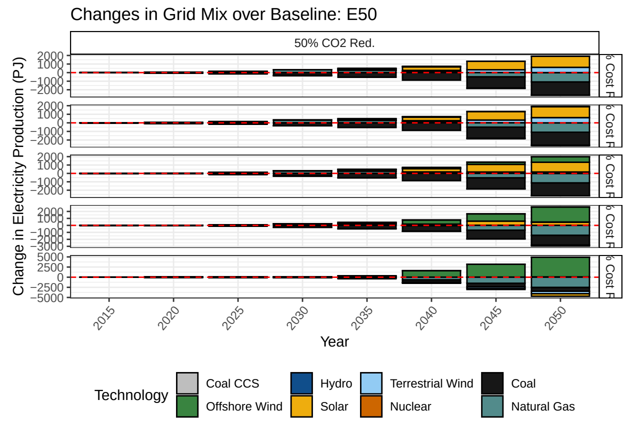


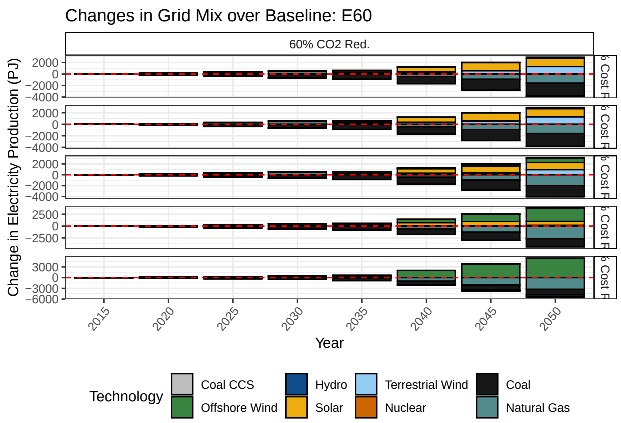
By Emissions Reduction %

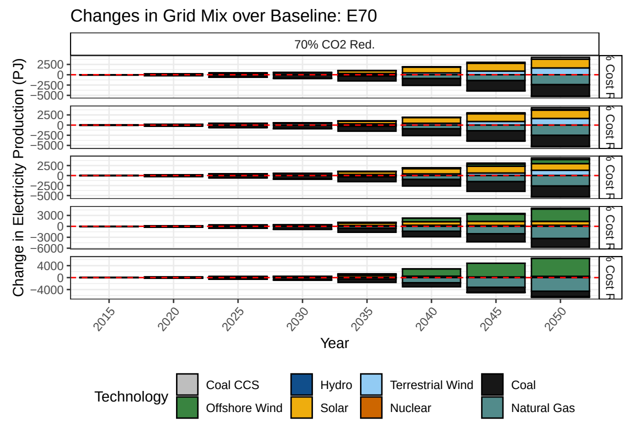


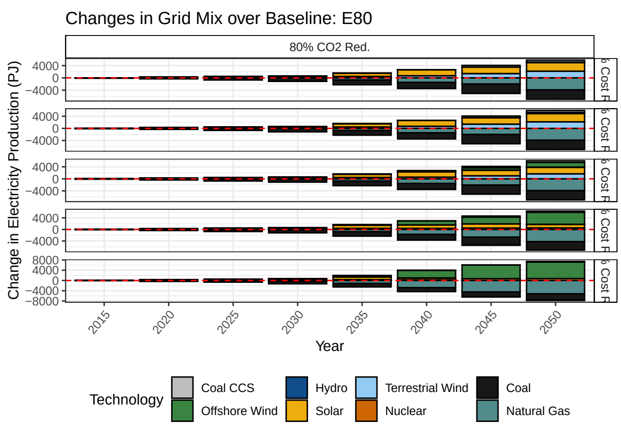




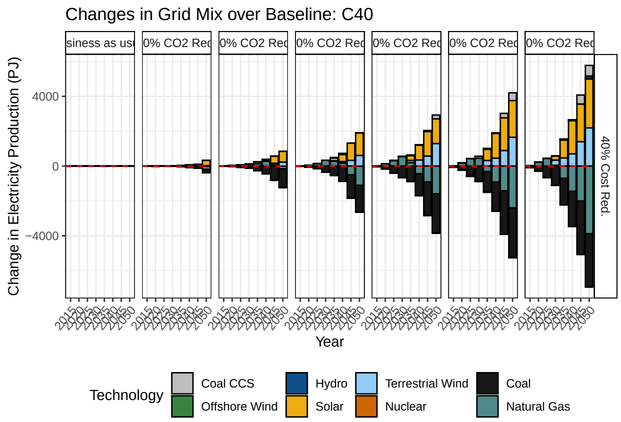


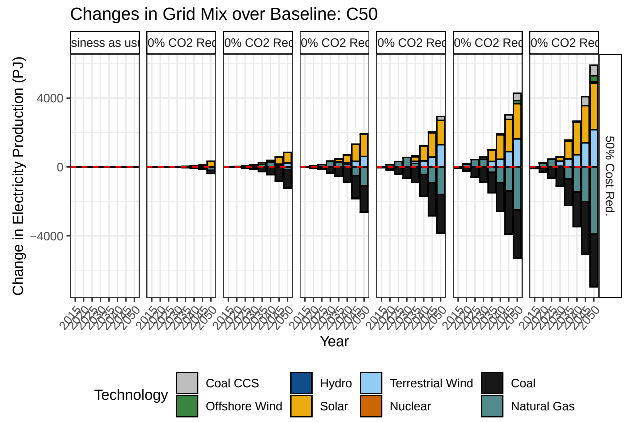


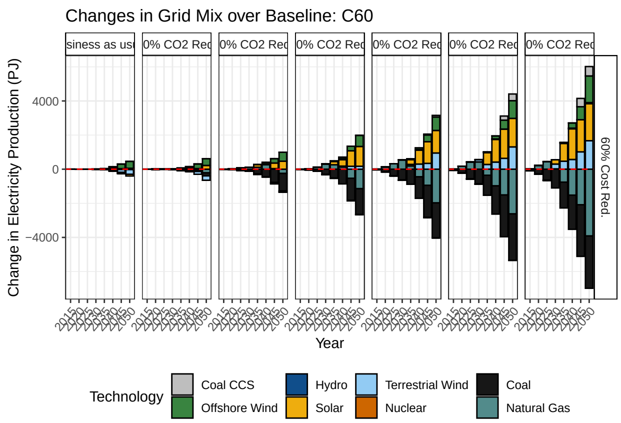


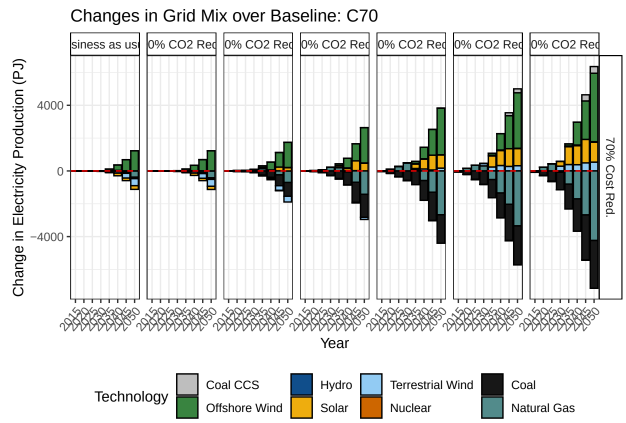


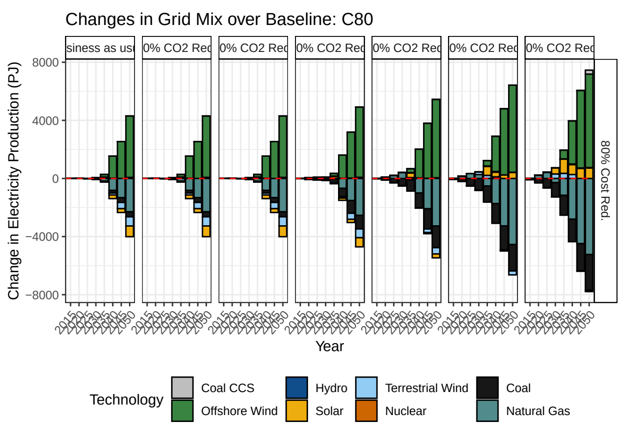
By Cost Reduction %


Changes in Grid Mix over Baseline: C40
Change in Electricity Production (PJ)
Year
40% Cost Red.
Technology
Coal CCS
Offshore Wind
Hydro
Solar
Terrestrial Wind
Nuclear
Coal
Natural Gas


Changes in Grid Mix over Baseline: C50
Change in Electricity Production (PJ)
Year
50% Cost Red.
Technology
Coal CCS
Offshore Wind
Hydro
Solar
Terrestrial Wind
Nuclear
Coal
Natural Gas

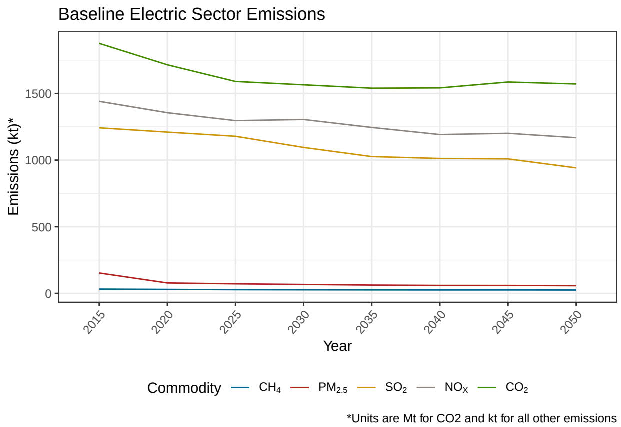

Changes in Grid Mix over Baseline: C60
Change in Electricity Production (PJ)
Year
60% Cost Red.
Technology
Coal CCS
Offshore Wind
Hydro
Solar
Terrestrial Wind
Nuclear
Coal
Natural Gas

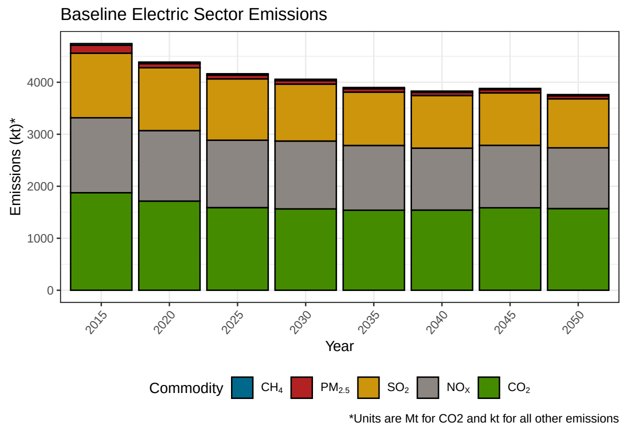

Changes in Grid Mix over Baseline: C70
Change in Electricity Production (PJ)
Year
70% Cost Red.
Technology
Coal CCS
Offshore Wind
Hydro
Solar
Terrestrial Wind
Nuclear
Coal
Natural Gas


Changes in Grid Mix over Baseline: C80
Change in Electricity Production (PJ)
Year
80% Cost Red.
Technology
Coal CCS
Offshore Wind
Hydro
Solar
Terrestrial Wind
Nuclear
Coal
Natural Gas

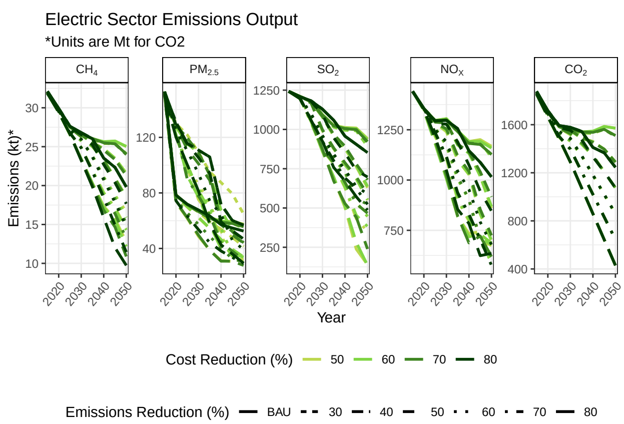
7 Emissions

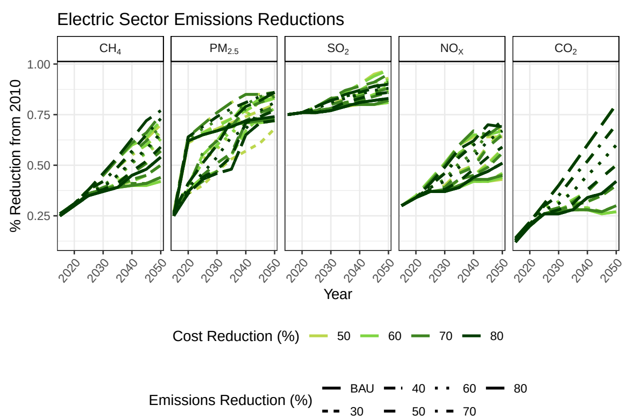
7.1 Baseline



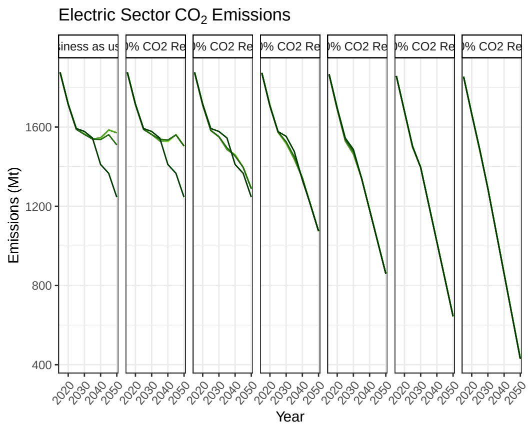


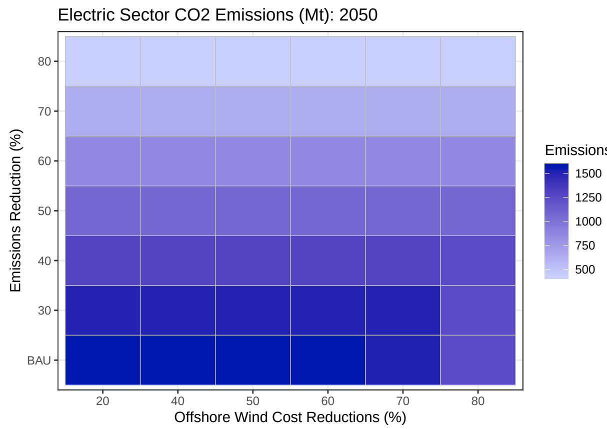
7.2 Emissions by Scenario and Commodity

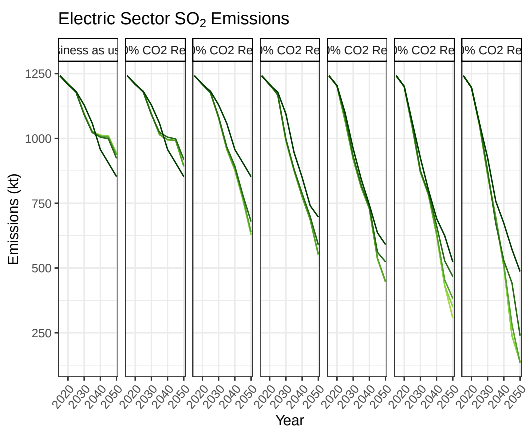


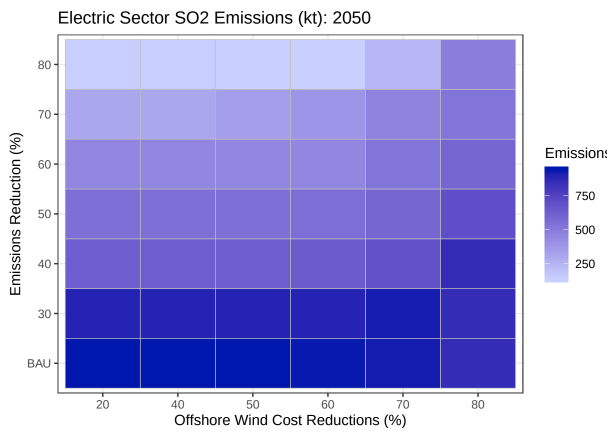


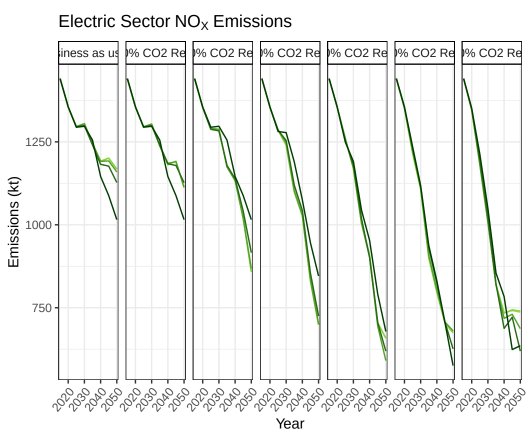
7.3 Emissions by Commodity - Values

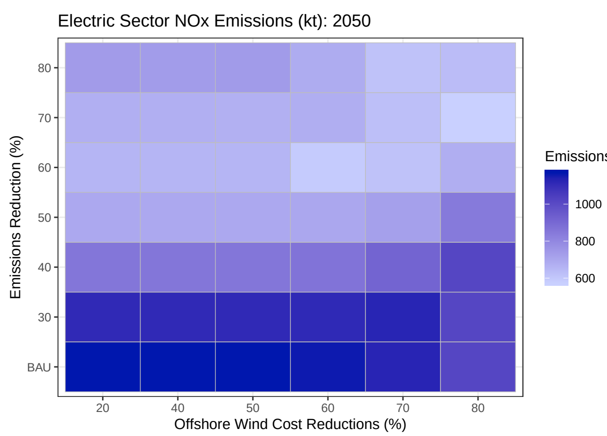


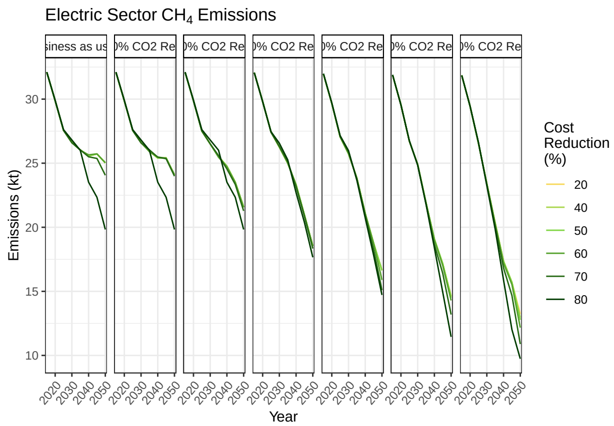


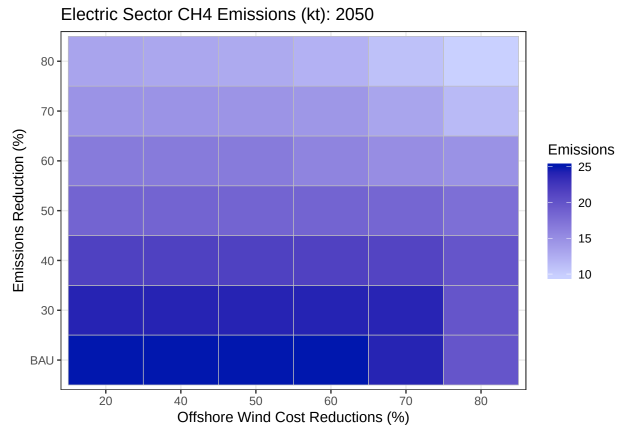


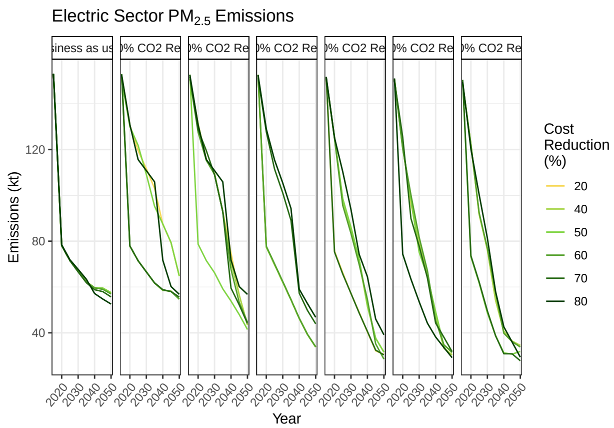


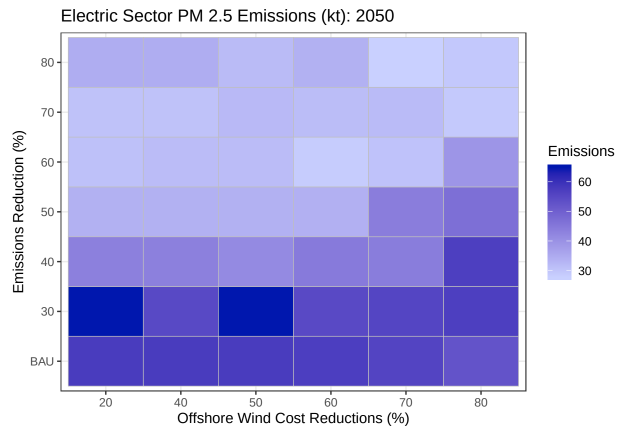




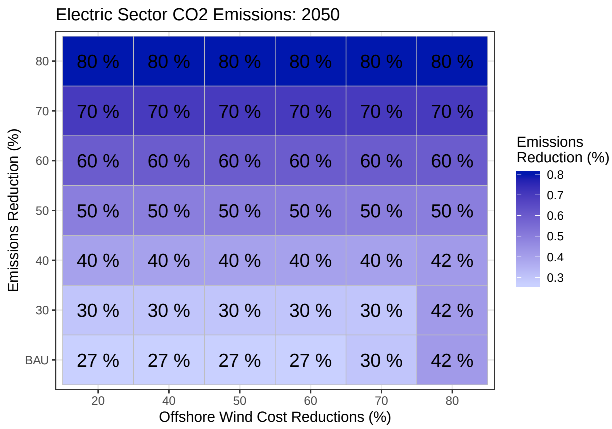

Electric Sector CH4 Emissions
Emissions (kt)
Year
Cost Reduction (%)
20
40
50
60
70
80

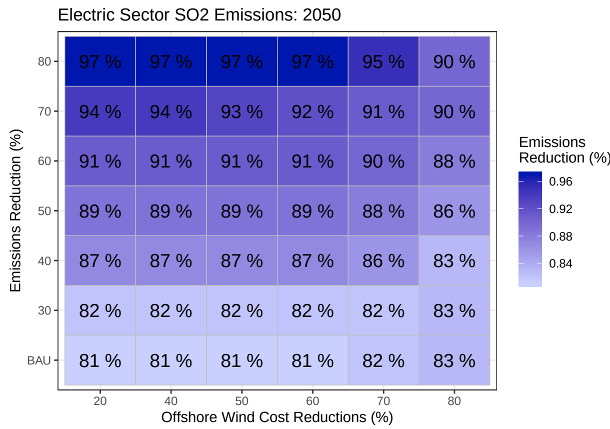

Electric Sector CH4 Emissions (kt): 2050
Emissions Reduction (%)
Offshore Wind Cost Reductions (%)
Emissions
BAU

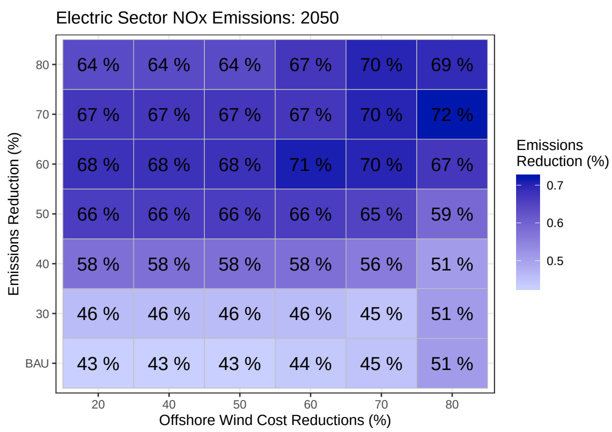

Electric Sector PM2.5 Emissions
Emissions (kt)
Year
Cost Reduction (%)
20
40
50
60
70
80

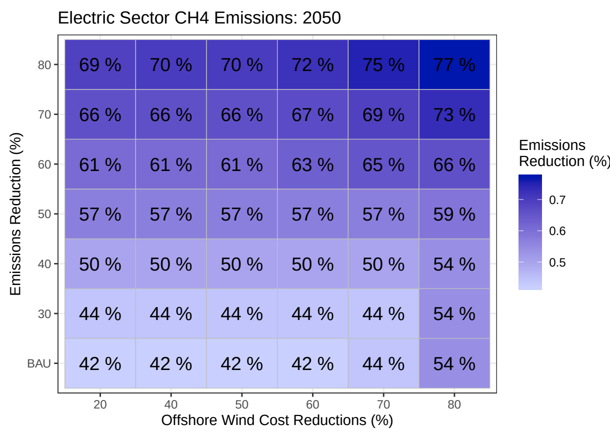

Electric Sector PM 2.5 Emissions (kt): 2050
Emissions Reduction (%)
Offshore Wind Cost Reductions (%)
Emissions
BAU

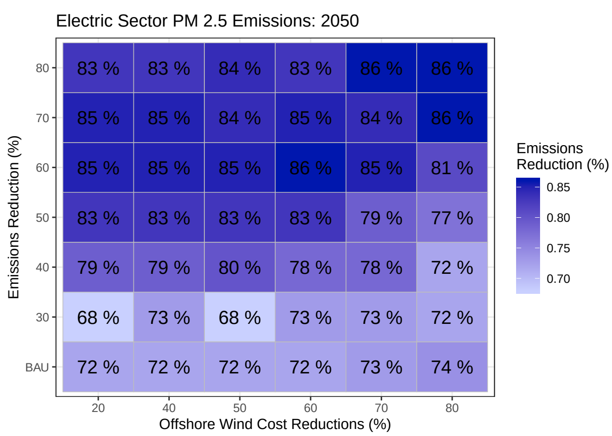
7.4 Emissions by Commodity - Percent Reduction



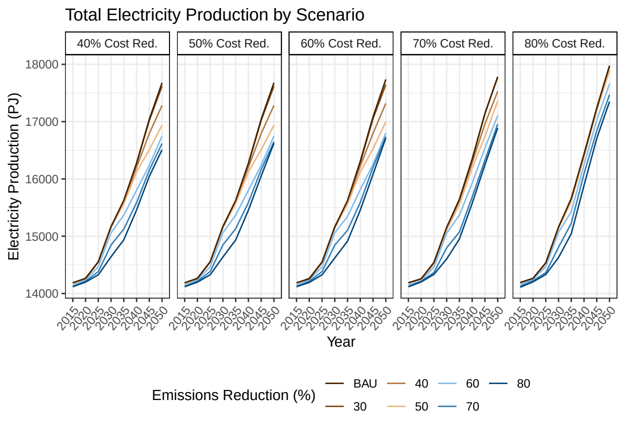


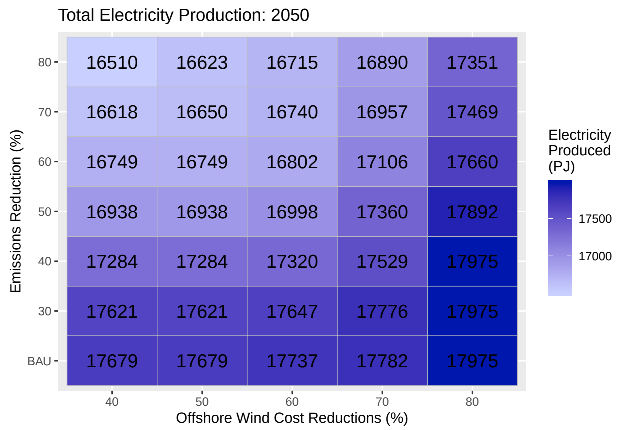




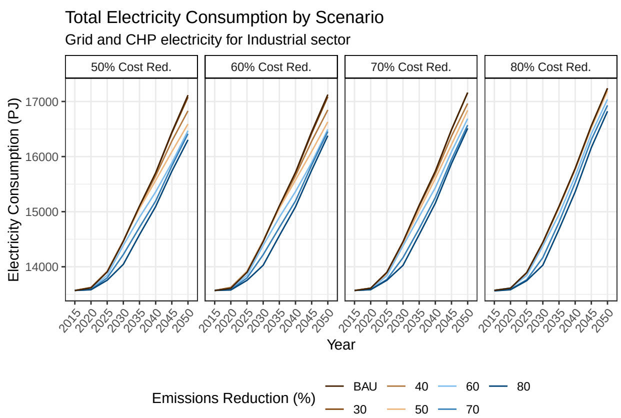


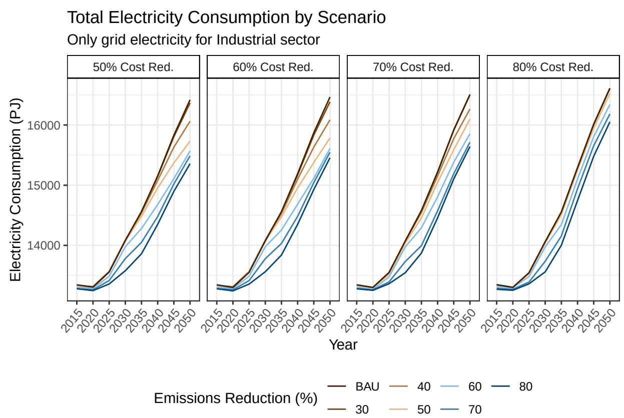
8 Total Electricity Production

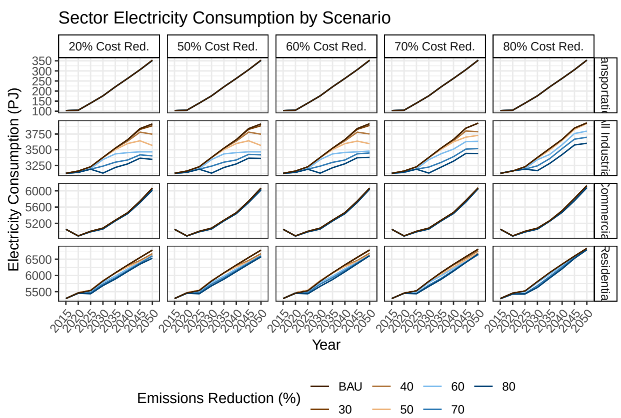


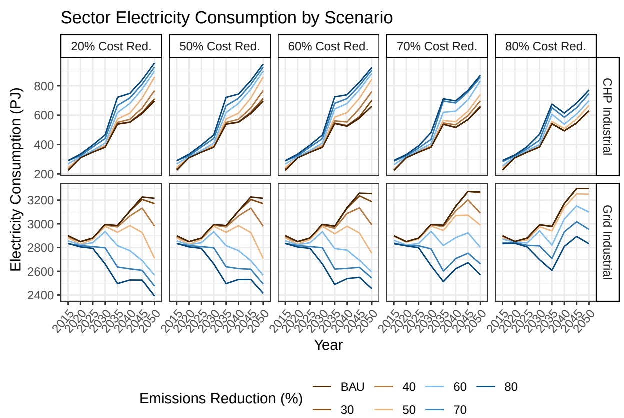


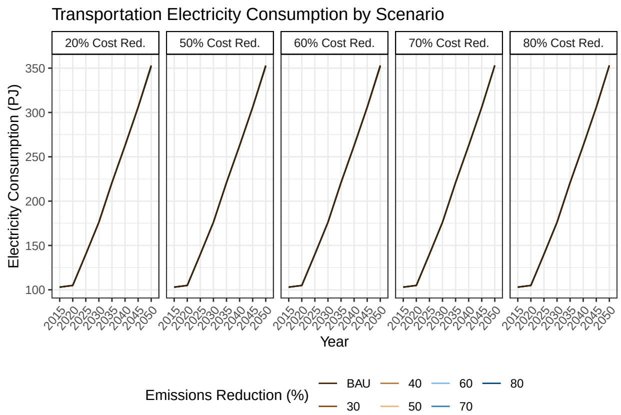
9 End Use ELC

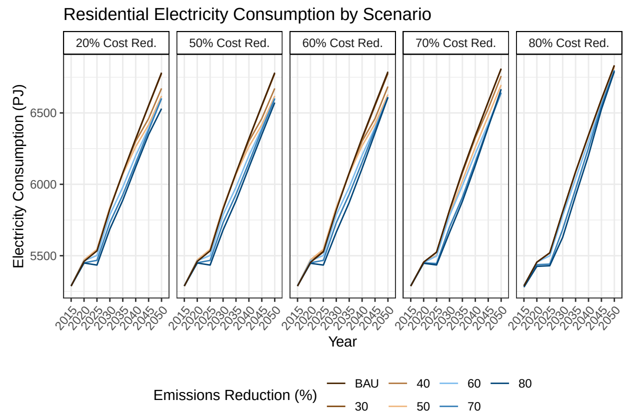


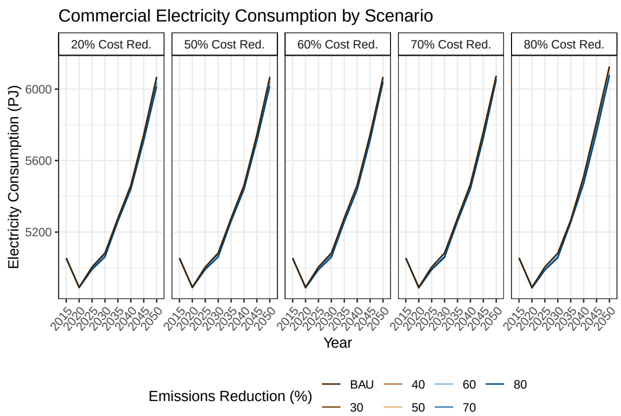


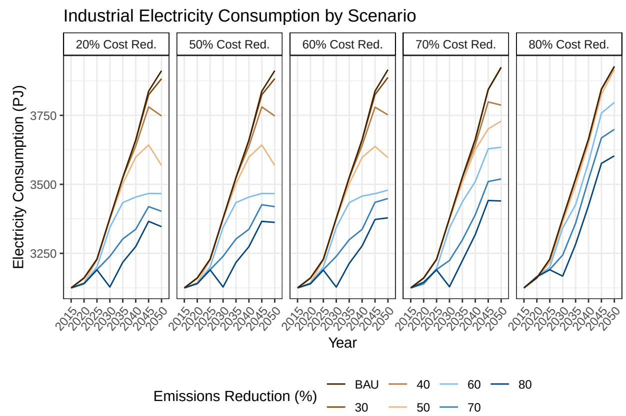


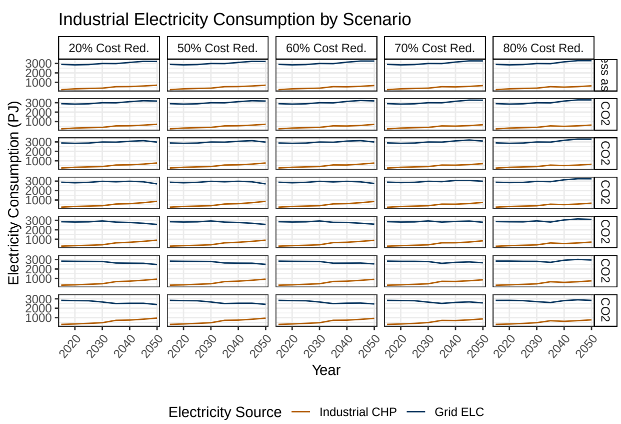



Transportation Electricity Consumption by Scenario
20% Cost Red.
50% Cost Red.
60% Cost Red.
70% Cost Red.
80% Cost Red.
Electricity Consumption (PJ)
350
300
250
200
150
100
2015 2020 2025 2030 2035 2040 2045 2050
Year
Emissions Reduction (%)
BAU 40 60 80
30 50 70

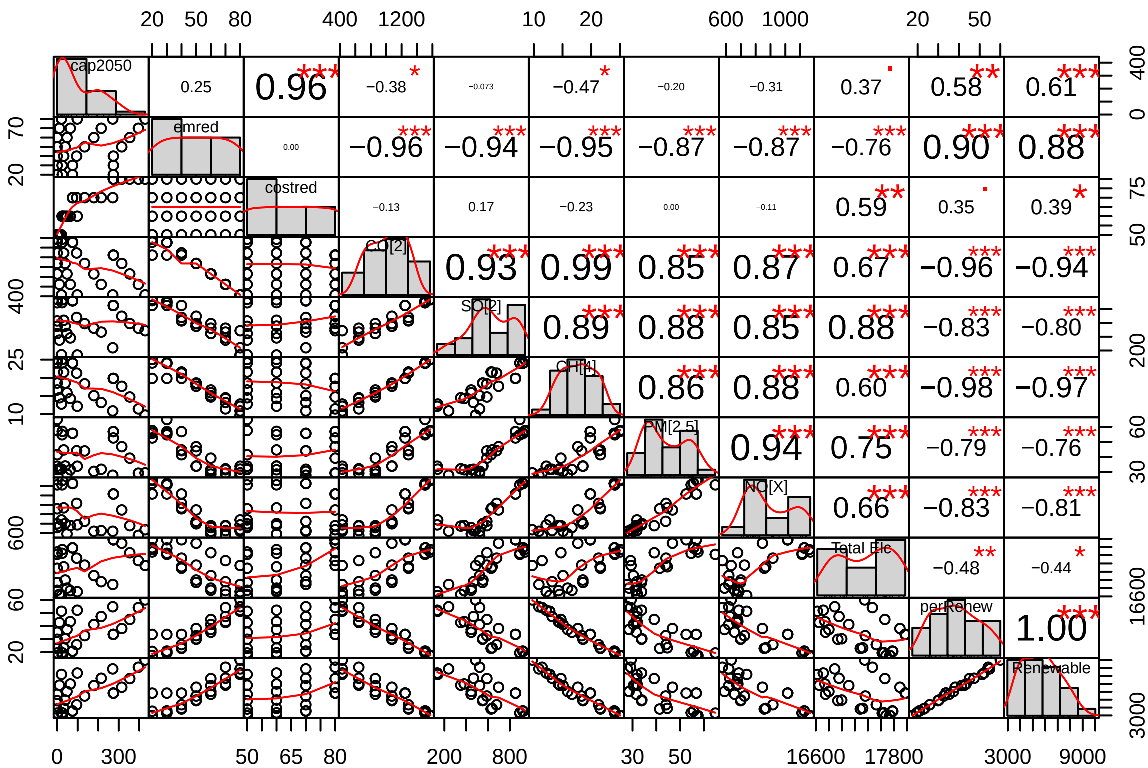

Residential Electricity Consumption by Scenario
20% Cost Red.
50% Cost Red.
60% Cost Red.
70% Cost Red.
80% Cost Red.
Electricity Consumption (PJ)
6500
6000
5500
2015 2020 2025 2030 2035 2040 2045 2050
Year
Emissions Reduction (%)
BAU 40 60 80
30 50 70


Commercial Electricity Consumption by Scenario
20% Cost Red.
50% Cost Red.
60% Cost Red.
70% Cost Red.
80% Cost Red.
Electricity Consumption (PJ)
6000
5600
5200
2015 2020 2025 2030 2035 2040 2045 2050
Year
Emissions Reduction (%)
BAU 40 60 80
30 50 70


Industrial Electricity Consumption by Scenario
20% Cost Red.
50% Cost Red.
60% Cost Red.
70% Cost Red.
80% Cost Red.
Electricity Consumption (PJ)
3750
3500
3250
2015 2020 2025 2030 2035 2040 2045 2050
Year
Emissions Reduction (%)
BAU 40 60 80
30 50 70


Industrial Electricity Consumption by Scenario
20% Cost Red.
50% Cost Red.
60% Cost Red.
70% Cost Red.
80% Cost Red.
Electricity Consumption (PJ)
3000
2000
1000
CO2
2020 2030 2040 2050
Year
Electricity Source
Industrial CHP
Grid ELC

10 Correlations

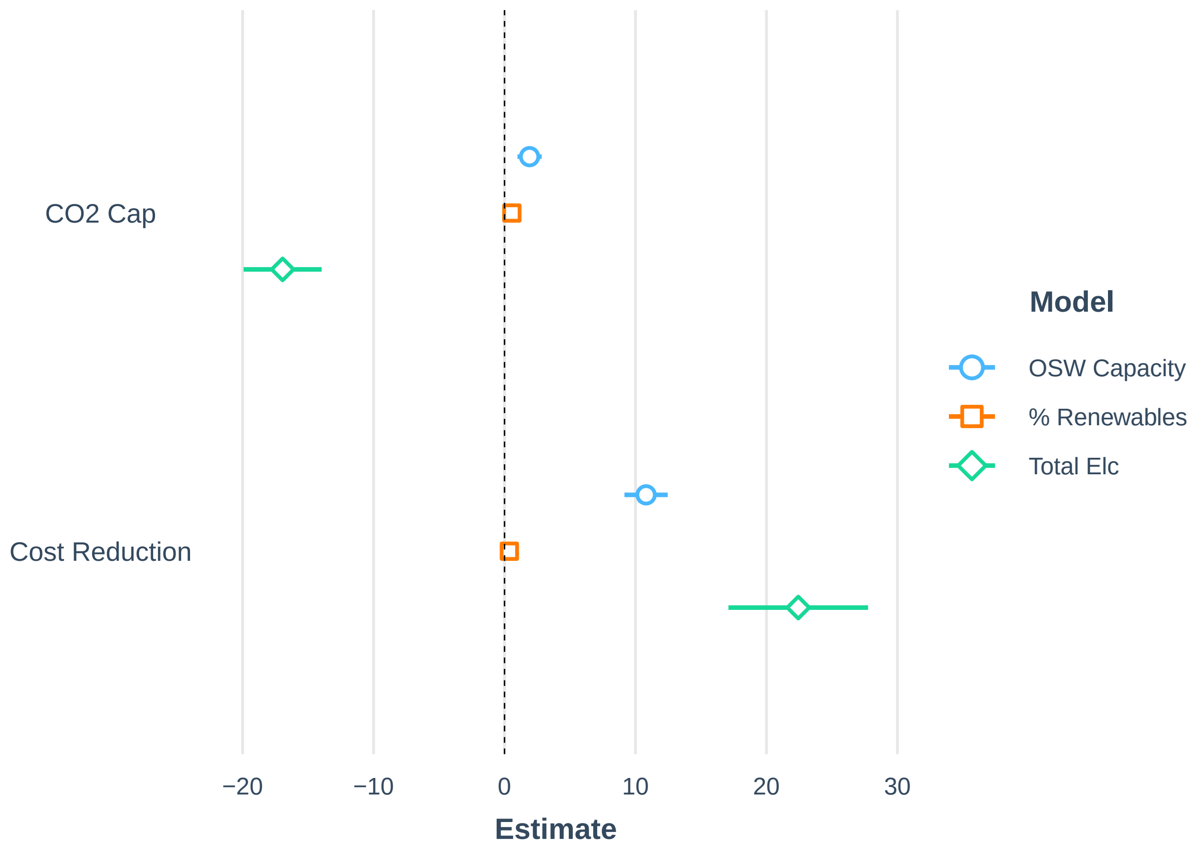


11 Regressions

Full set of models

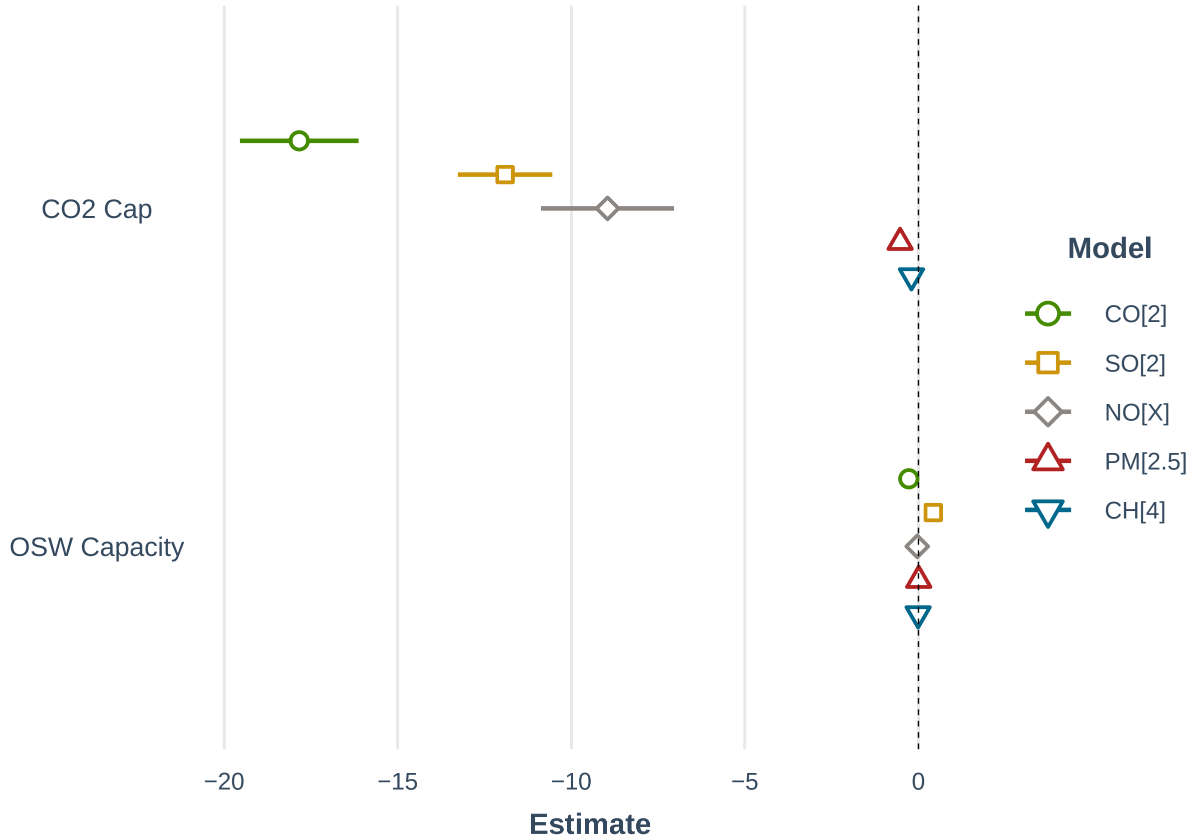
	OSW Capacity	% Renewables	Total Elc
CO2 Cap	1.91 ***	0.56 ***	-16.94 ***
	(0.45)	(0.03)	(1.45)
Cost Reduction	10.81 ***	0.37 ***	22.43 ***
	(0.80)	(0.06)	(2.59)
N	28	28	28
R2	0.89	0.93	0.89

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



	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

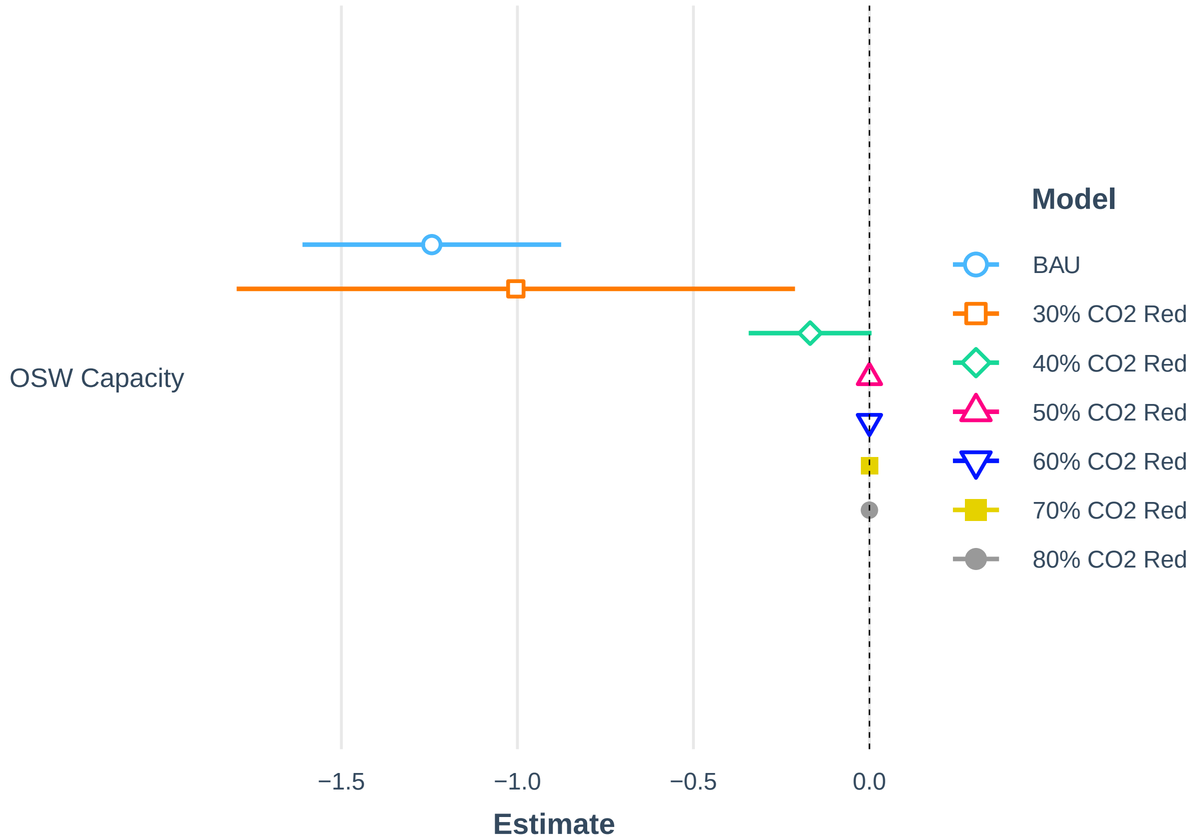
*** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$.



Emission-specific regressions by CO2 cap scenario

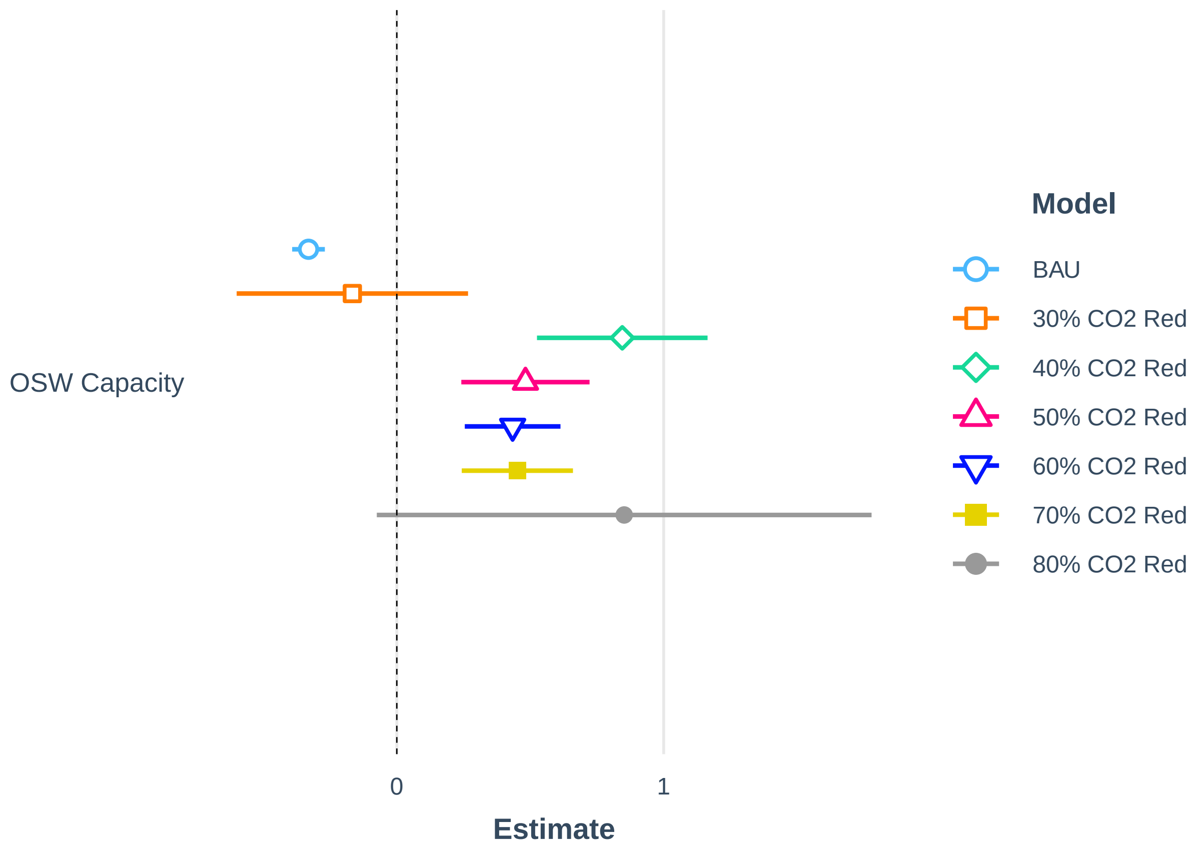
	BAU	30% CO2 Red	40% CO2 Red	50% CO2 Red	60% CO2 Red
OSW Capacity	-1.24 **	-1.00 *	-0.17	0.00	-0.00
	(0.09)	(0.18)	(0.04)	(0.00)	(0.00)
N	4	4	4	4	4
R2	0.99	0.94	0.90	0.84	0.20

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



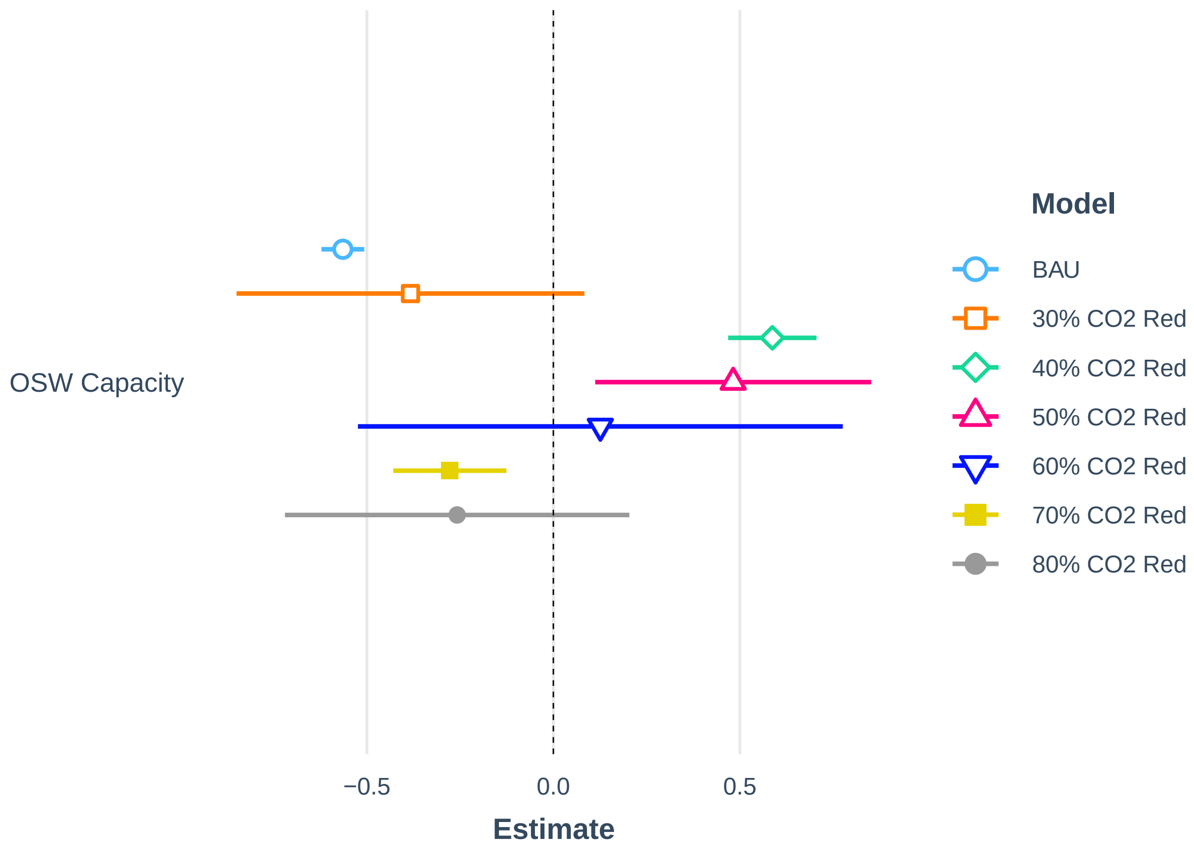
	BAU	30% CO2 Red	40% CO2 Red	50% CO2 Red	60% CO2 Red
OSW Capacity	-0.33 **	-0.17	0.84 **	0.48 *	0.43 **
	(0.01)	(0.10)	(0.07)	(0.06)	(0.04)
N	4	4	4	4	4
R2	1.00	0.58	0.98	0.97	0.98

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



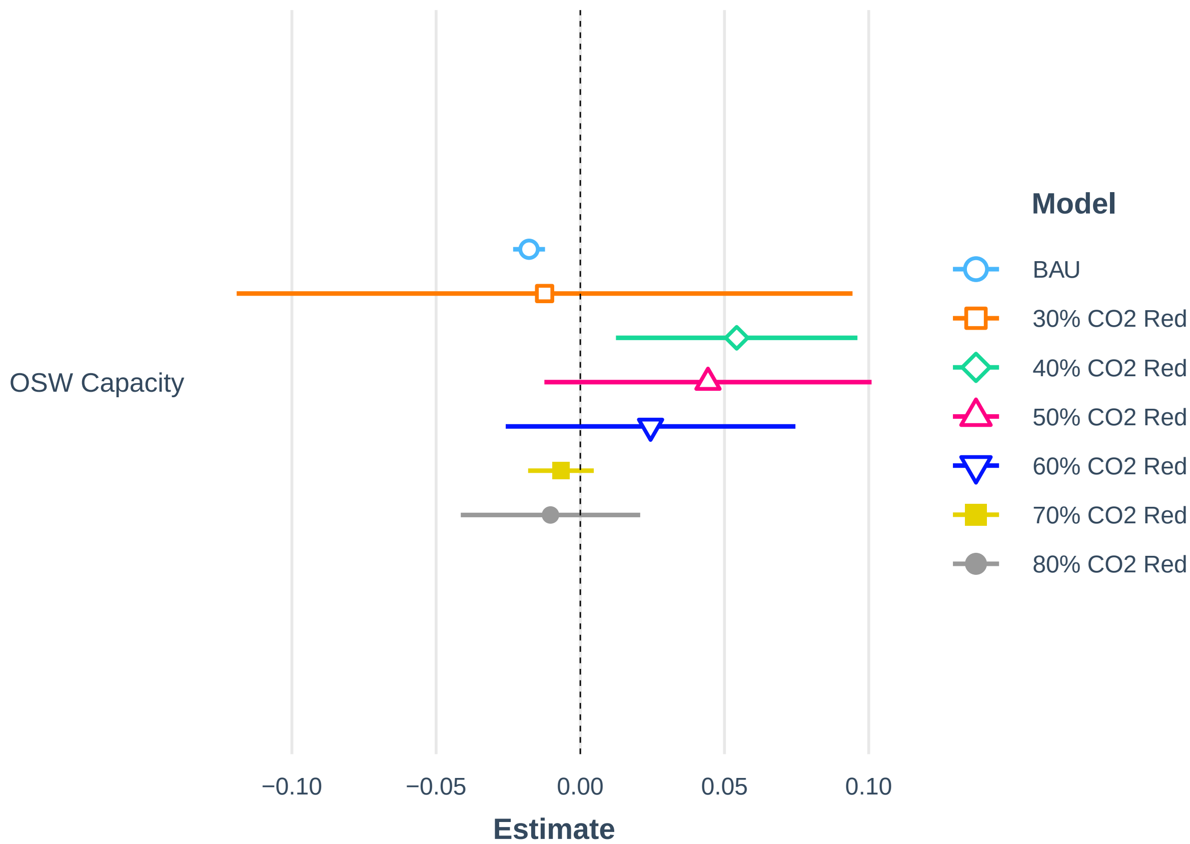
	BAU	30% CO2 Red	40% CO2 Red	50% CO2 Red	60% CO2 Red
OSW Capacity	-0.56 ***	-0.38	0.59 **	0.48 *	0.13
	(0.01)	(0.11)	(0.03)	(0.09)	(0.15)
N	4	4	4	4	4
R2	1.00	0.86	1.00	0.94	0.26

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



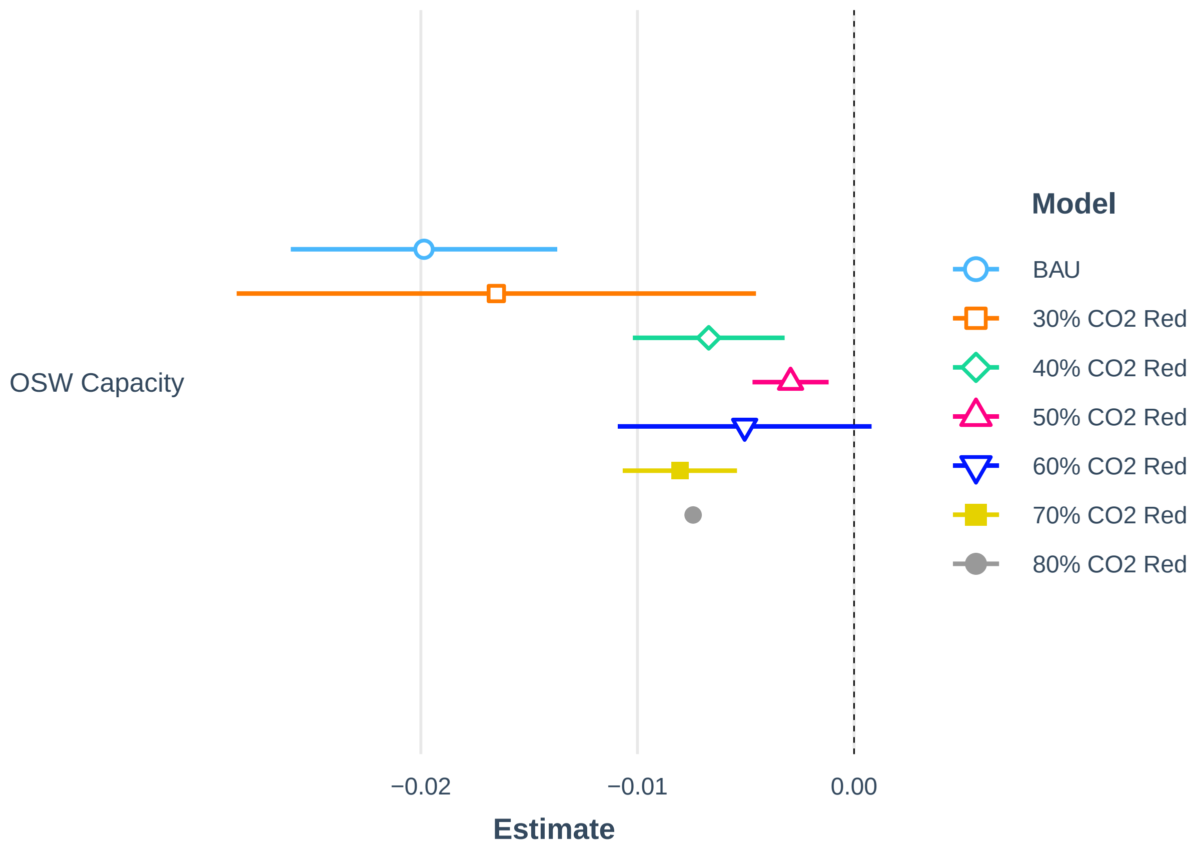
	BAU	30% CO2 Red	40% CO2 Red	50% CO2 Red	60% CO2 Red
OSW Capacity	-0.02 **	-0.01	0.05 *	0.04	0.02
	(0.00)	(0.02)	(0.01)	(0.01)	(0.01)
N	4	4	4	4	4
R2	0.99	0.11	0.94	0.85	0.69

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



	BAU	30% CO2 Red	40% CO2 Red	50% CO2 Red	60% CO2 Red
OSW Capacity	-0.02 **	-0.02 *	-0.01 *	-0.00 *	-0.01
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
N	4	4	4	4	4
R2	0.99	0.95	0.97	0.96	0.87

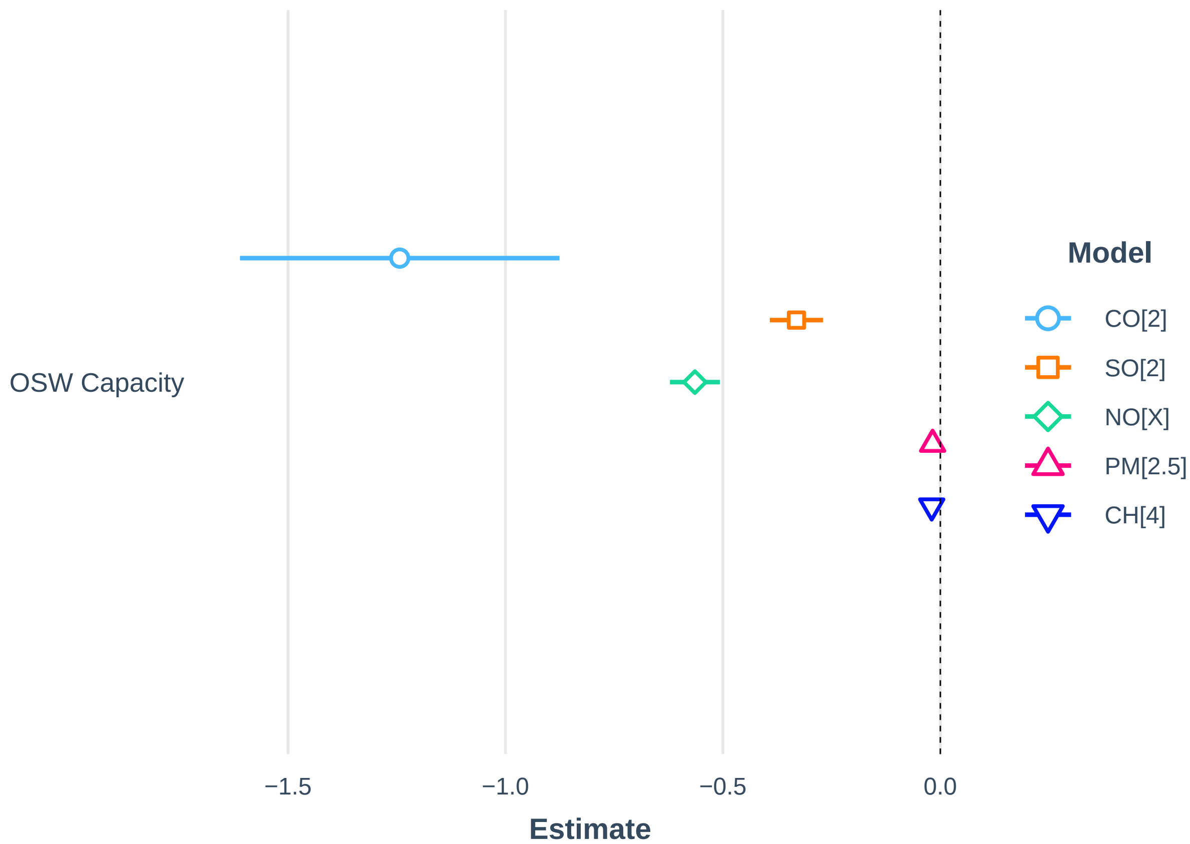
*** p < 0.001; ** p < 0.01; * p < 0.05.



CO2 cap regressions by emissions type

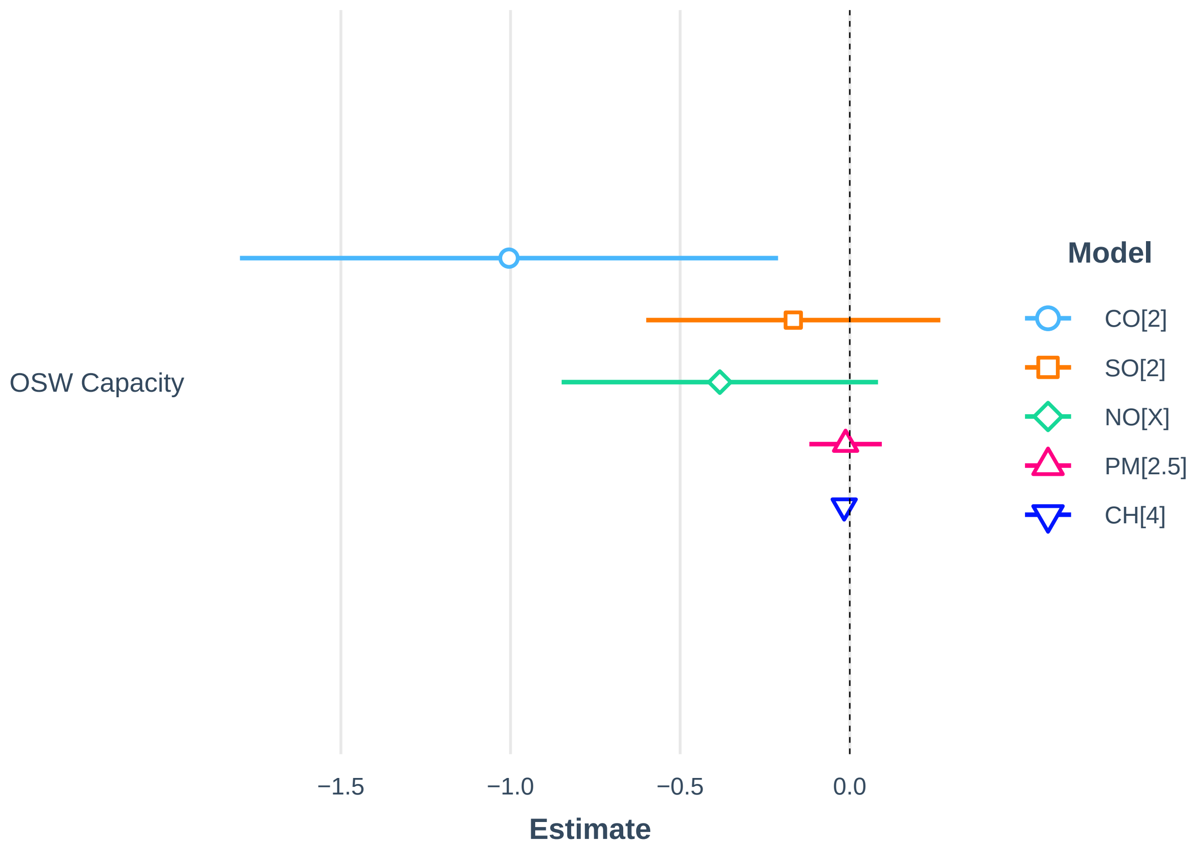
	CO[2]	SO[2]	NO[X]	PM[2.5]	CH[4]
OSW Capacity	-1.24 **	-0.33 **	-0.56 ***	-0.02 **	-0.02 **
	(0.09)	(0.01)	(0.01)	(0.00)	(0.00)
N	4	4	4	4	4
R2	0.99	1.00	1.00	0.99	0.99

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



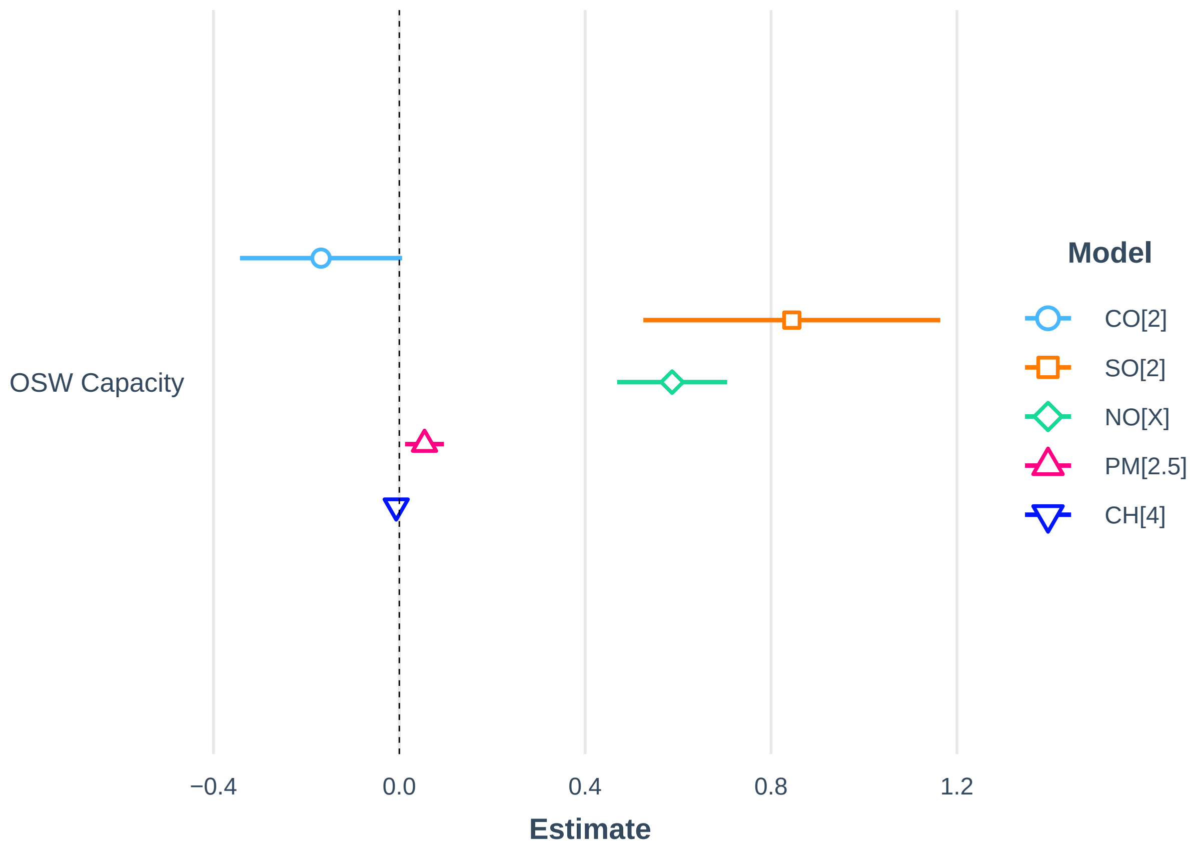
	CO_2	SO_2	NO_X	$PM_{2.5}$	CH_4
OSW Capacity	-1.00 *	-0.17	-0.38	-0.01	-0.02 *
	(0.18)	(0.10)	(0.11)	(0.02)	(0.00)
N	4	4	4	4	4
R2	0.94	0.58	0.86	0.11	0.95

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



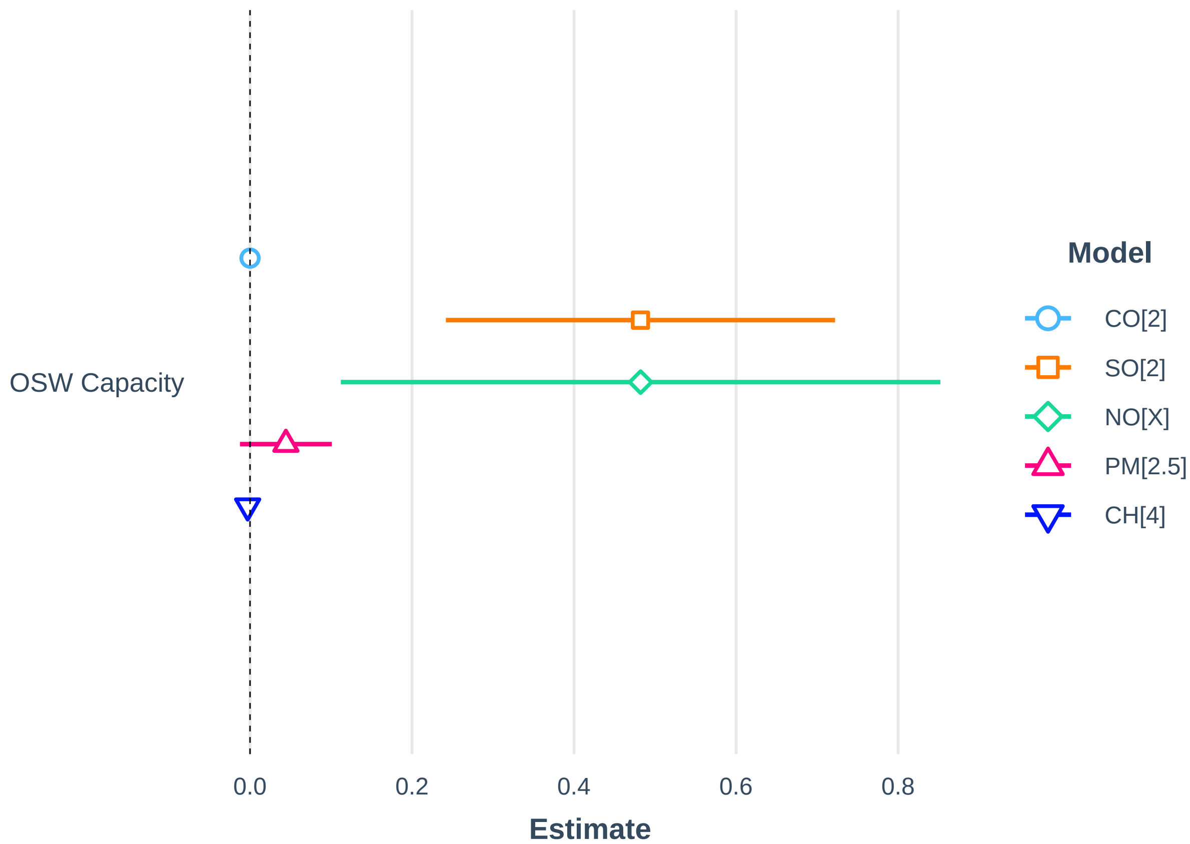
	CO[2]	SO[2]	NO[X]	PM[2.5]	CH[4]
OSW Capacity	-0.17	0.84 **	0.59 **	0.05 *	-0.01 *
	(0.04)	(0.07)	(0.03)	(0.01)	(0.00)
N	4	4	4	4	4
R2	0.90	0.98	1.00	0.94	0.97

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



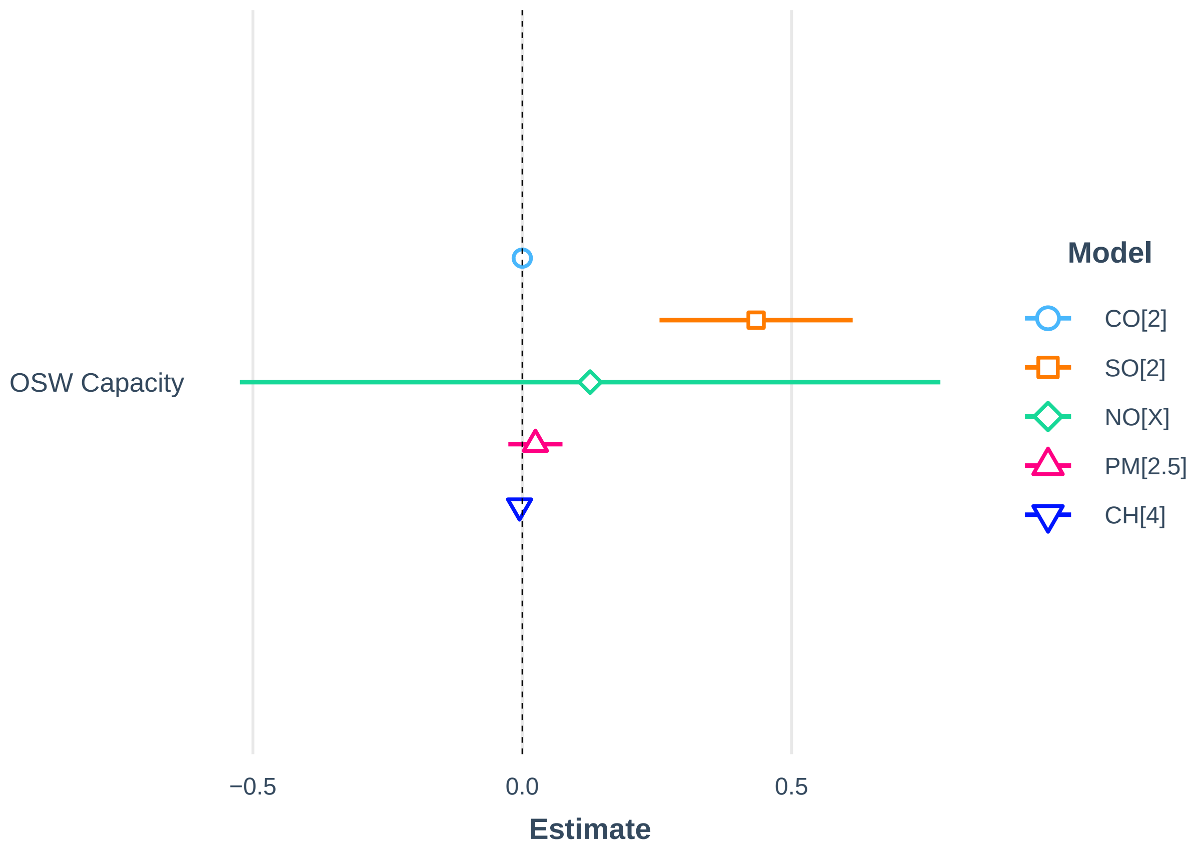
	CO[2]	SO[2]	NO[X]	PM[2.5]	CH[4]
OSW Capacity	0.00	0.48 *	0.48 *	0.04	-0.00 *
	(0.00)	(0.06)	(0.09)	(0.01)	(0.00)
N	4	4	4	4	4
R2	0.84	0.97	0.94	0.85	0.96

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



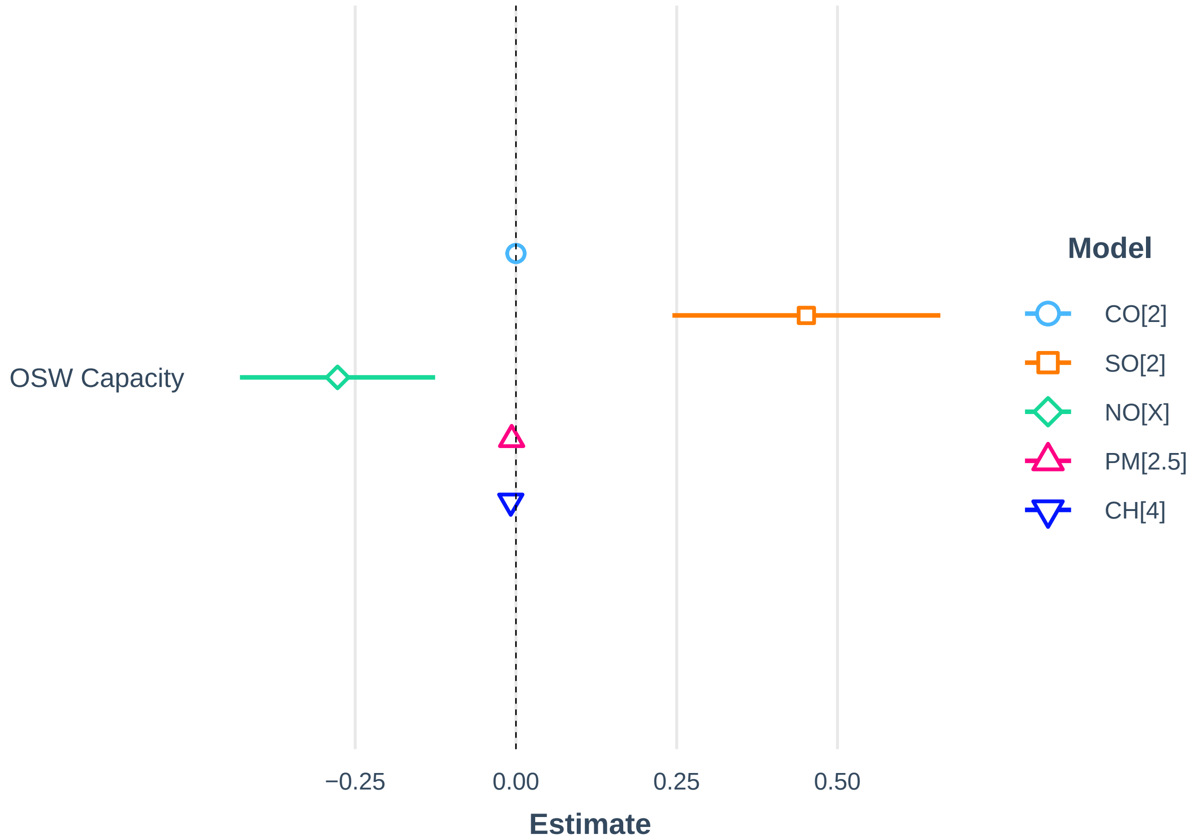
	CO[2]	SO[2]	NO[X]	PM[2.5]	CH[4]
OSW Capacity	-0.00	0.43 **	0.13	0.02	-0.01
	(0.00)	(0.04)	(0.15)	(0.01)	(0.00)
N	4	4	4	4	4
R2	0.20	0.98	0.26	0.69	0.87

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



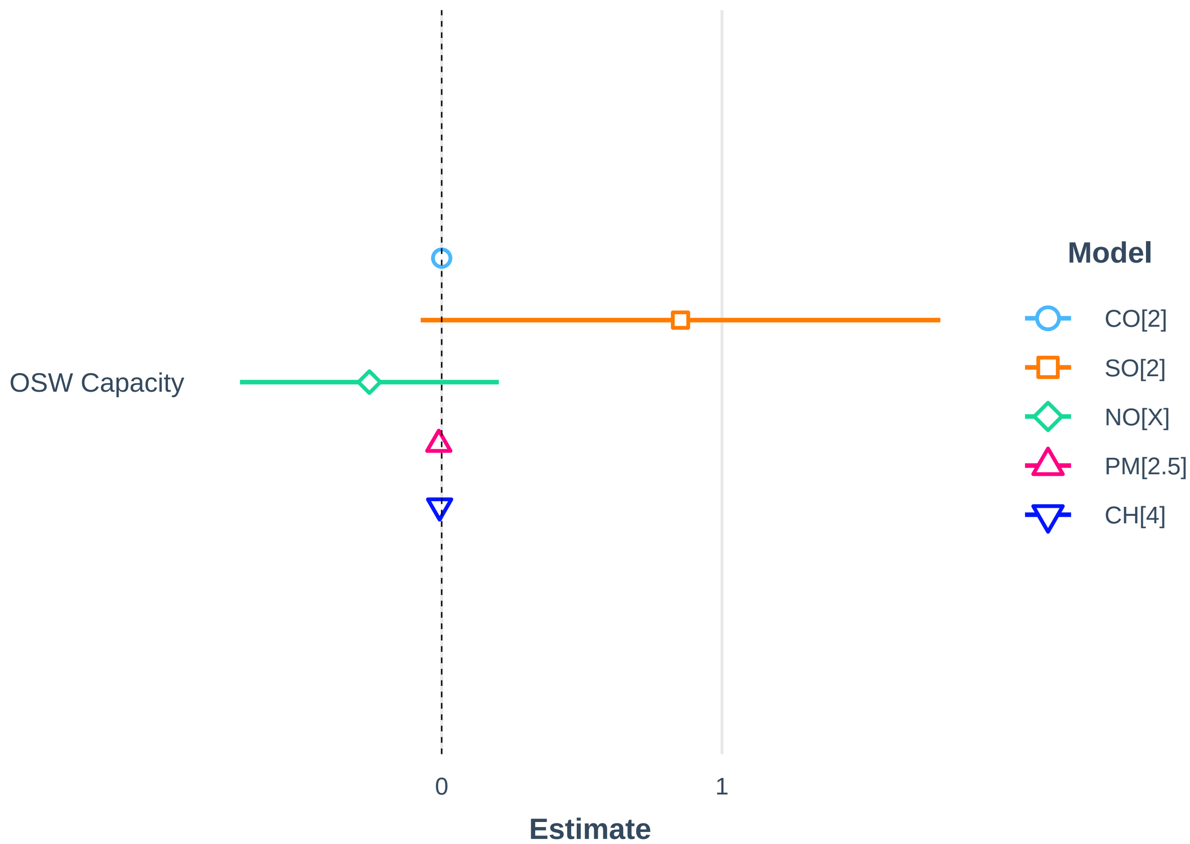
	CO_2	SO_2	NO_X	$PM_{2.5}$	CH_4
OSW Capacity	-0.00	0.45 *	-0.28 *	-0.01	-0.01 **
	(0.00)	(0.05)	(0.04)	(0.00)	(0.00)
N	4	4	4	4	4
R2	0.00	0.98	0.97	0.76	0.99

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



	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]