

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

## Results and Analysis

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# 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 reproducibility and a general understanding of the results.

## 2 Setup

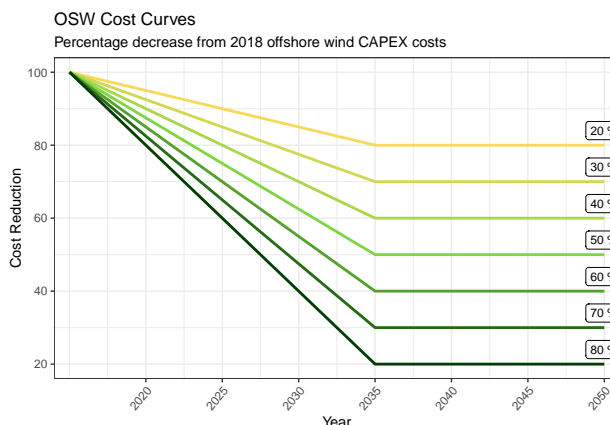
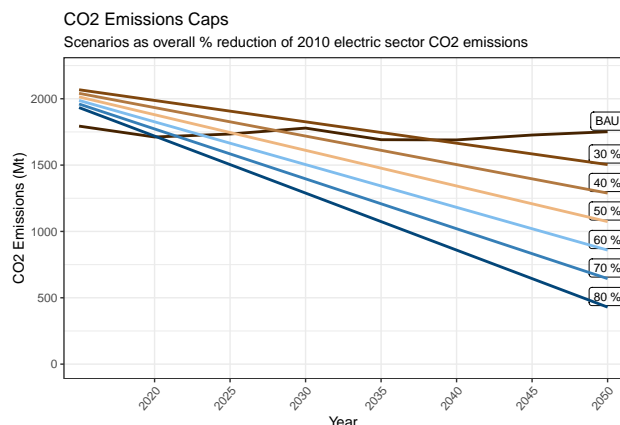
Three scripts are loaded into this markdown document to allow for analysis of the data. The setup script loads the library, creates generalized functions, and creates global variables for color scales and factors. The data script loads an excel spreadsheet with all of the results data and performs the 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<sub>2</sub> 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<sub>2</sub> 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 transmission cost	Total system LCOE	Levelized tax credit	Total LCOE including tax credit
<b>Dispatchable technologies</b>								
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
<b>Non-dispatchable technologies</b>								
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:

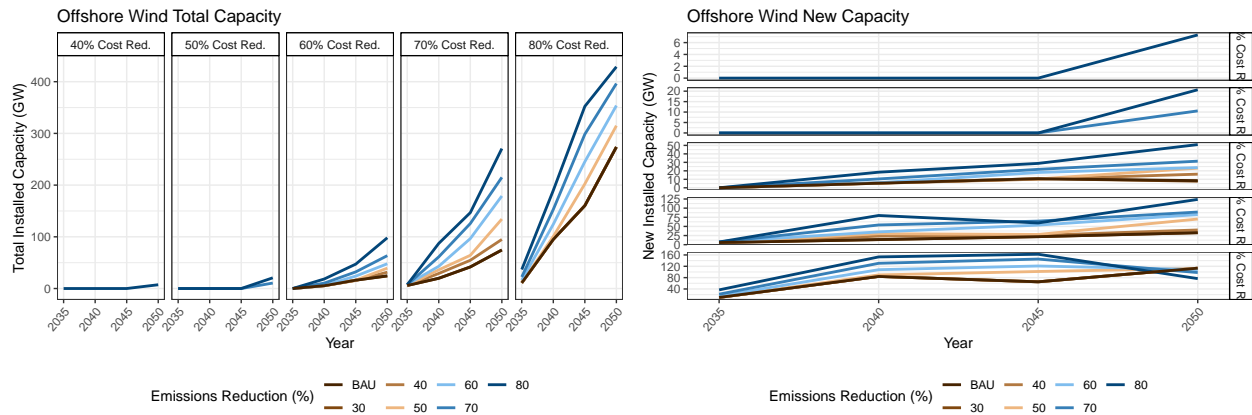
U.S. EIA Annual Energy Outlook 2019

## 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.

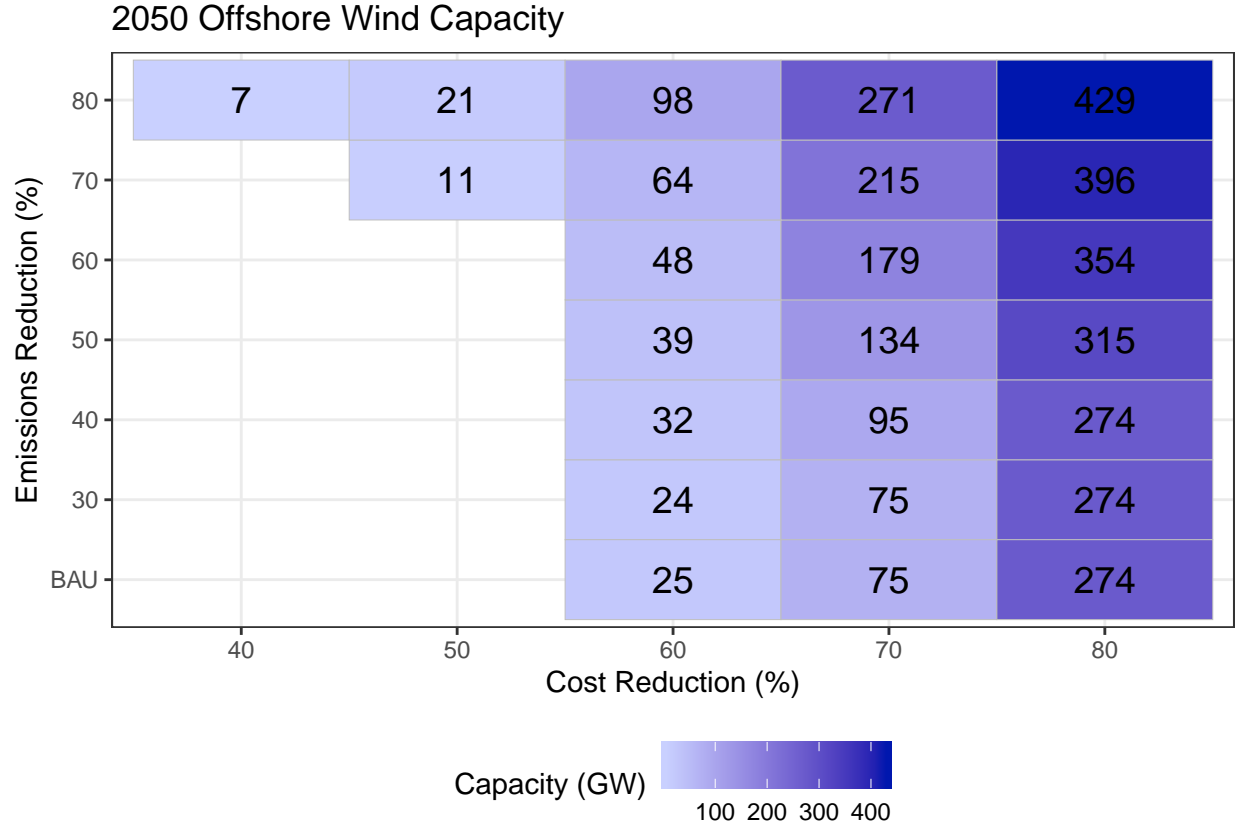


Table 2: Offshore Wind Total Installed Capacity (GW): 2050

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.

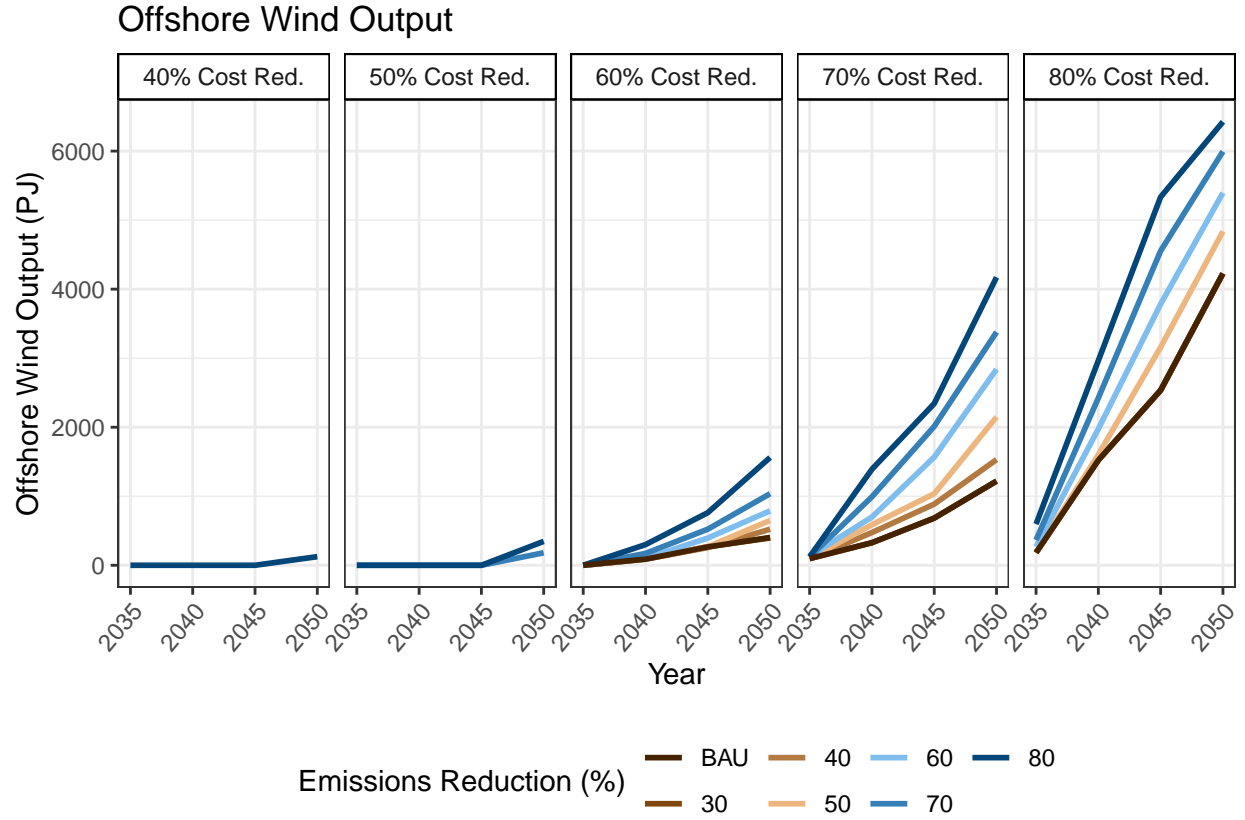
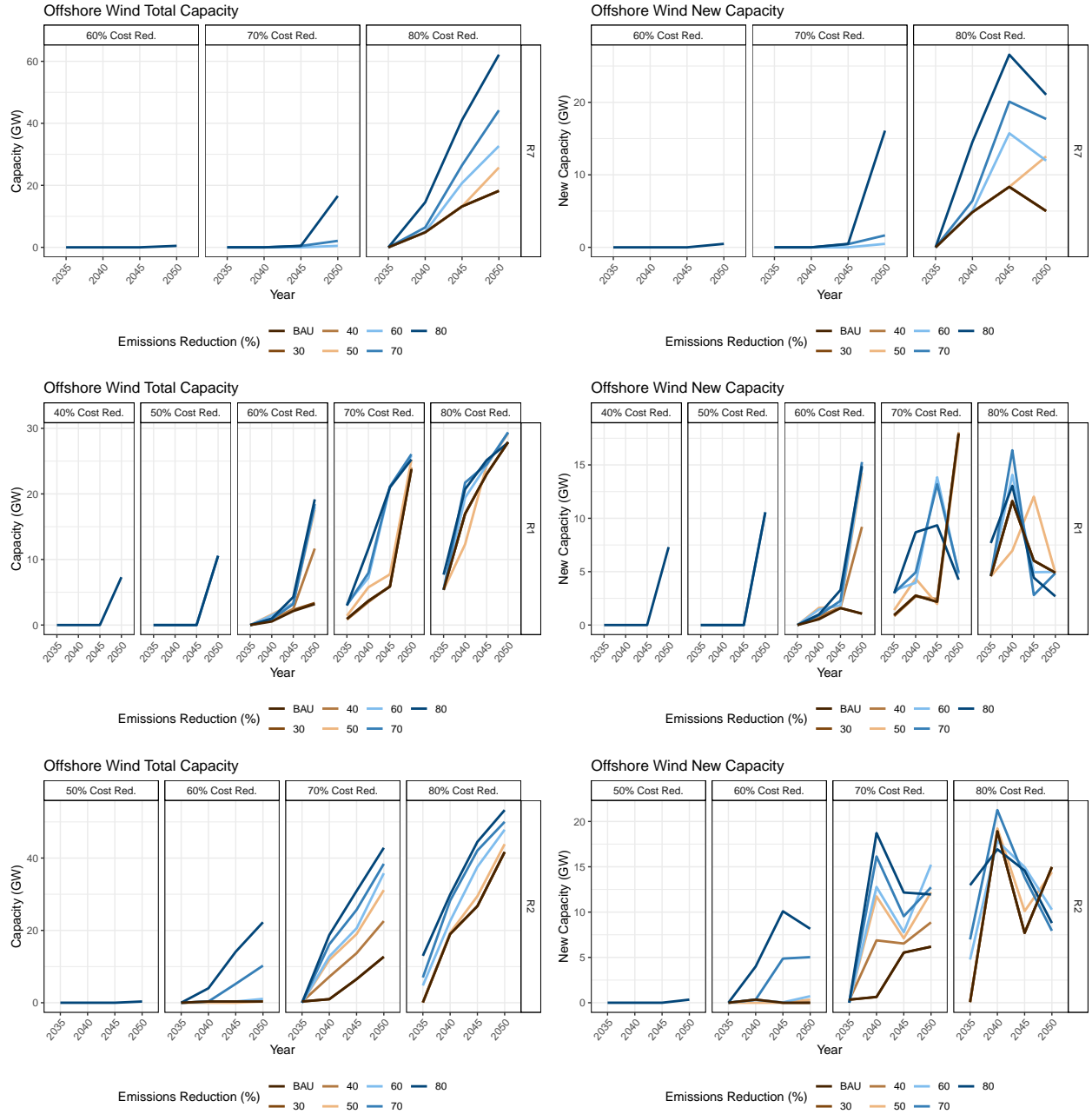


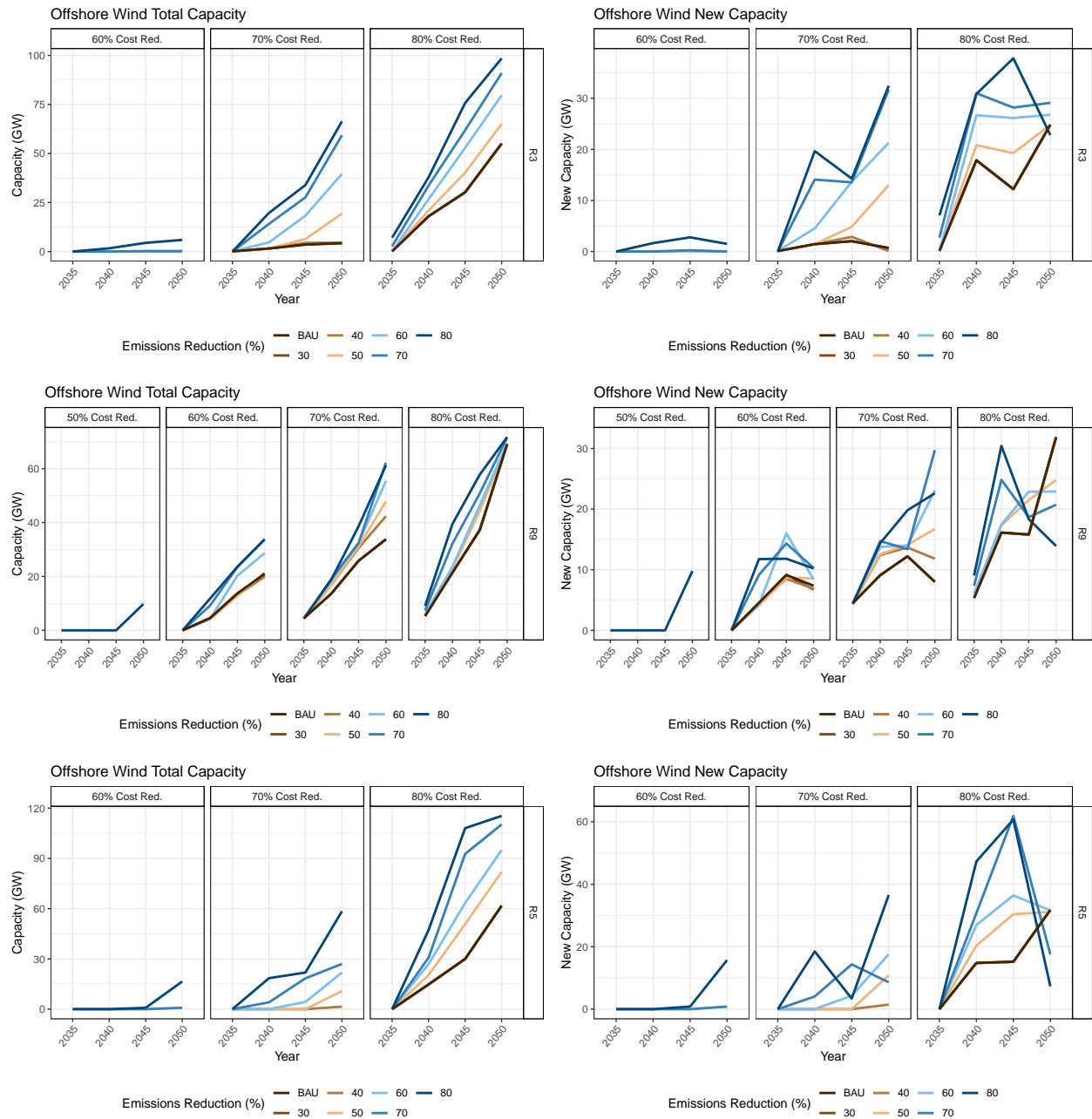
Table 3: Offshore Wind Total Output (PJ): 2050

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.





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

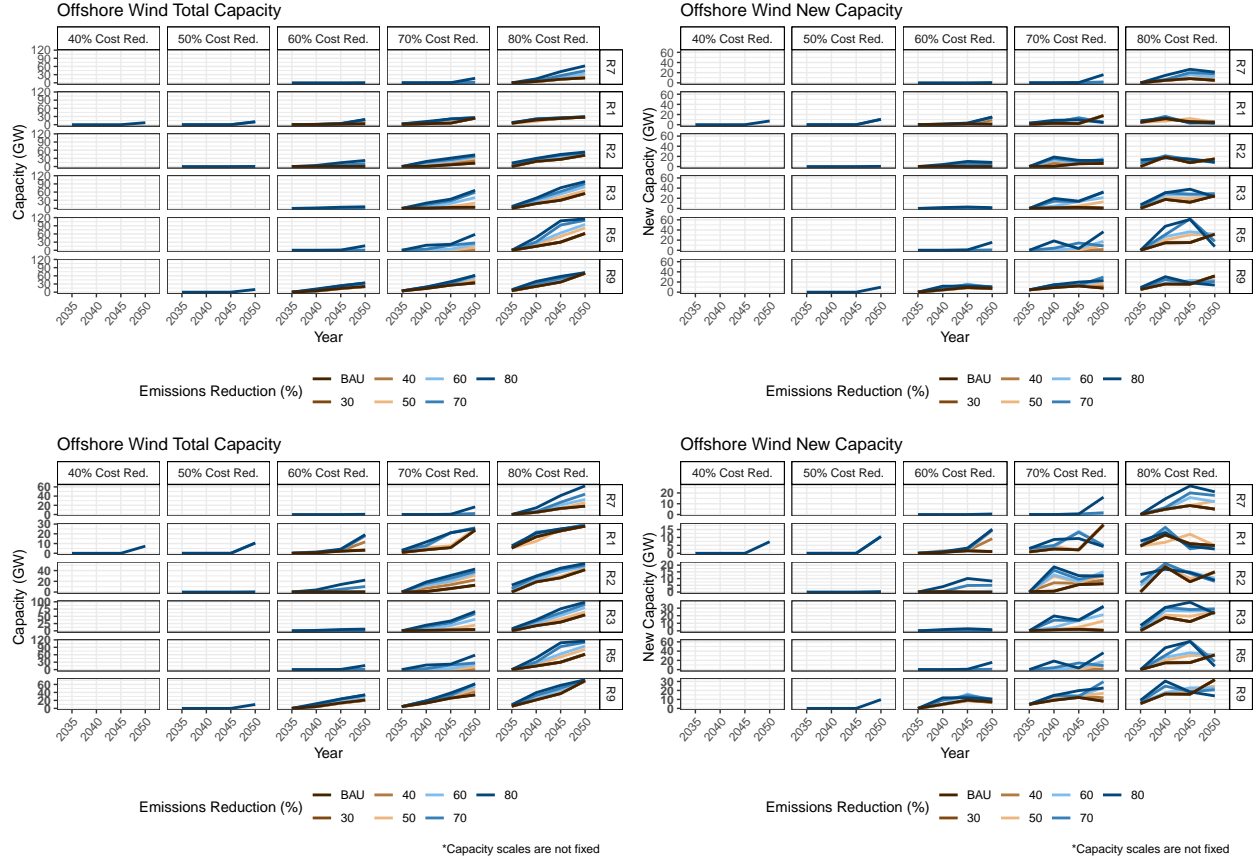


Table 4: Average Installed Capacity (GW)

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:*

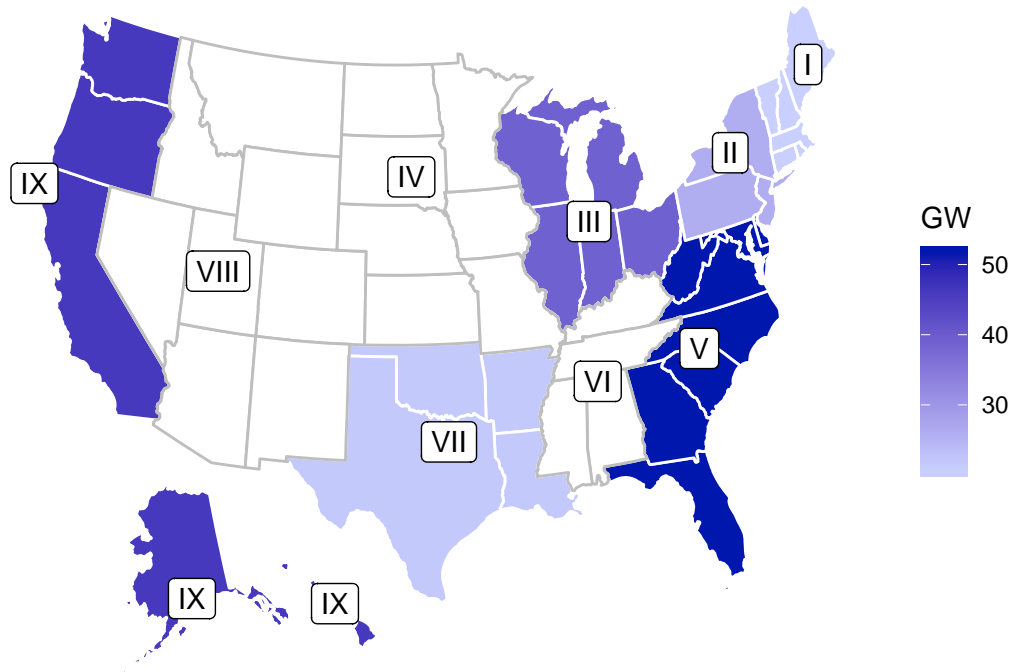
Average is across all scenarios



Map of average total capacity

## Distribution of Offshore Wind Capacity

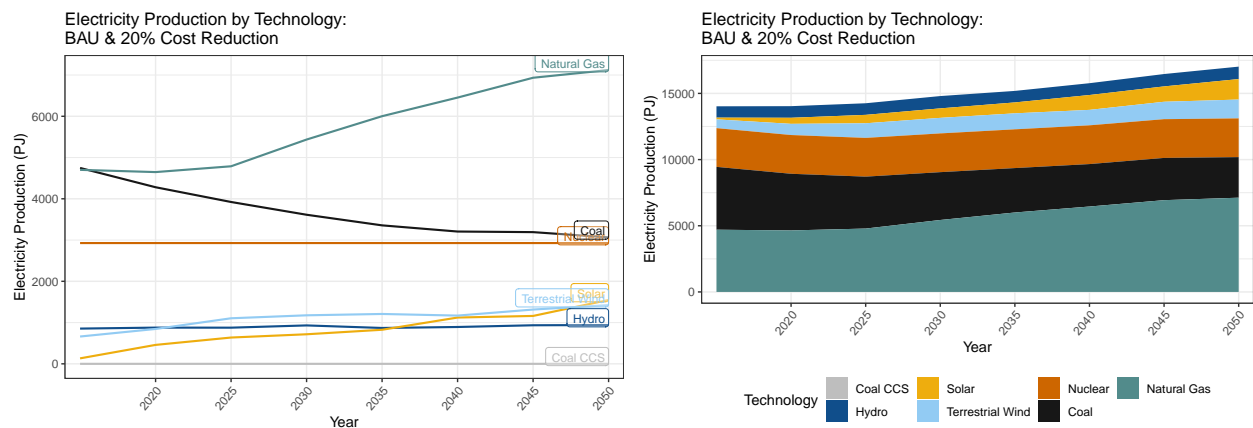
Average cumulative capacity across all scenarios



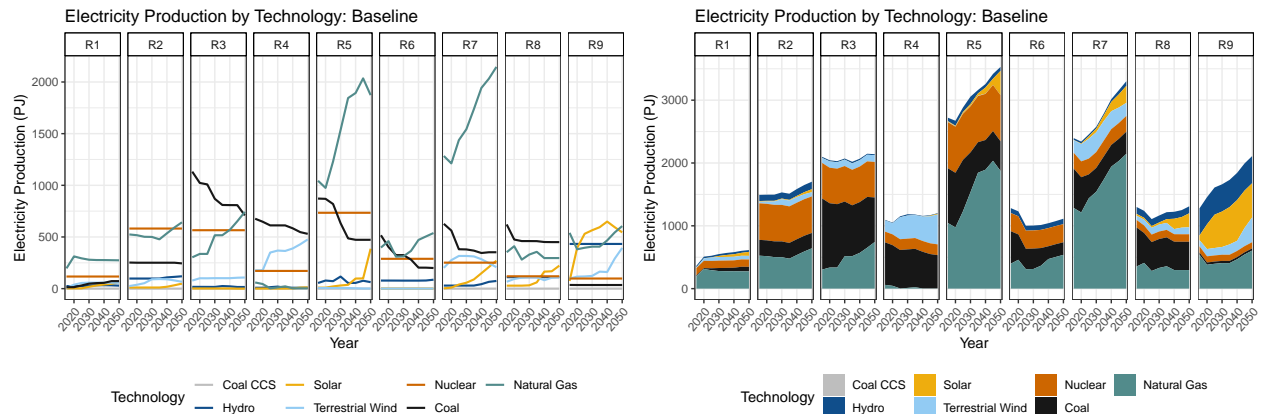
## 6 Grid Mix

### 6.1 Baseline Production

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

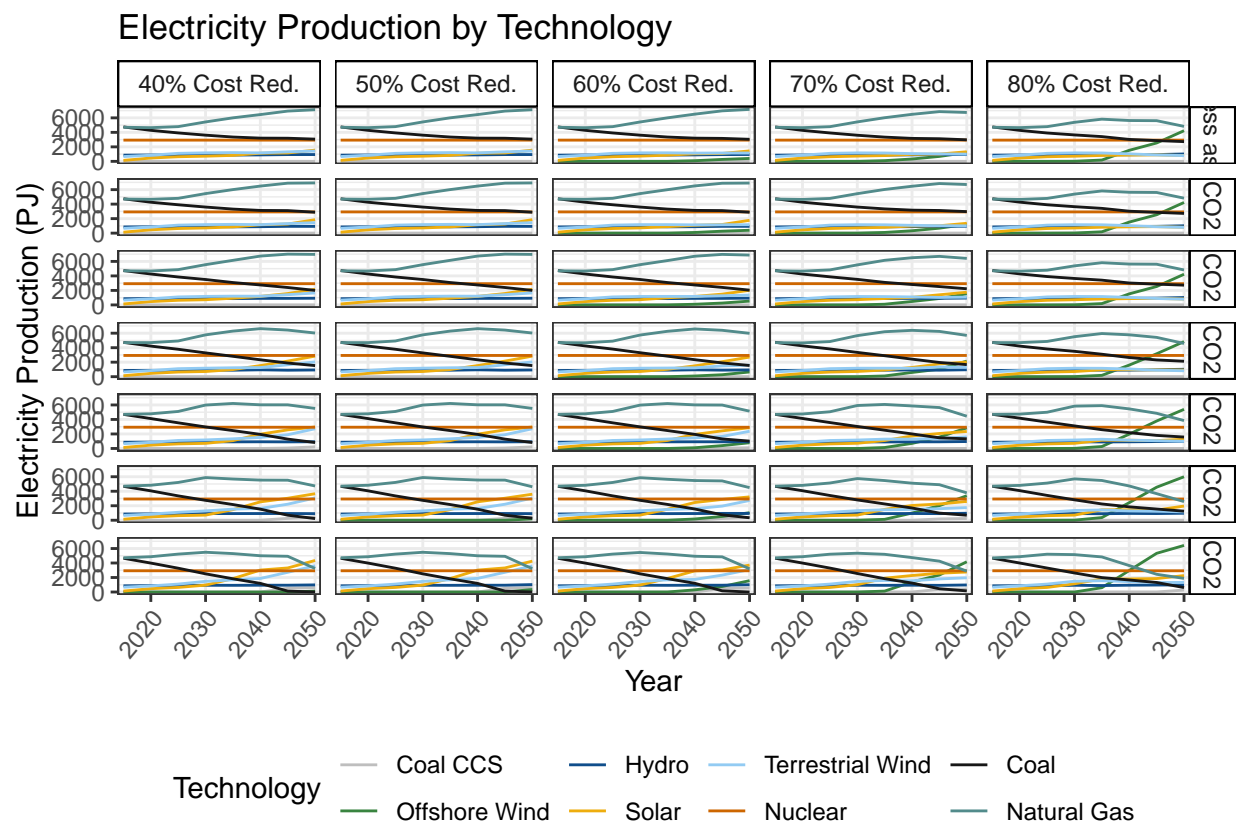


Regional baseline production



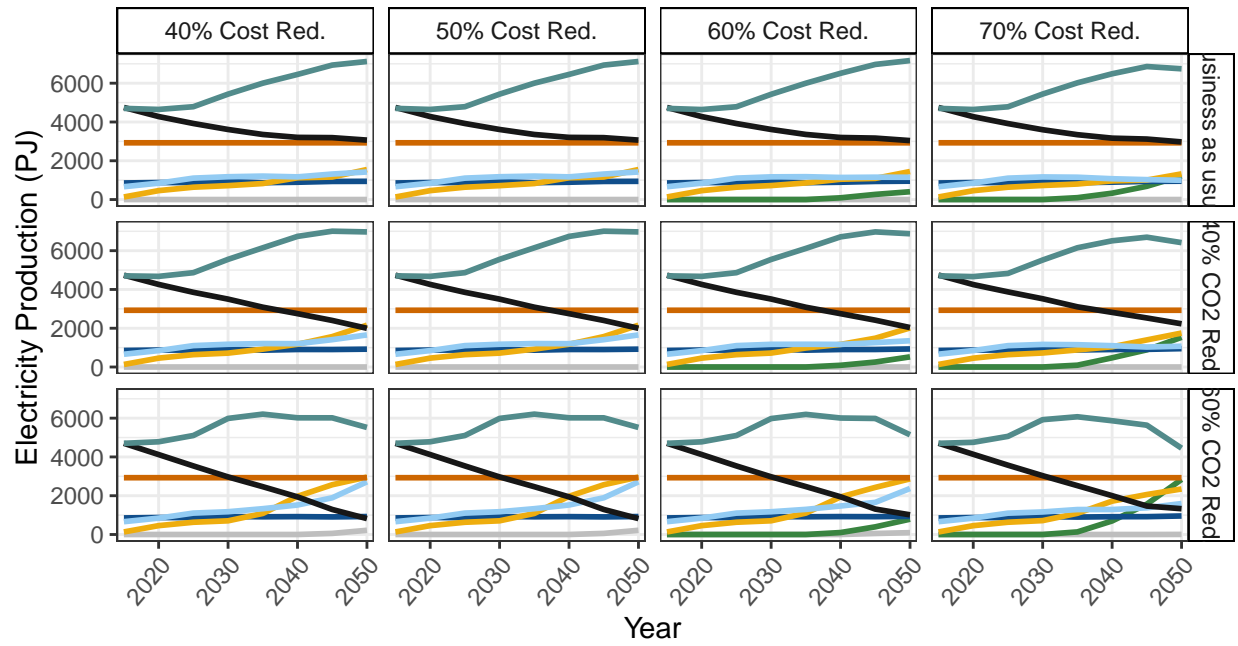
## 6.2 All Scenarios

Complete Set



Parsed Set

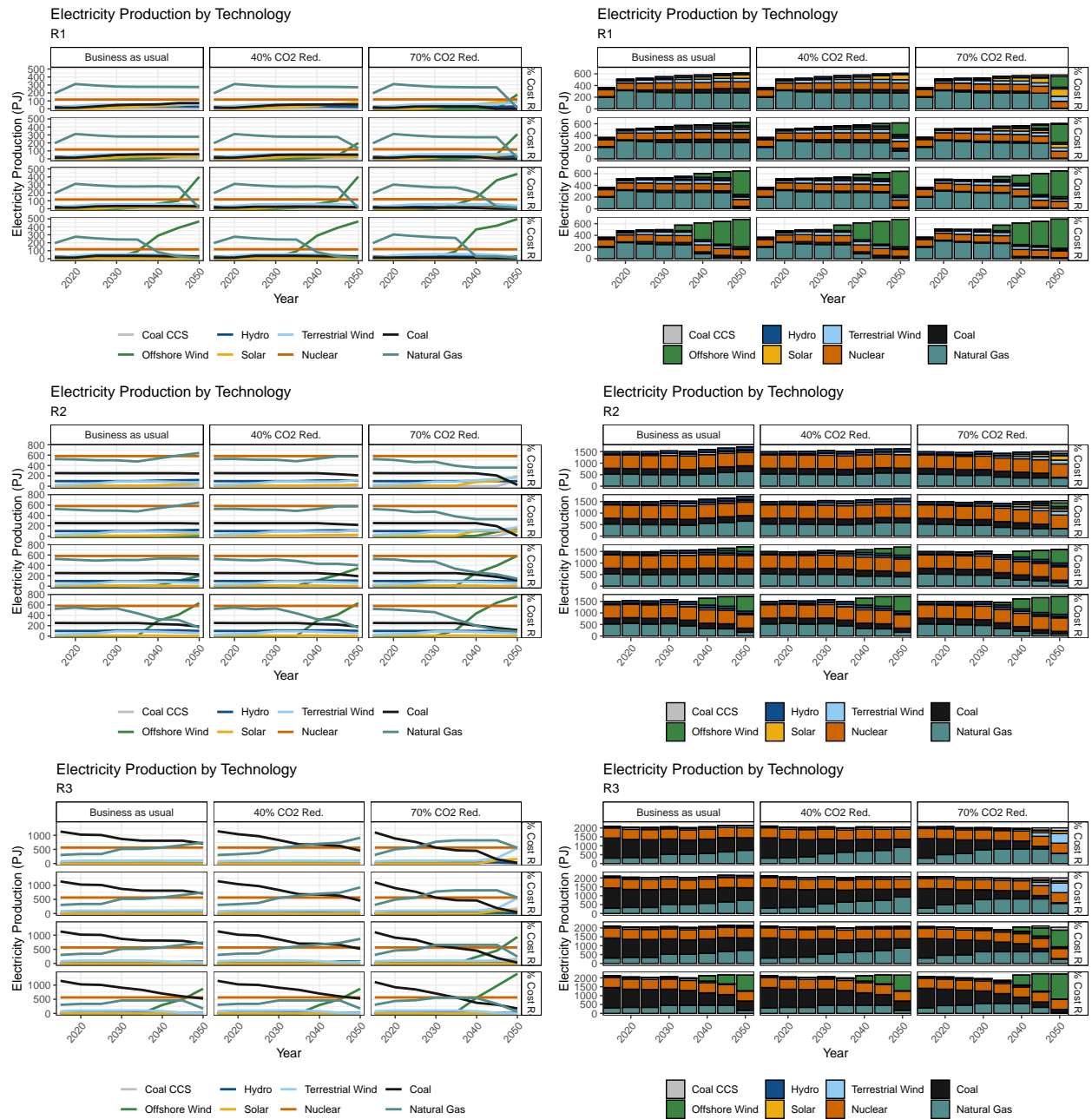
## Electricity Production by Technology

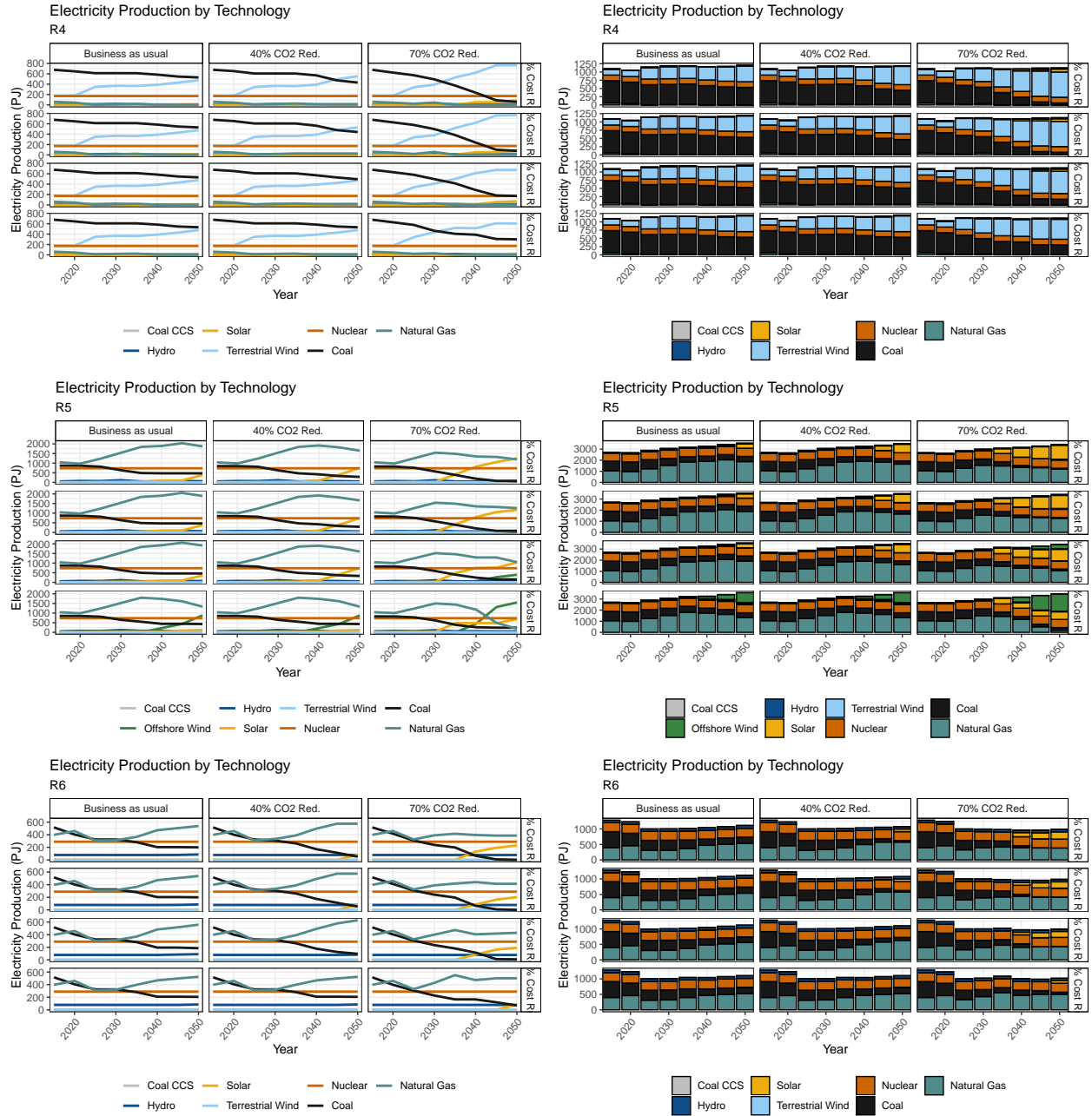


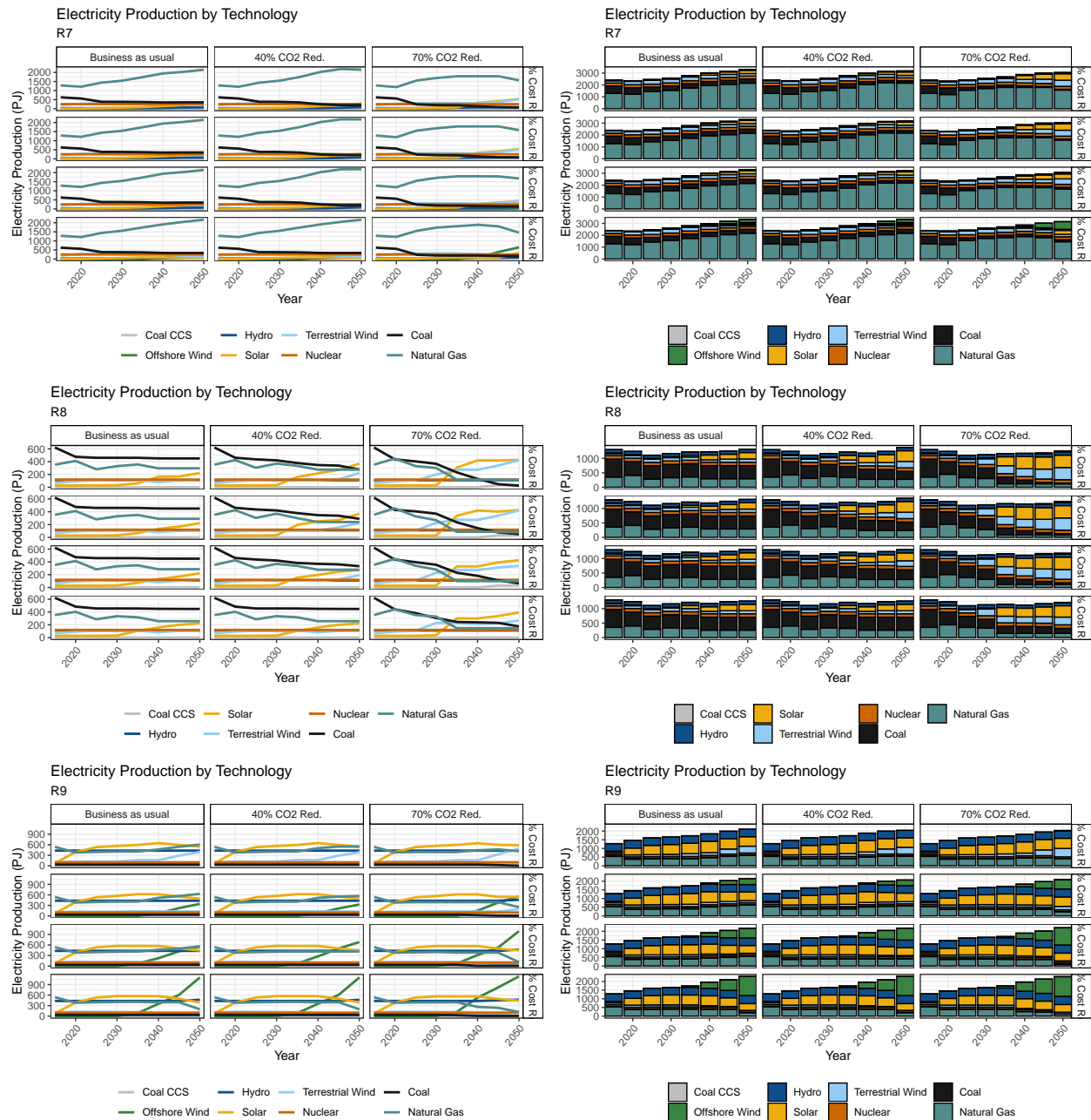
Technology

Coal CCS	Hydro	Terrestrial Wind	Coal
Offshore Wind	Solar	Nuclear	Natural Gas

## 6.3 Regional Mix

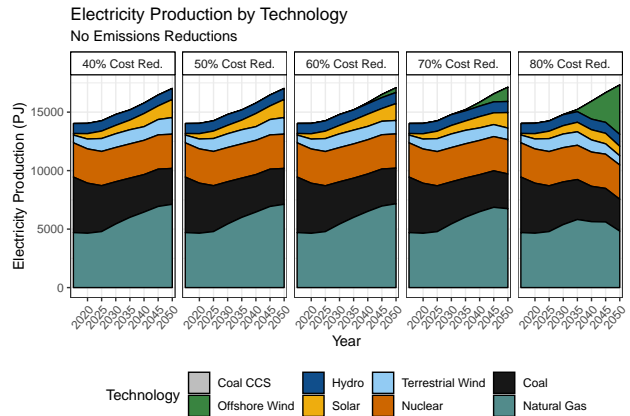
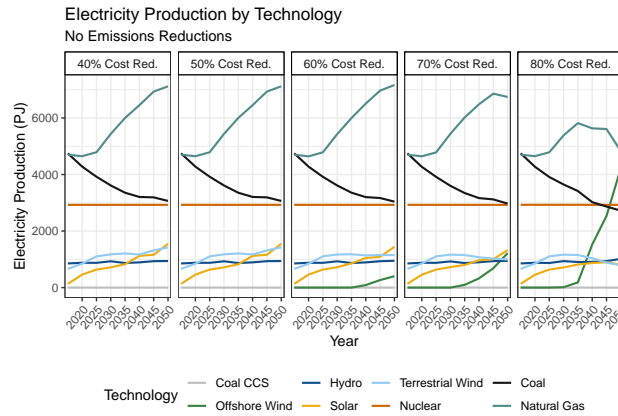




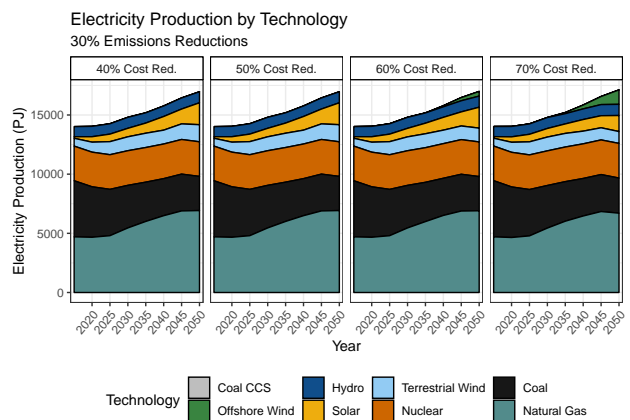
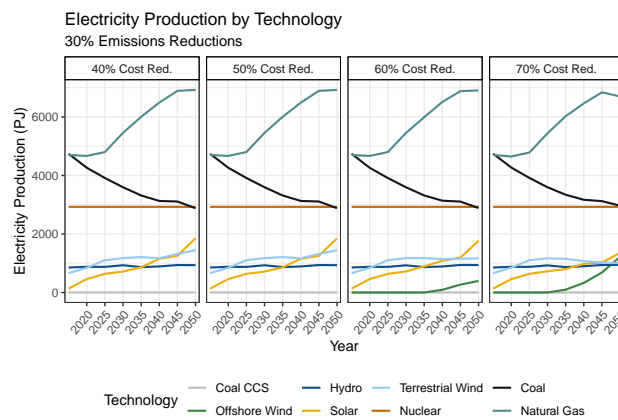


## 6.4 Emissions Cap

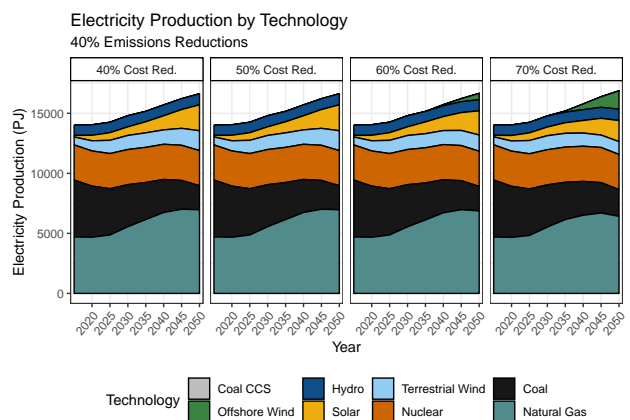
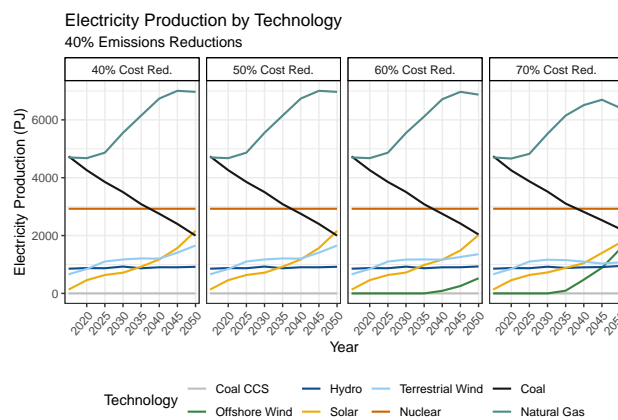
BAU emissions



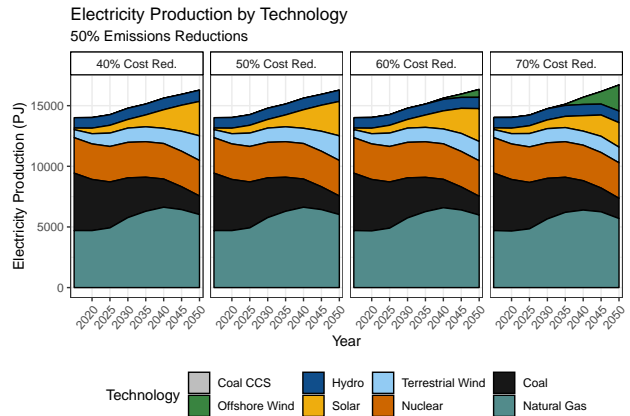
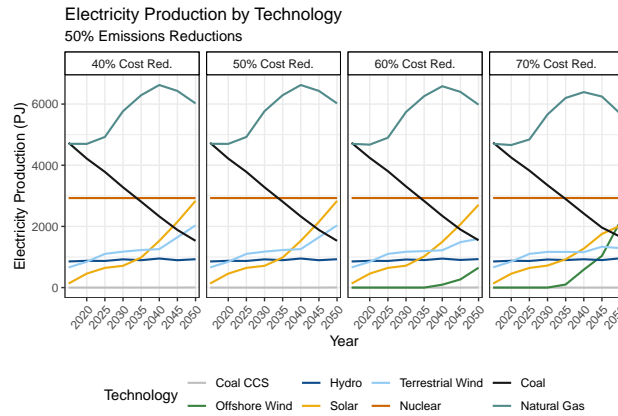
### 30% emissions reduction



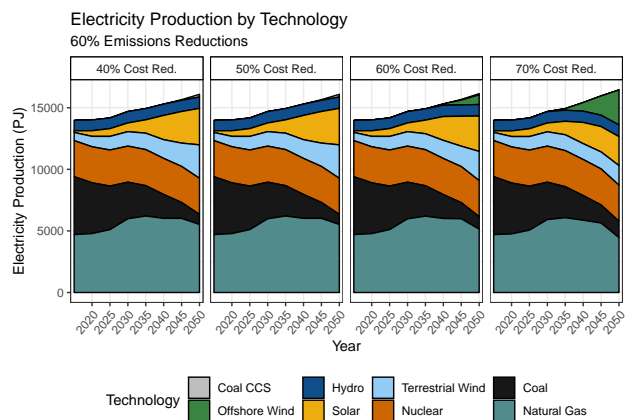
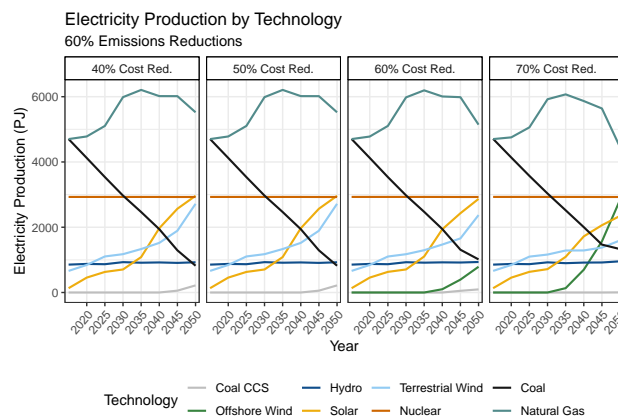
### 40% emissions reduction



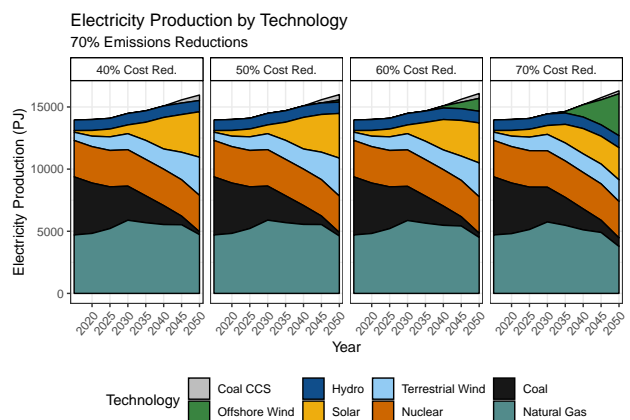
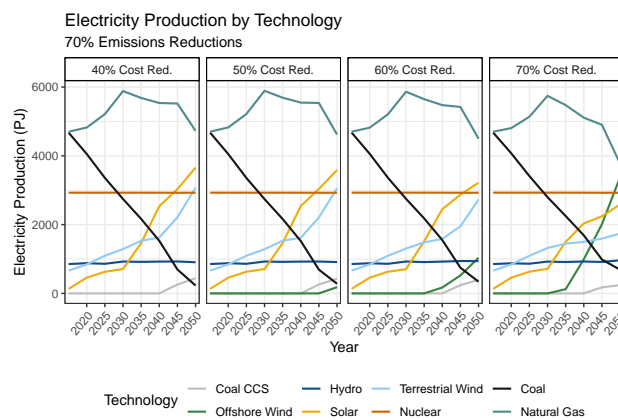
### 50% emissions reduction



## 60% emissions reduction

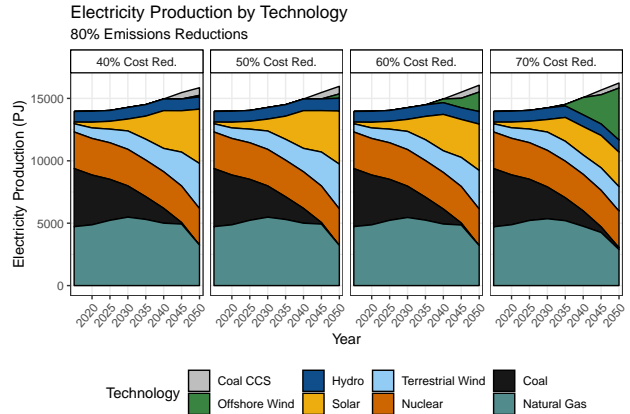
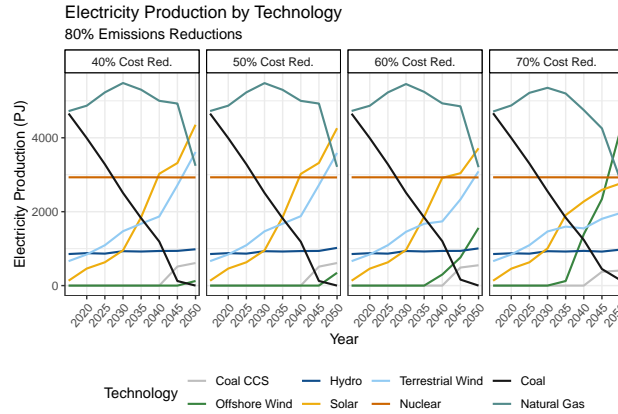


## 70% emissions reduction



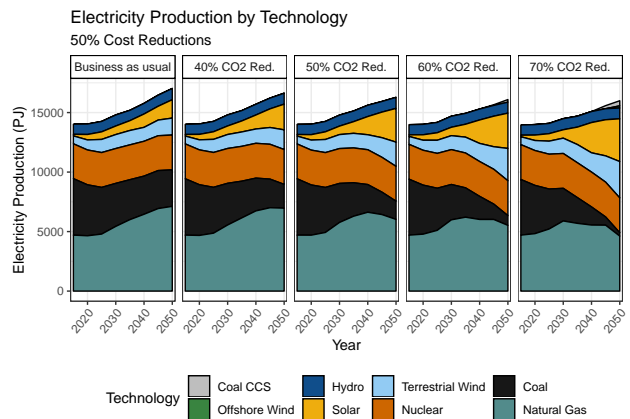
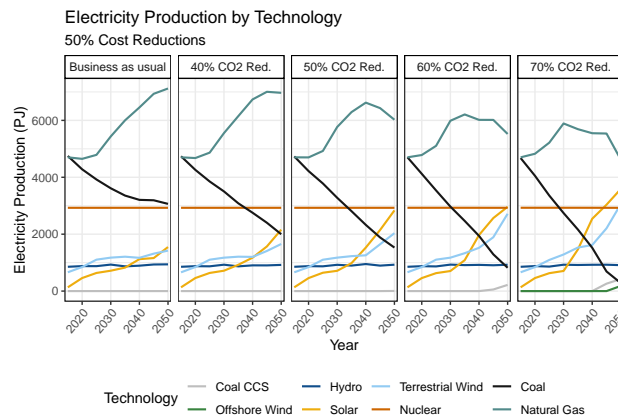
## 80% emissions reduction



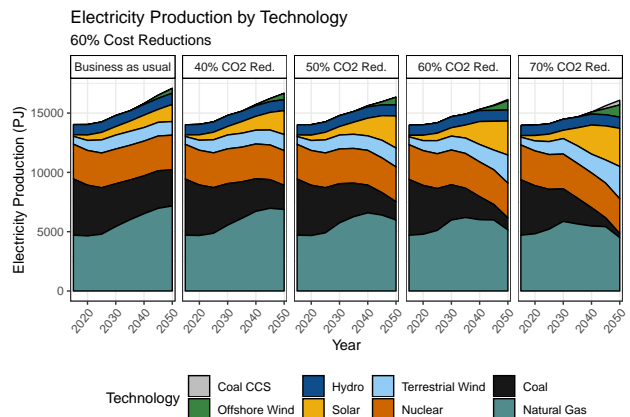
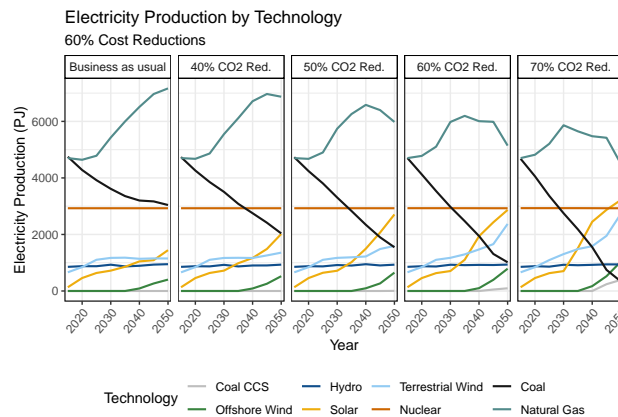


## 6.5 Cost Reductions

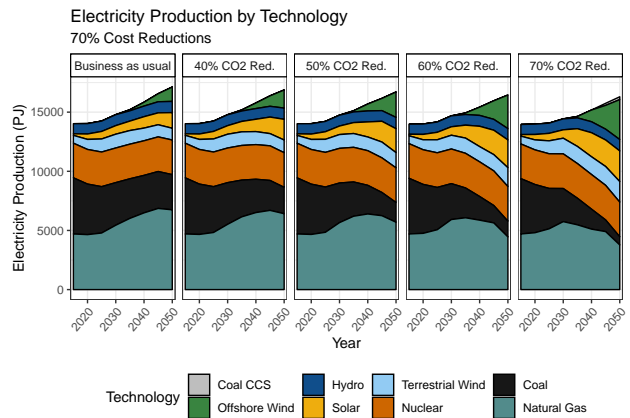
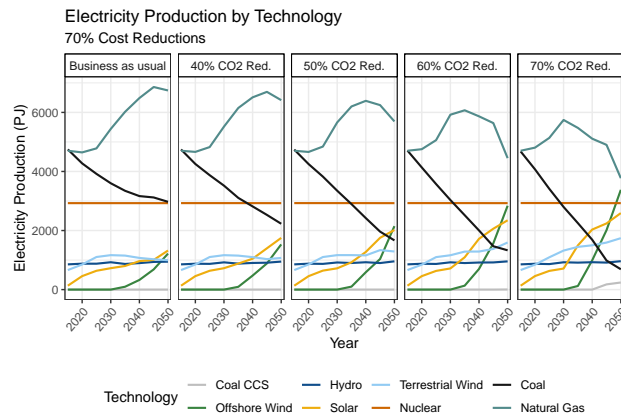
50% cost reduction



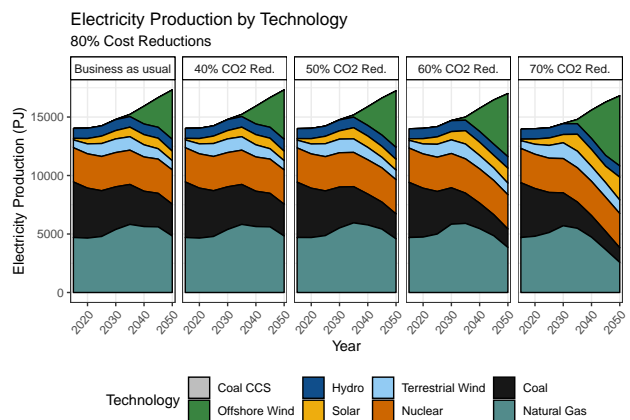
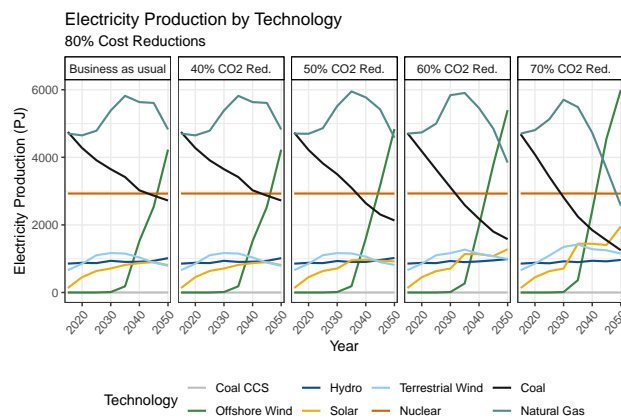
60% cost reduction



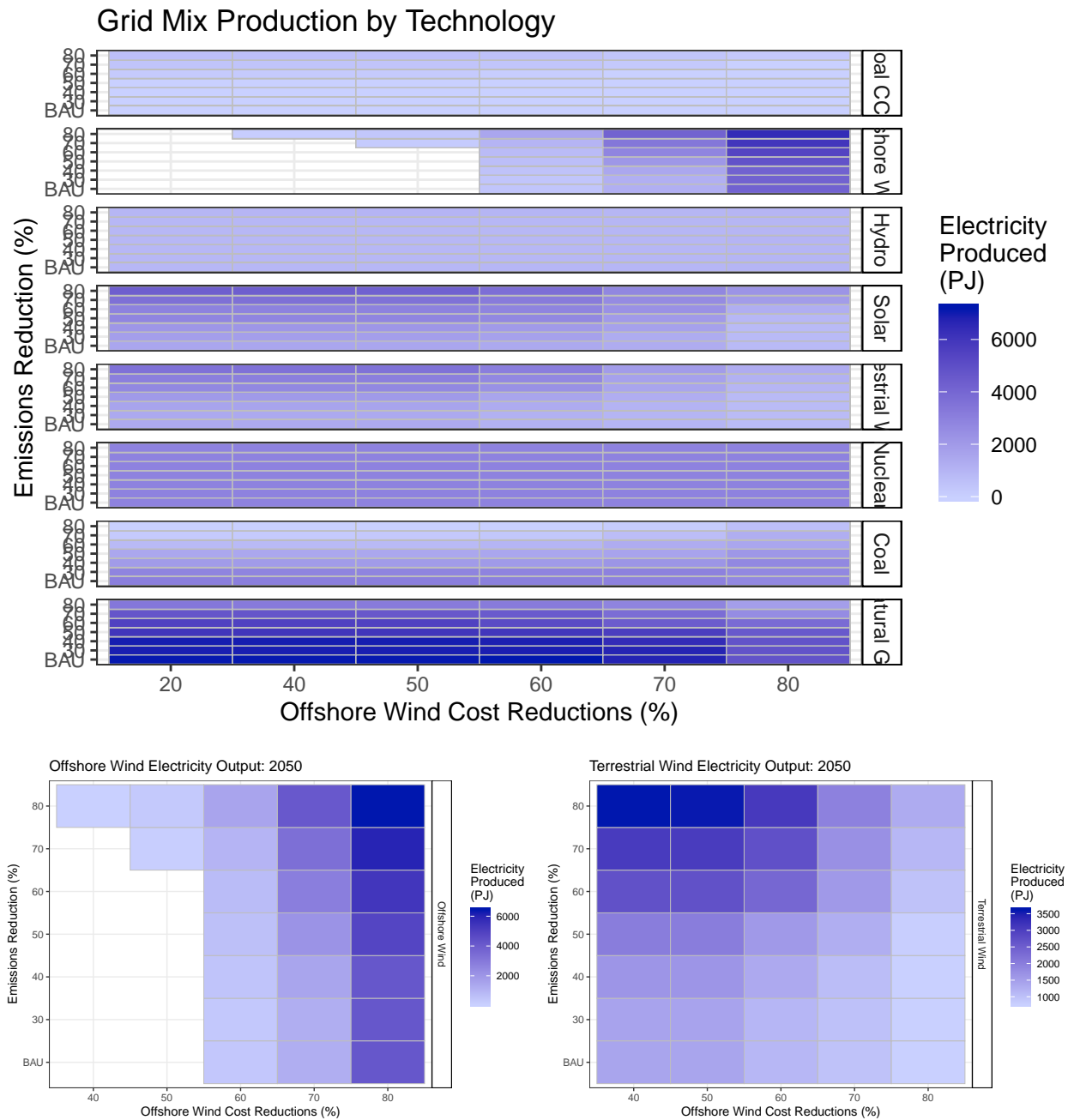
70% cost reduction

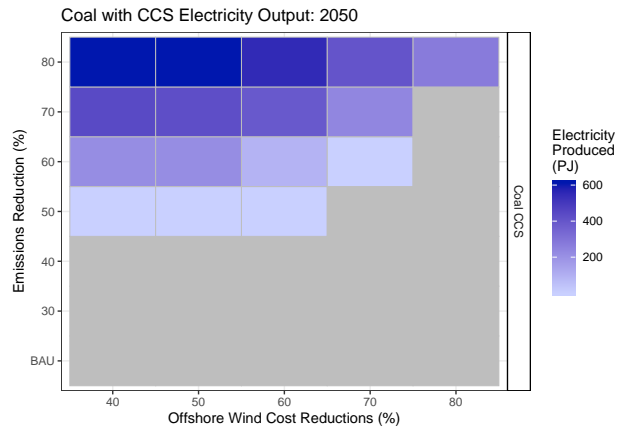
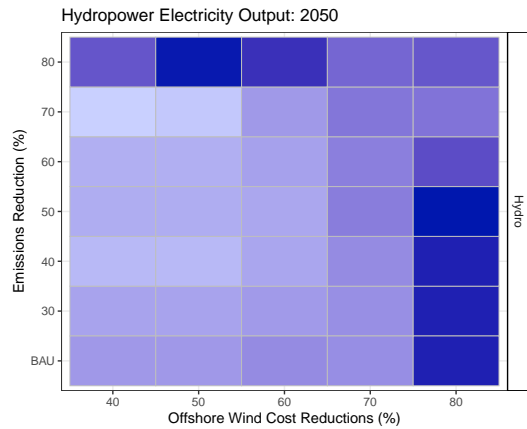
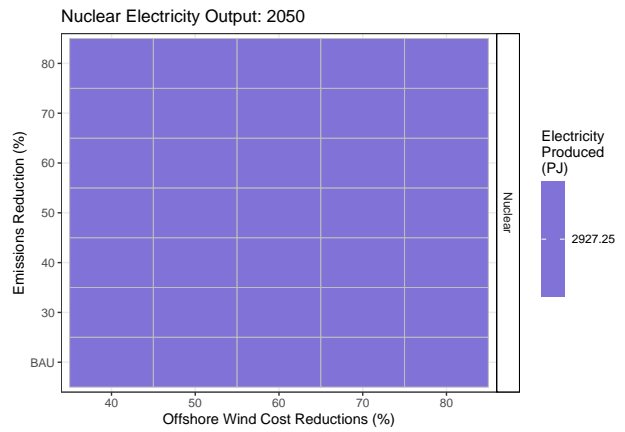
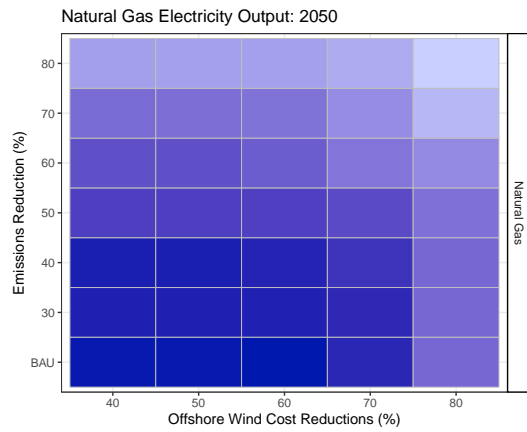
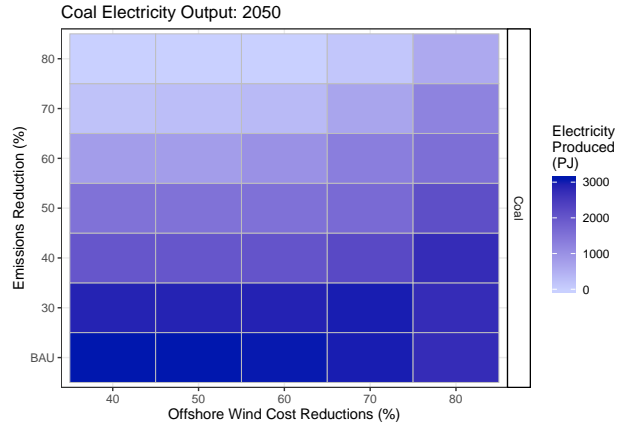
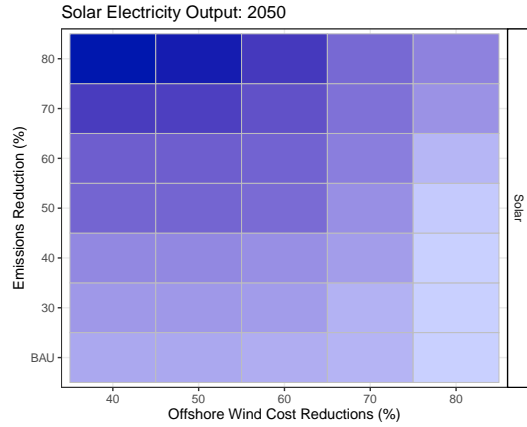


80% cost reduction



6.6 Heatmaps





## 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
##
##

```

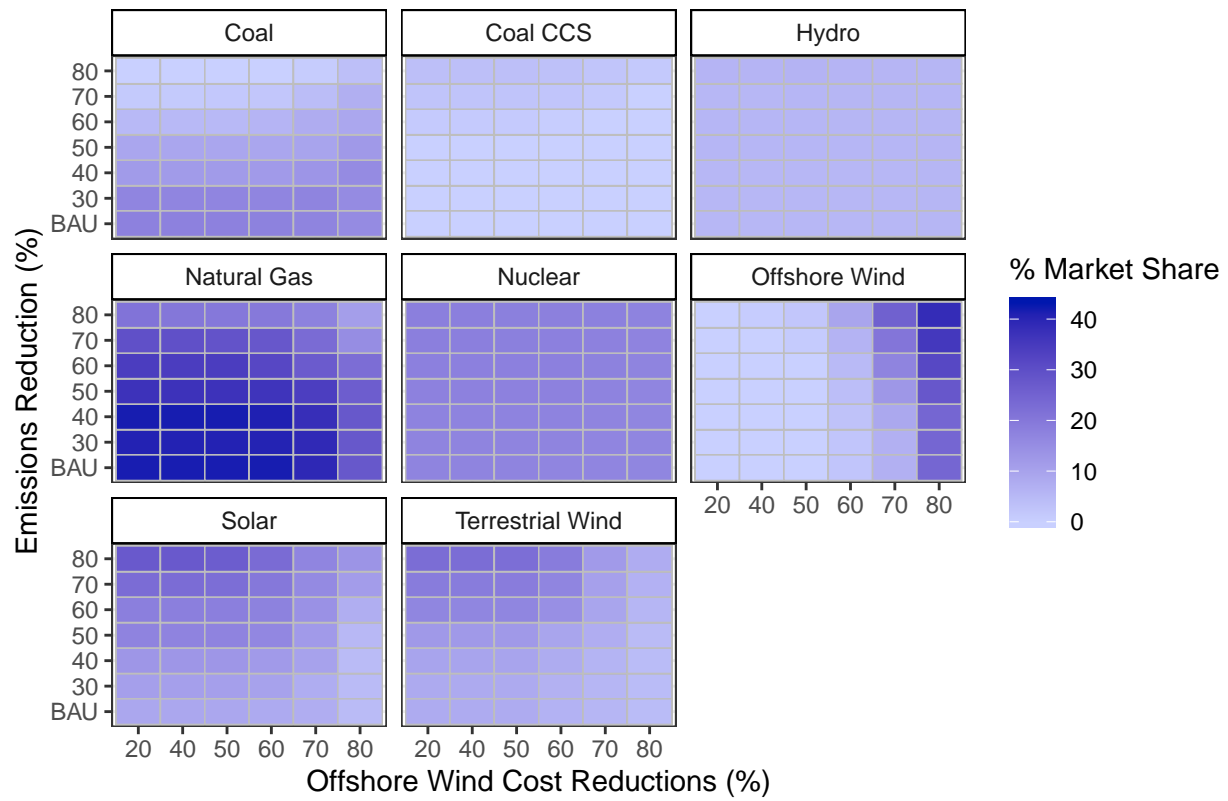
Table 6: 2050 Percent Market Share by Technology

Technology	CO2 Cap	Cost Reduction (%)					
		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

	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
Natural Gas	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
	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
Nuclear	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
	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
Offshore Wind	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
	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
Solar	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
	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
Terrestrial Wind	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

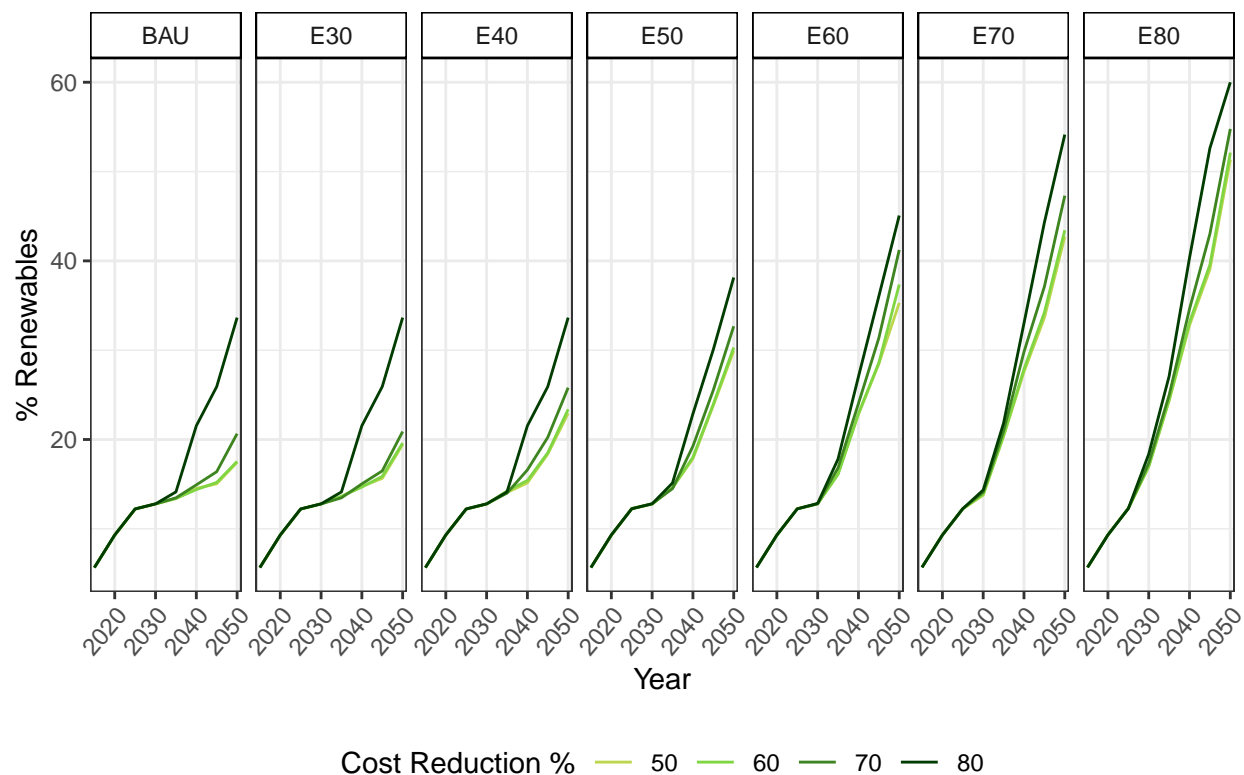


## Technology Market Share: 2050



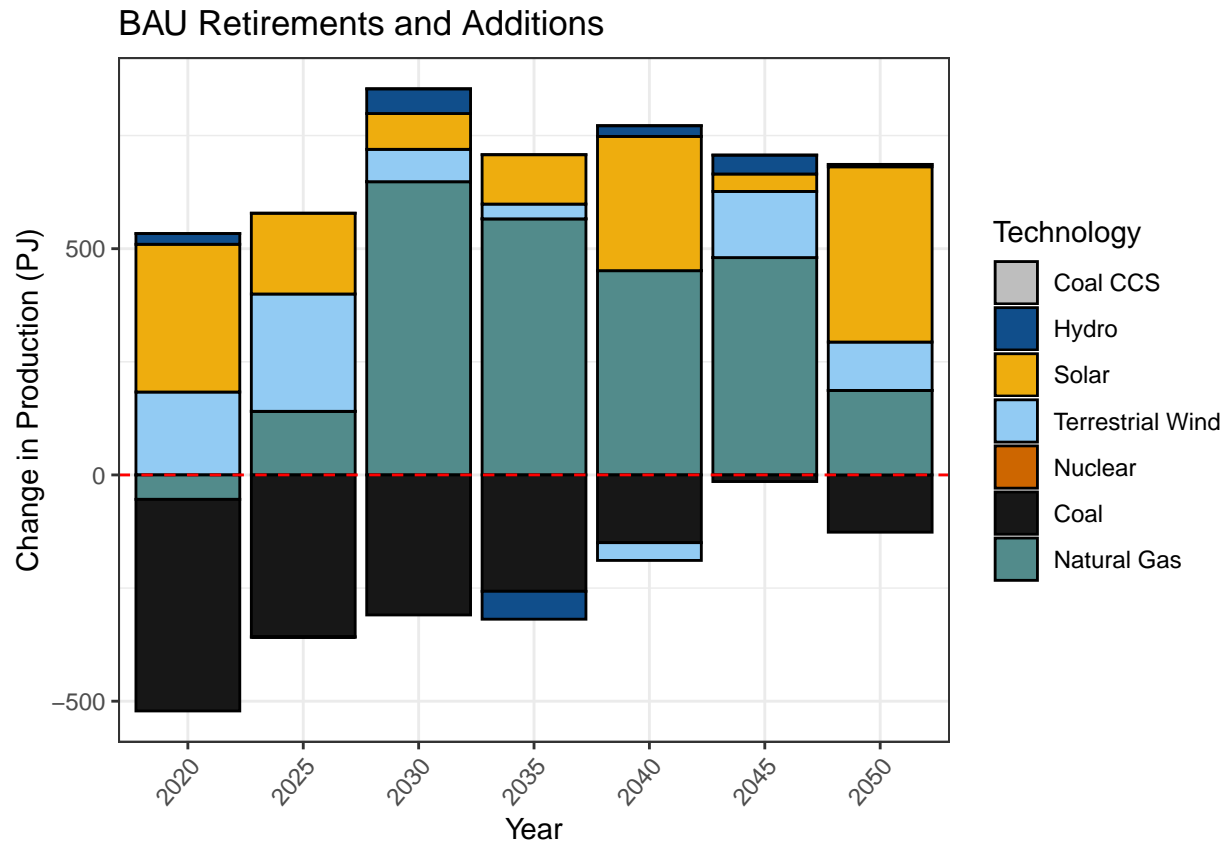
## 6.8 Renewable Contributions

### Renewable Technology Contribution to Electricity Production



## 6.9 Retirements and Additions

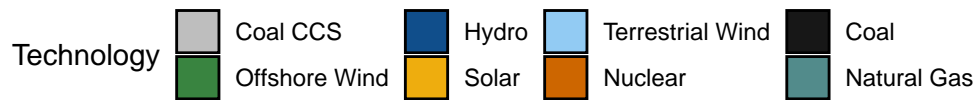
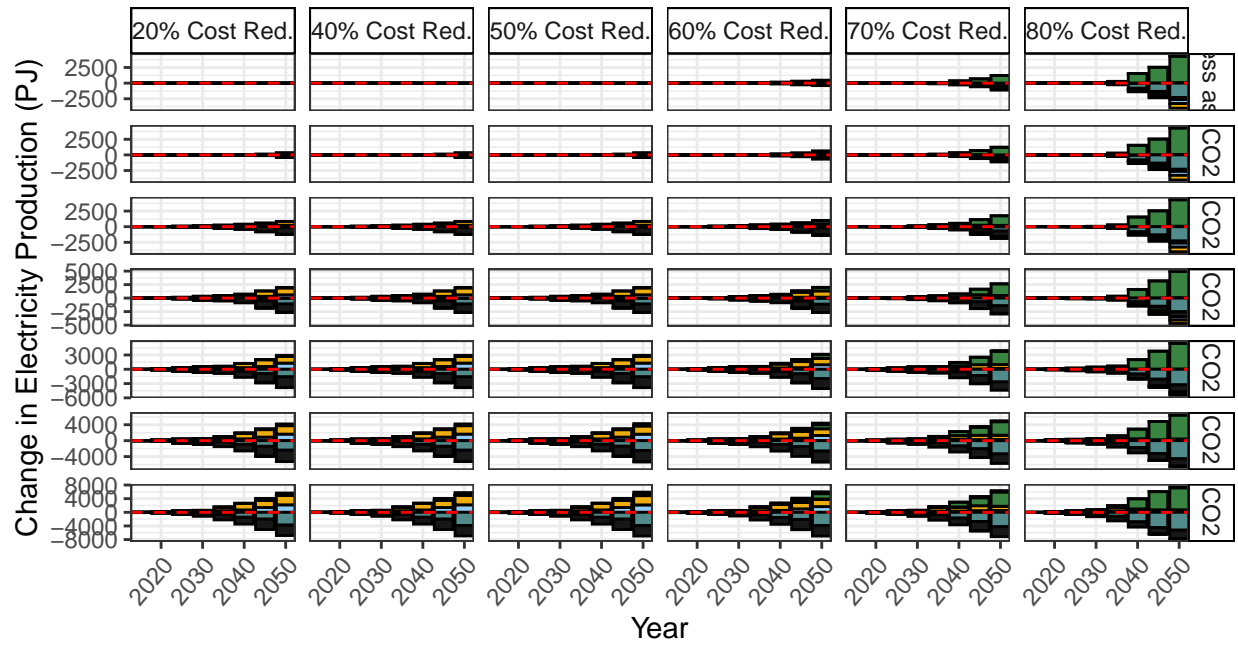
Basecase year-on-year changes in the grid mix. Shows the modeled fluctuations in generation. All following quantifications of grid mix changes are as compared to these changes in the basecase.



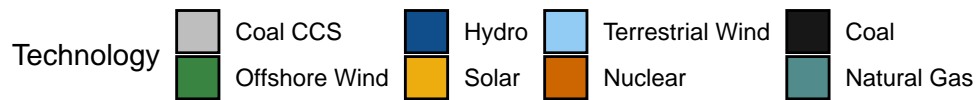
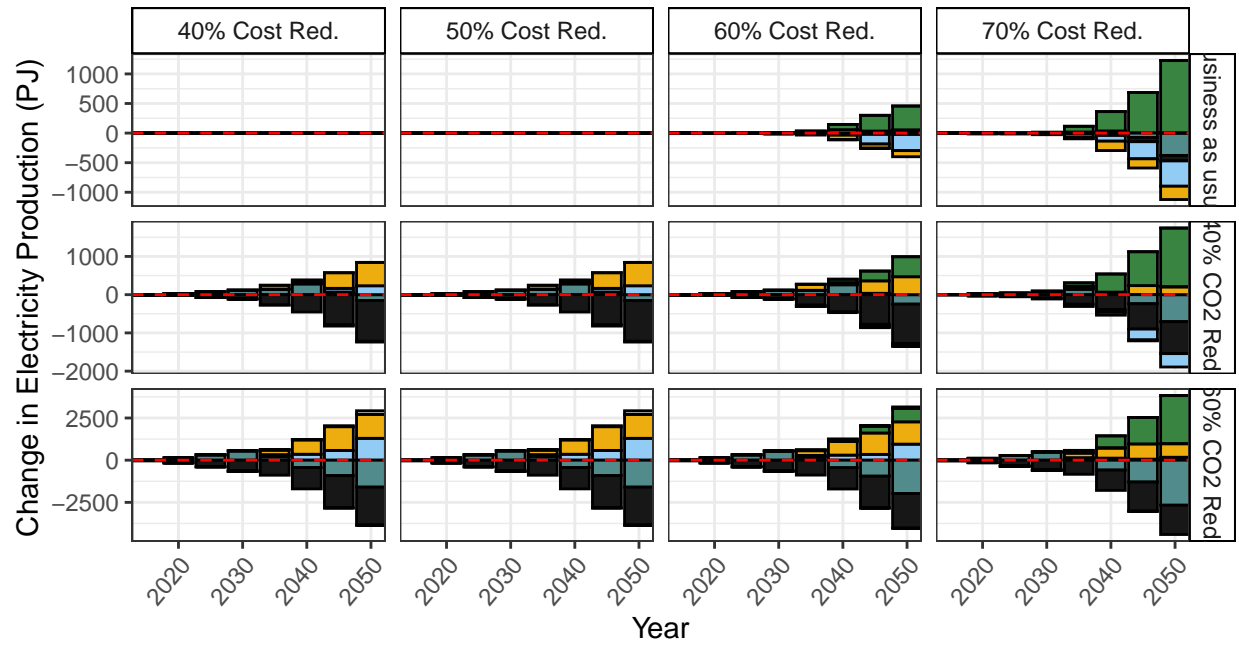
## 6.10 Changes Over Baseline

Summary Graph

## Changes in Grid Mix over Baseline



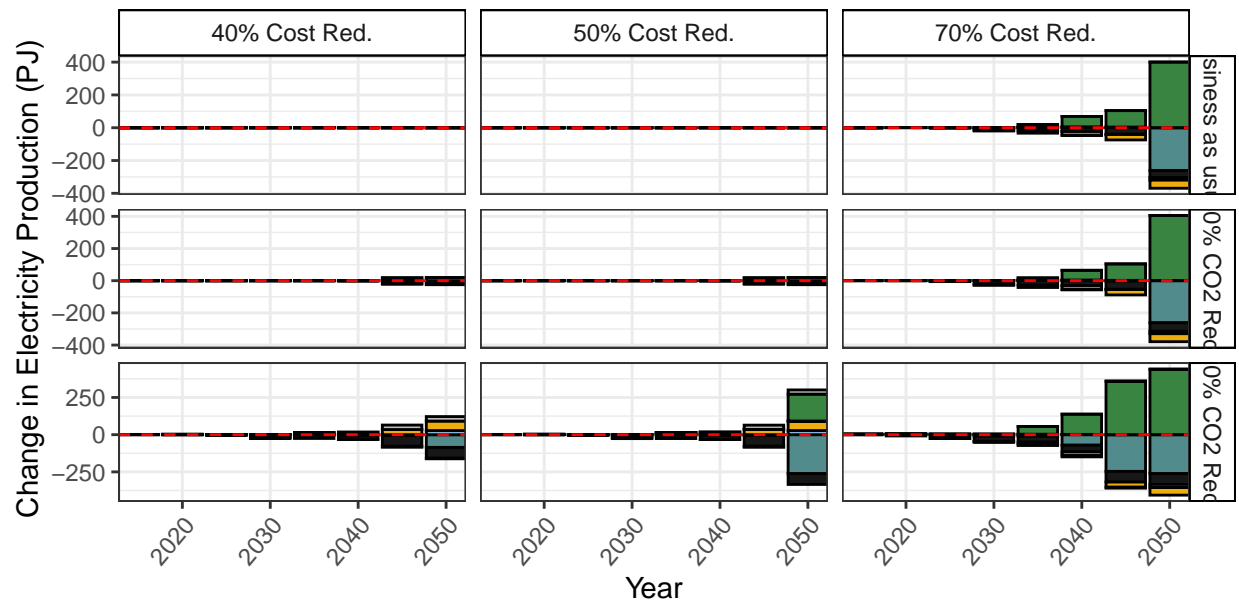
## Changes in Grid Mix over Baseline



Regional Summary Graphs

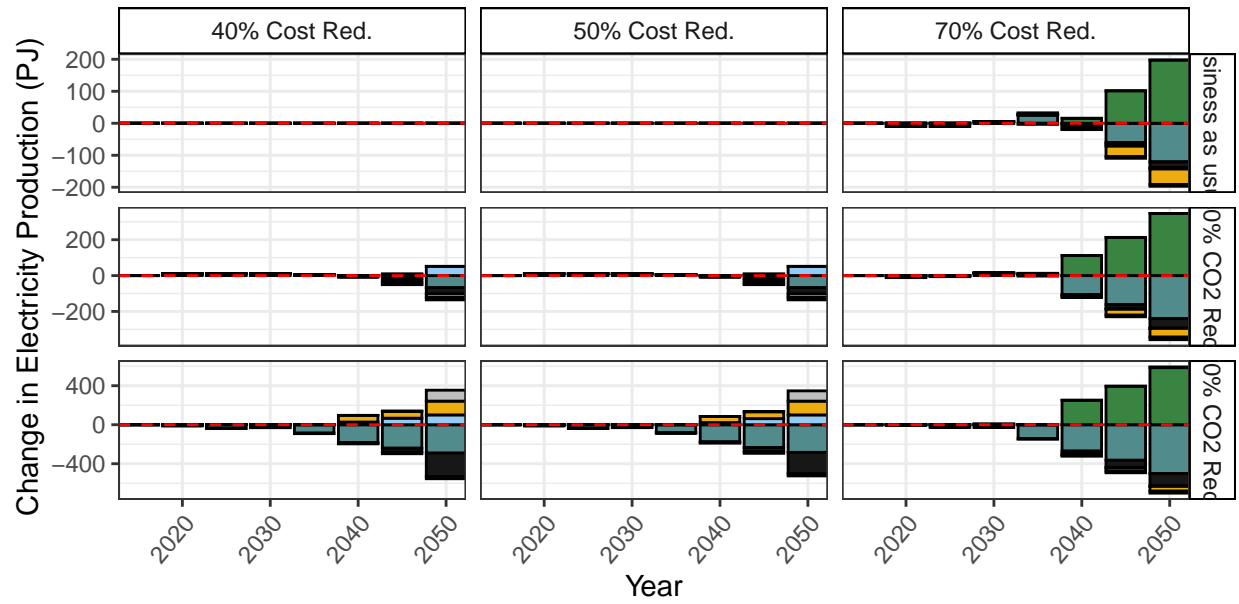
# Changes in Grid Mix over Baseline

R1



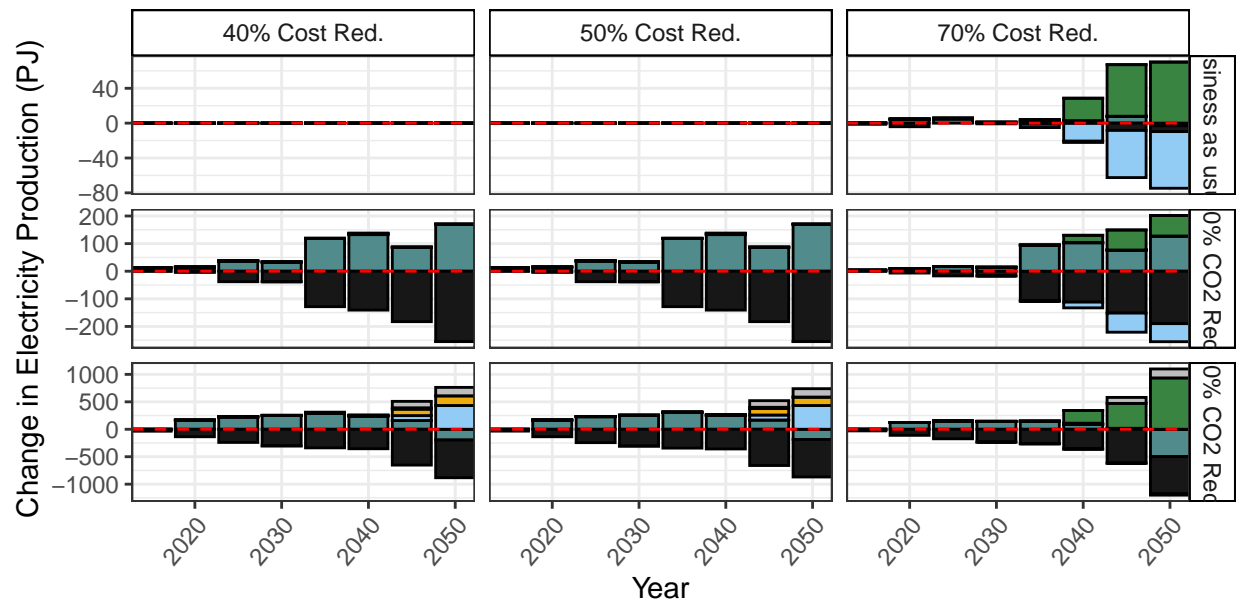
## Changes in Grid Mix over Baseline

R2



## Changes in Grid Mix over Baseline

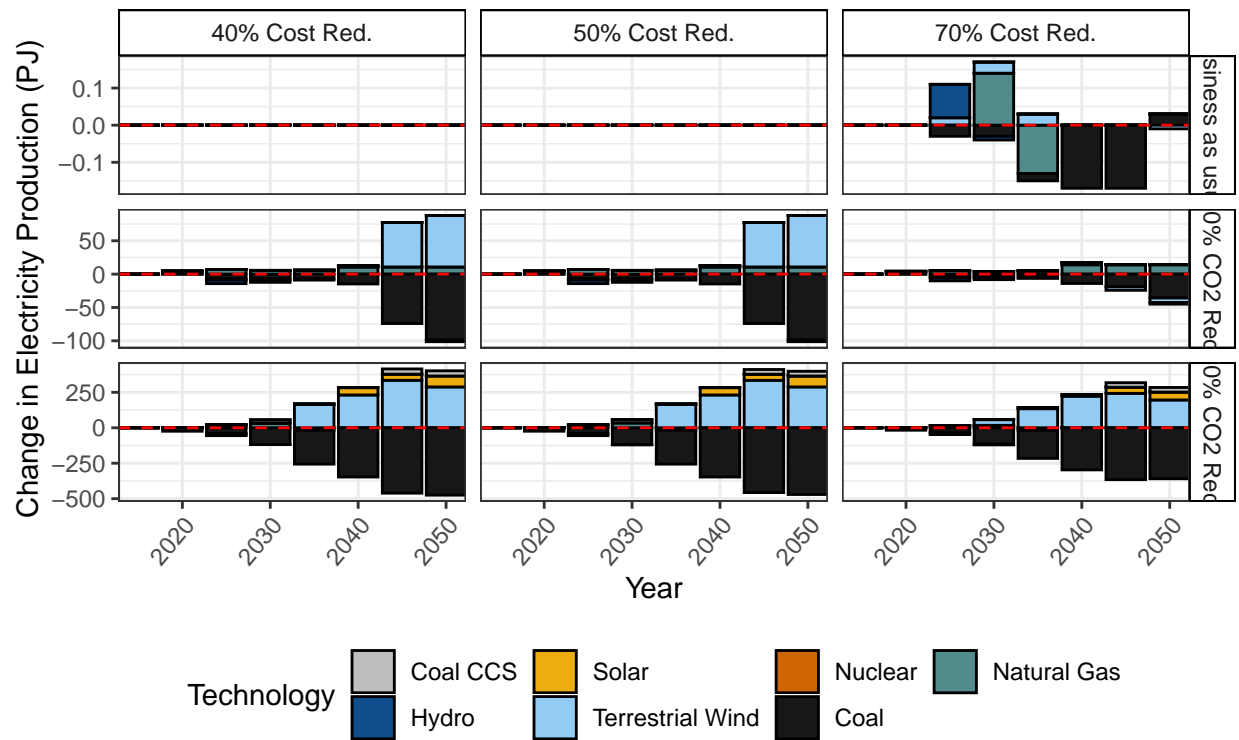
R3





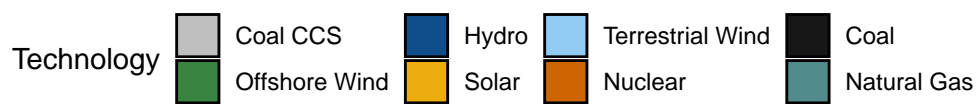
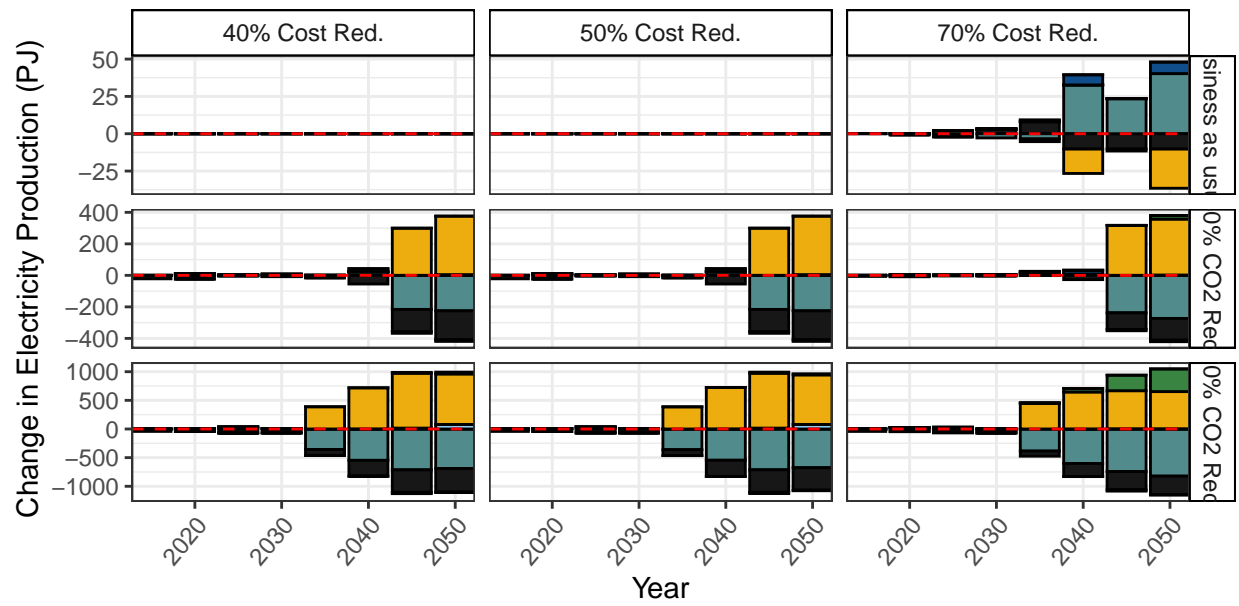
# Changes in Grid Mix over Baseline

R4



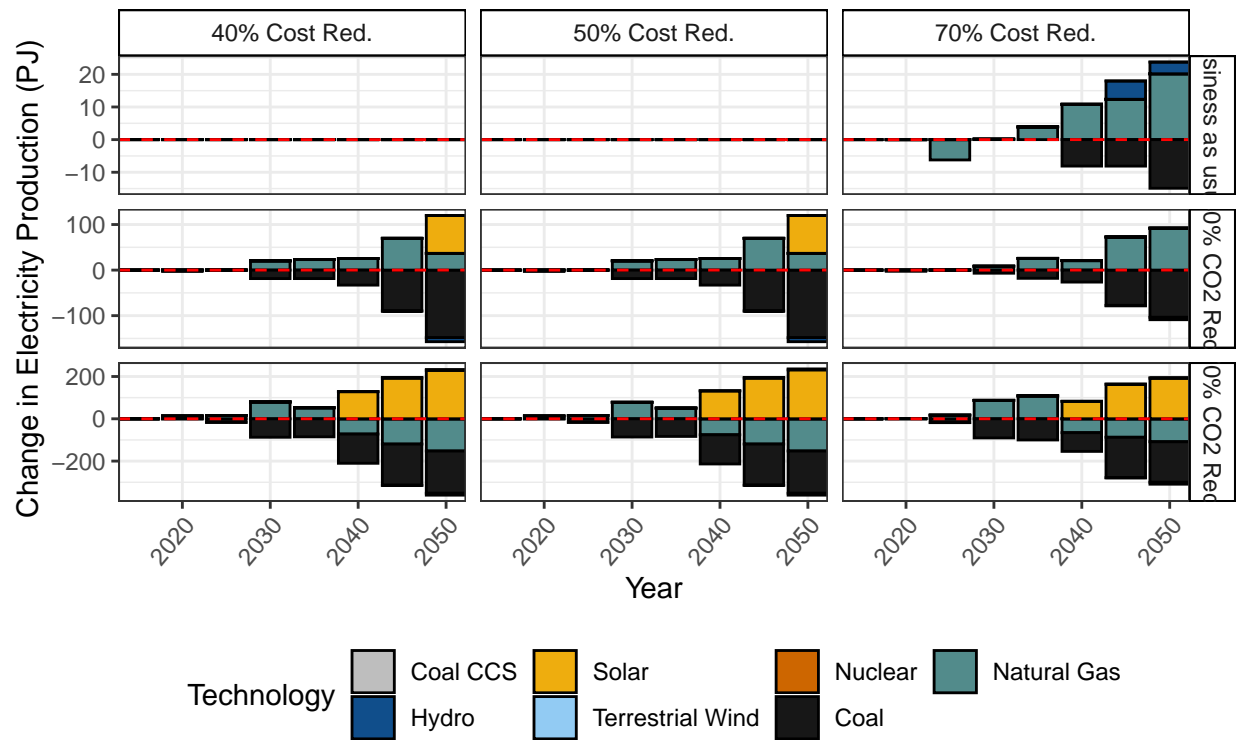
## Changes in Grid Mix over Baseline

R5



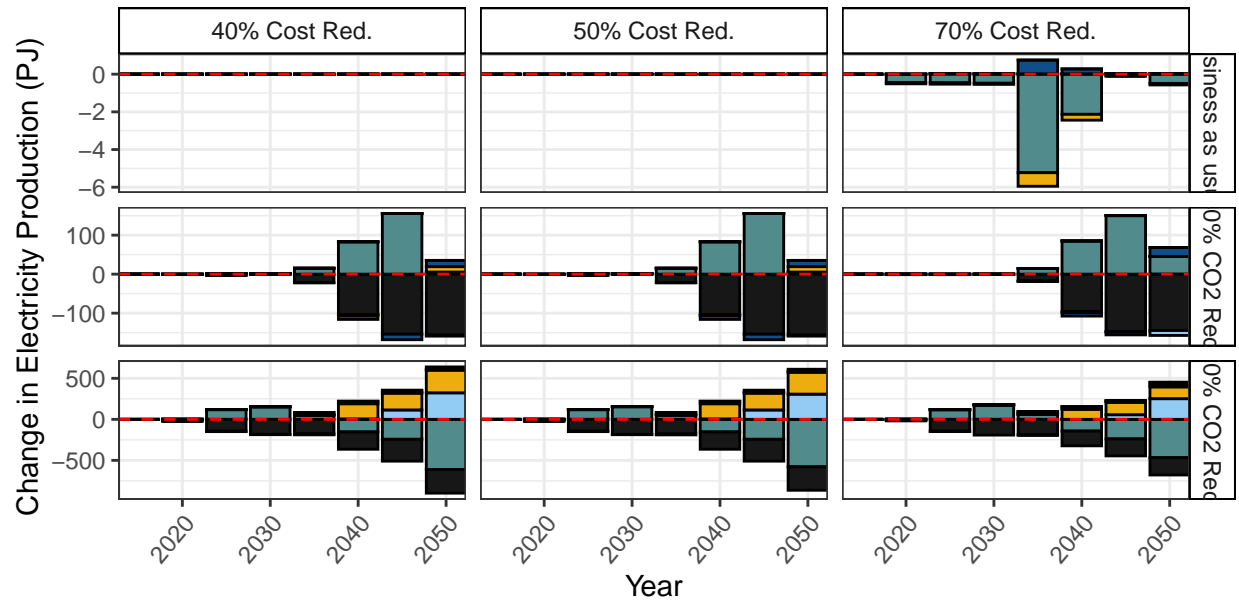
# Changes in Grid Mix over Baseline

R6



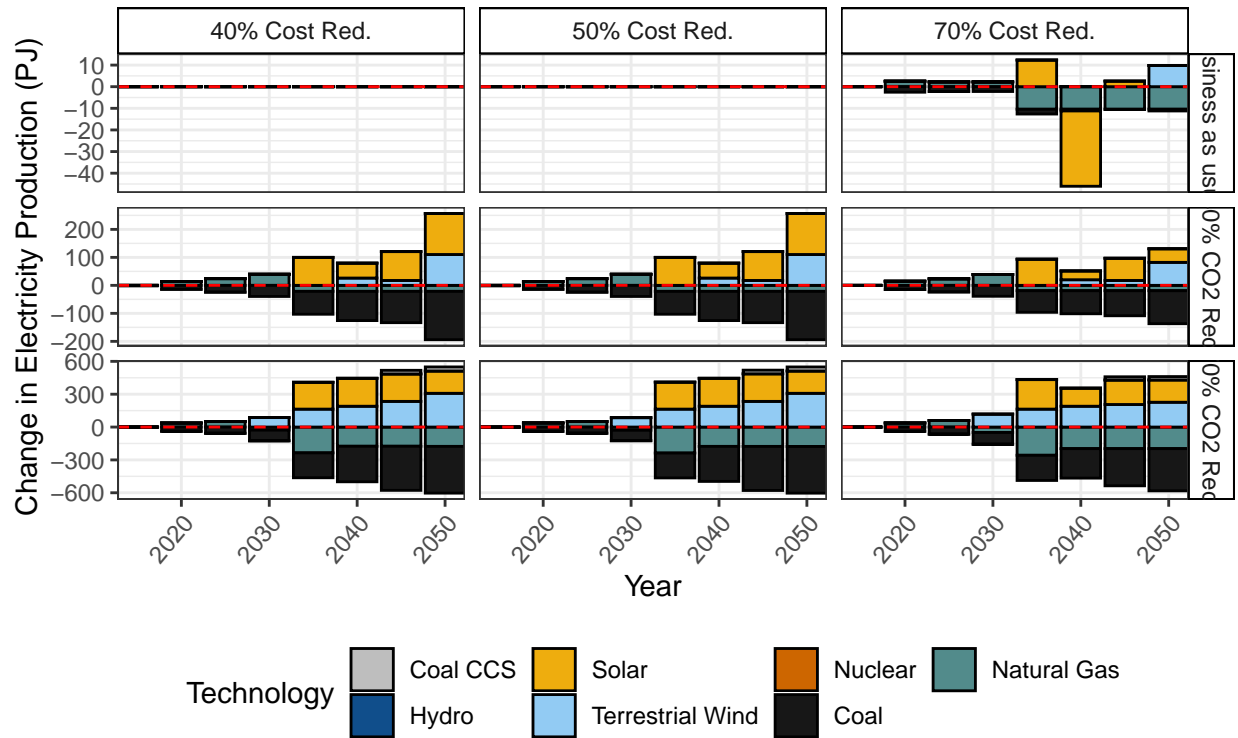
# Changes in Grid Mix over Baseline

R7



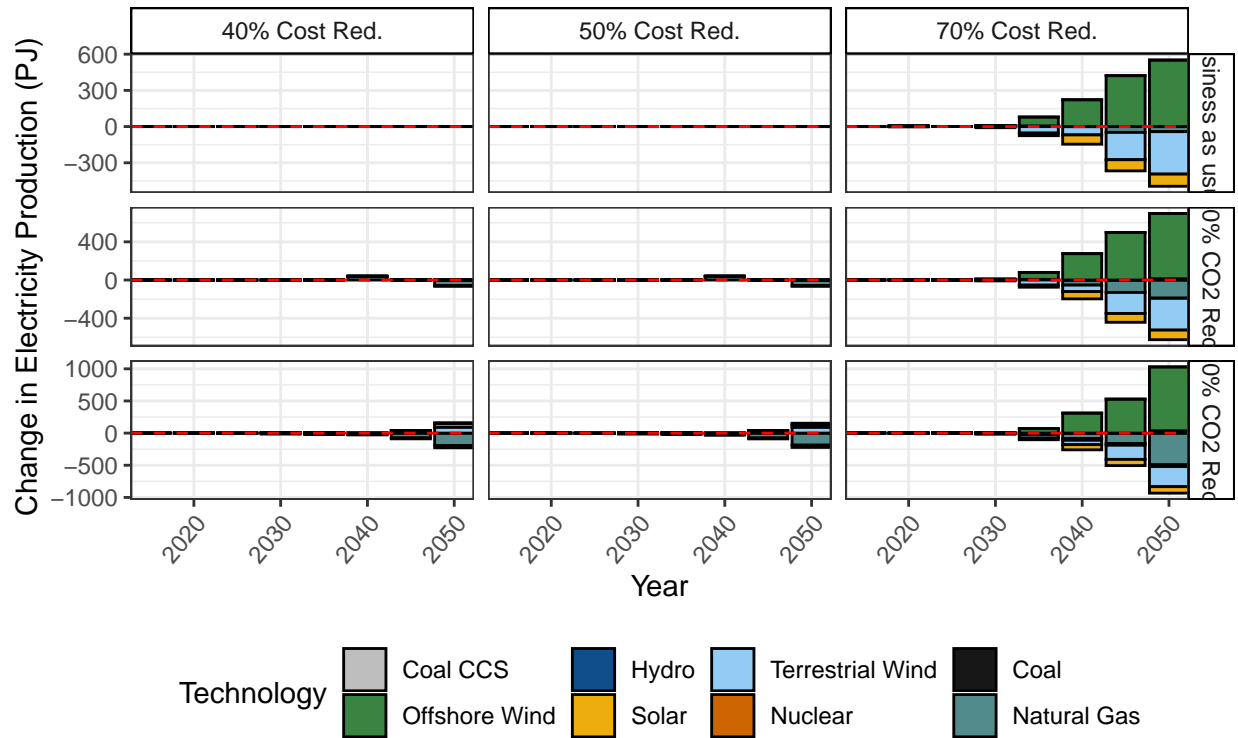
# Changes in Grid Mix over Baseline

R8

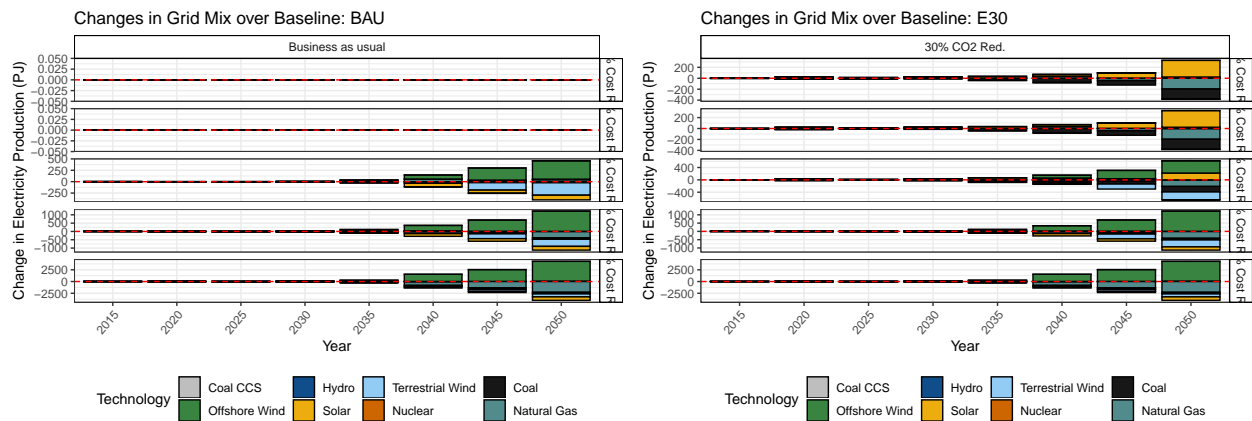


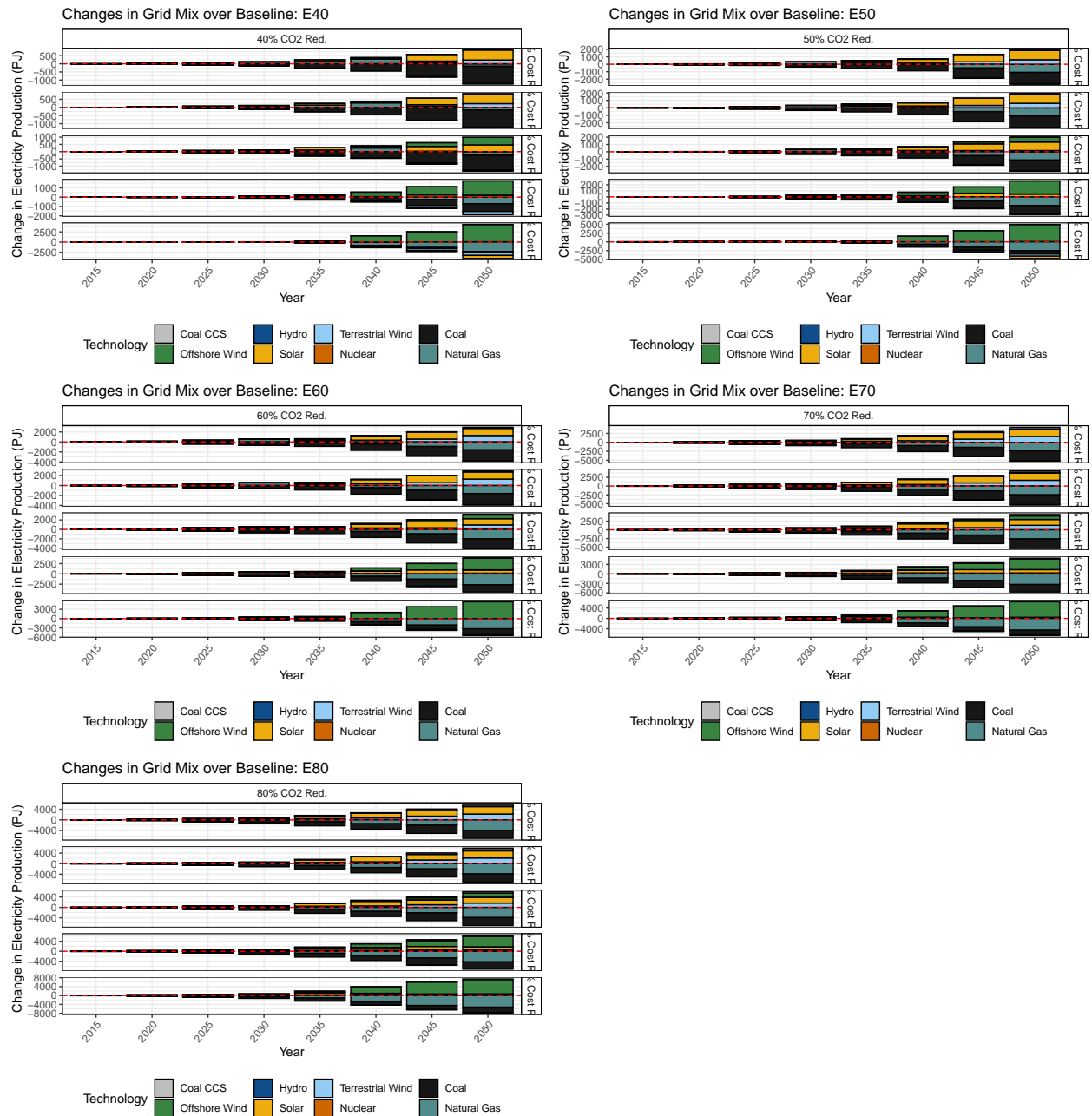
## Changes in Grid Mix over Baseline

R9

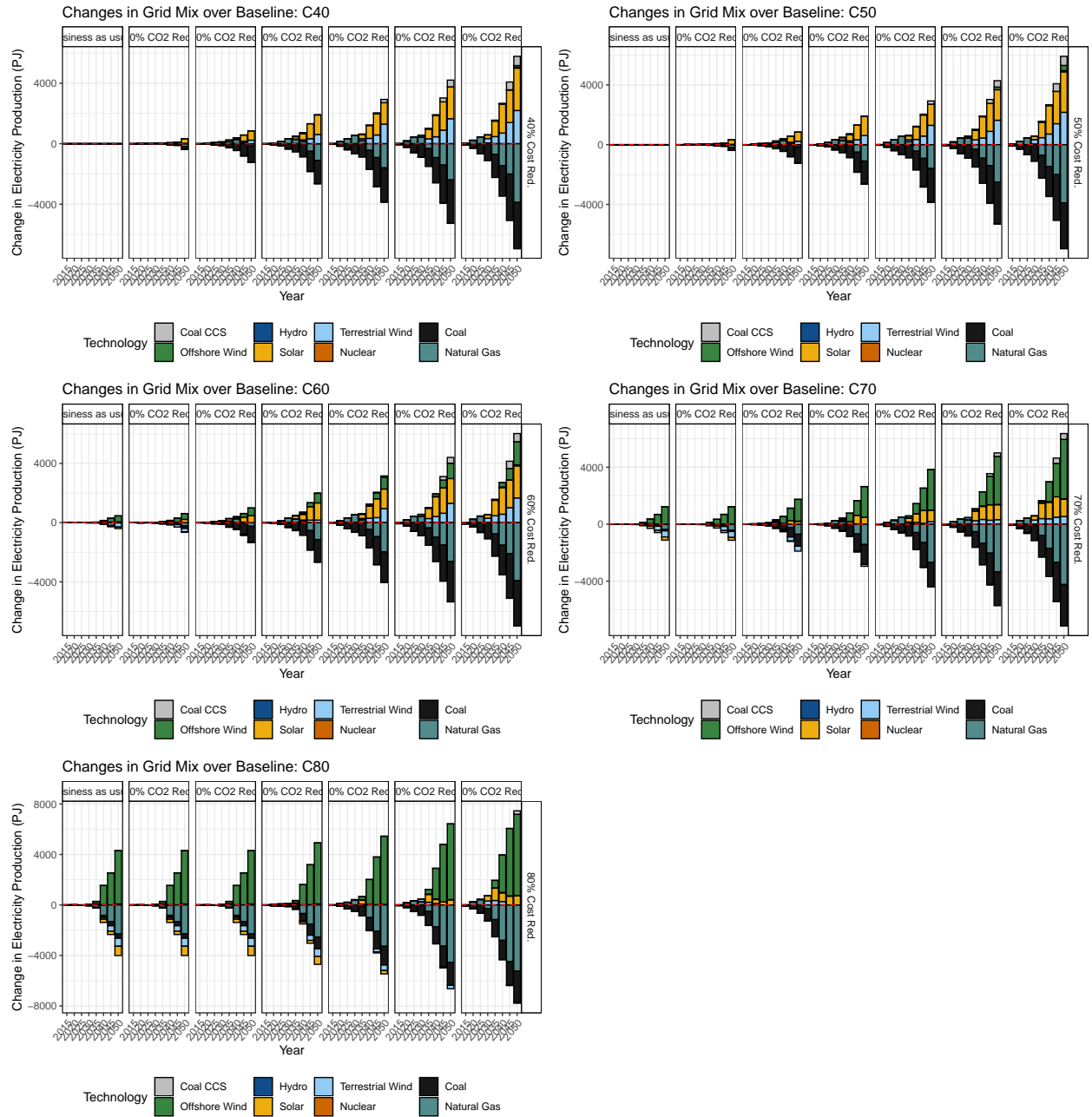


By Emissions Reduction %





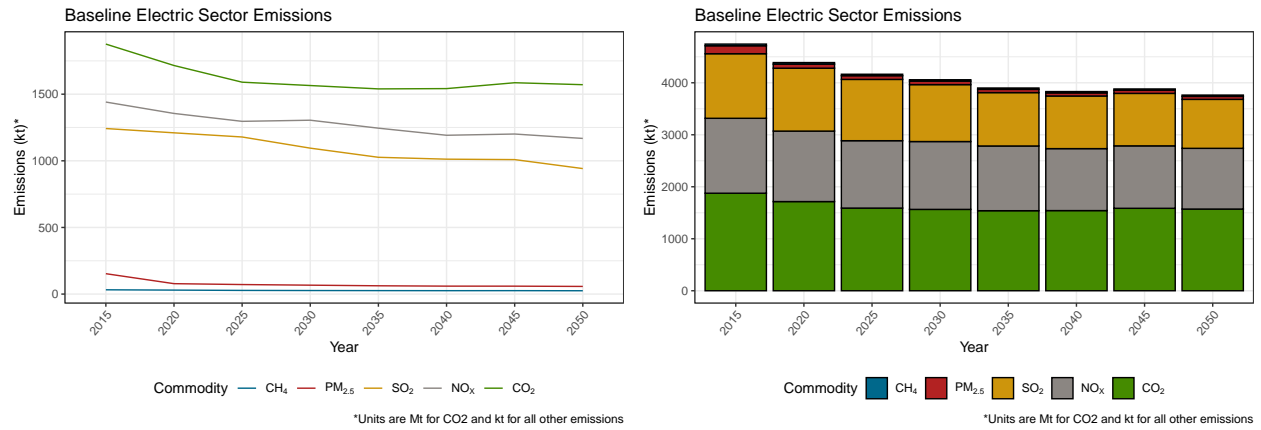
By Cost Reduction %



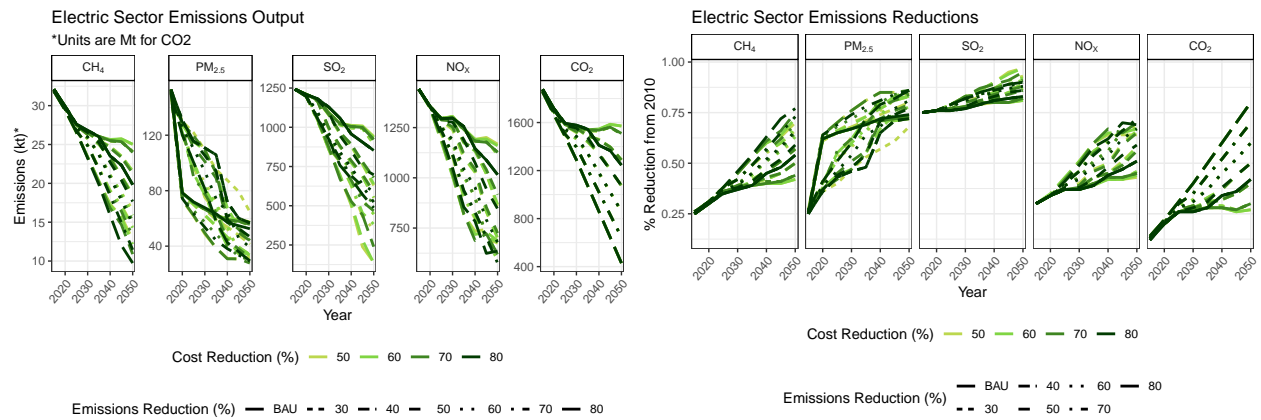


## 7 Emissions

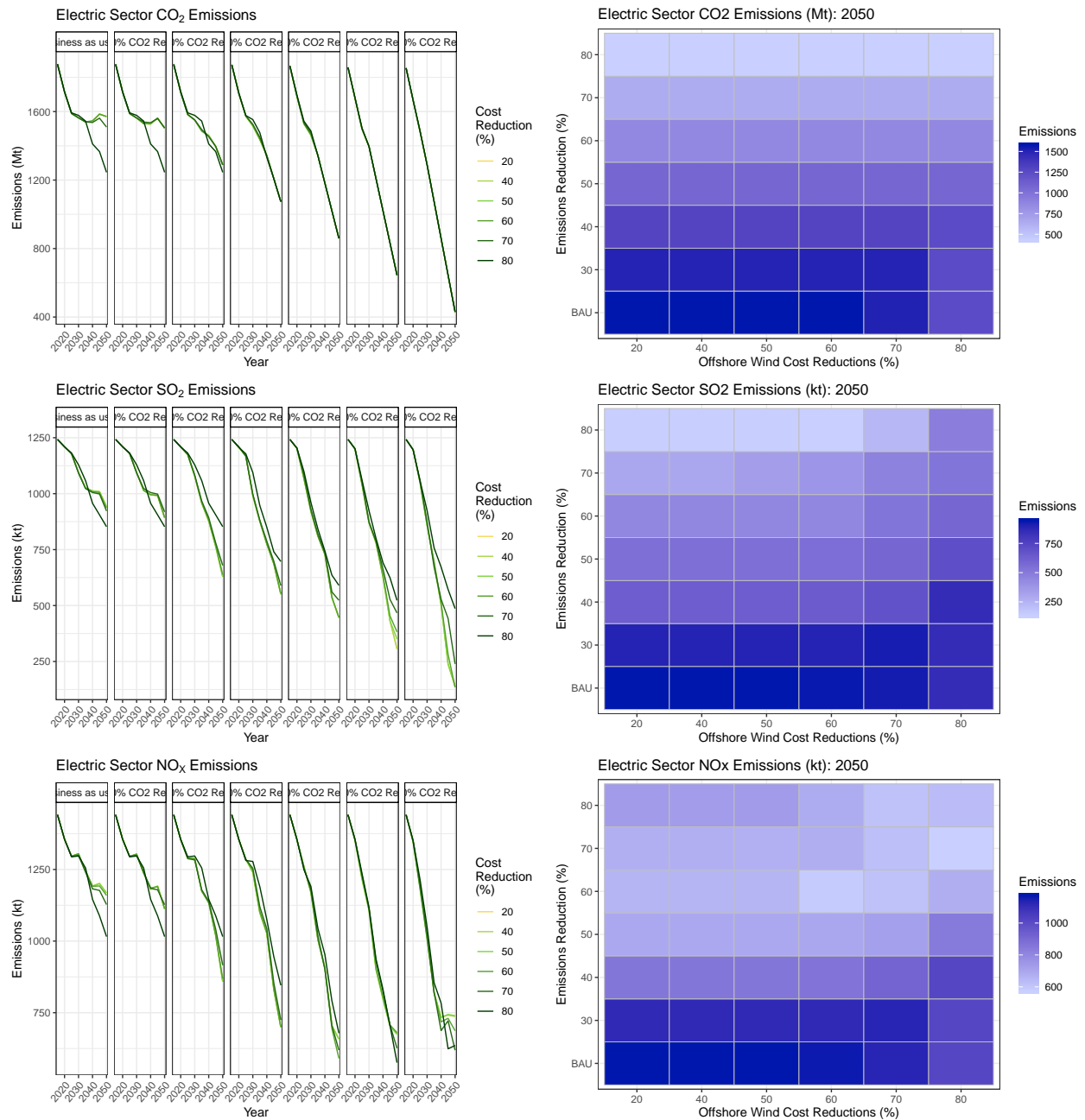
### 7.1 Baseline

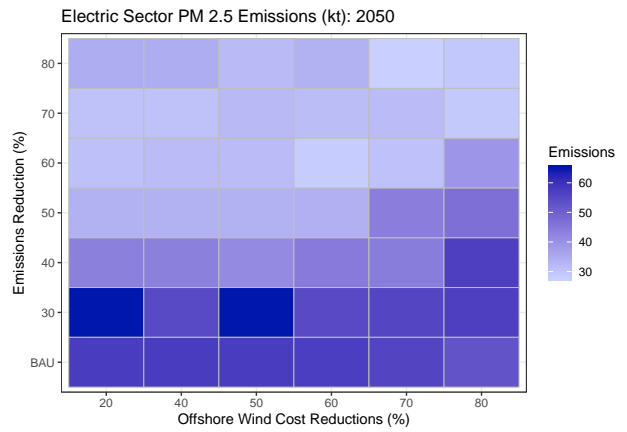
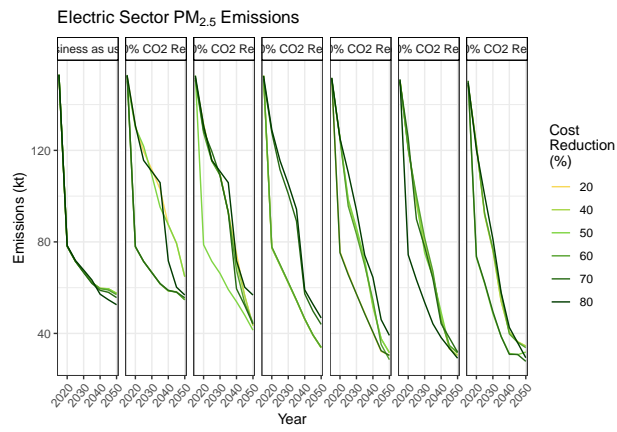
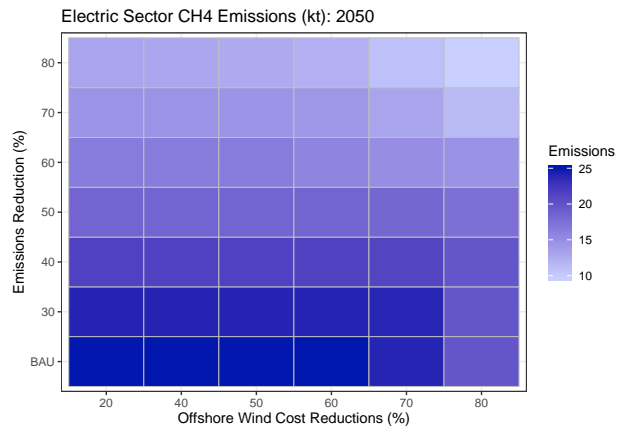
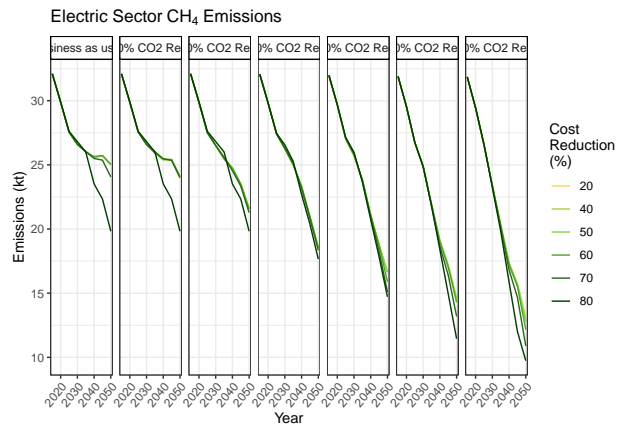


### 7.2 Emissions by Scenario and Commodity

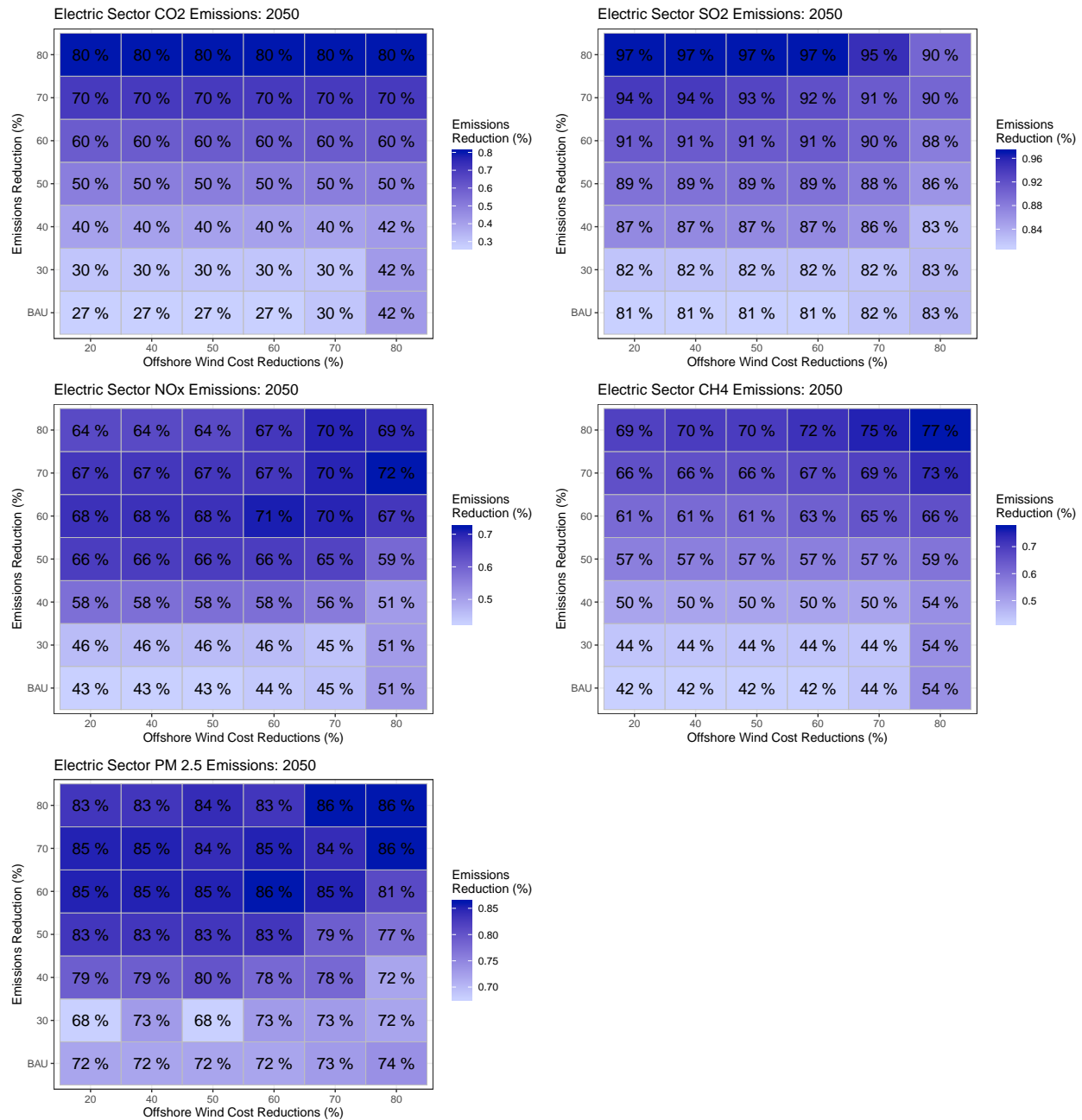


## 7.3 Emissions by Commodity - Values

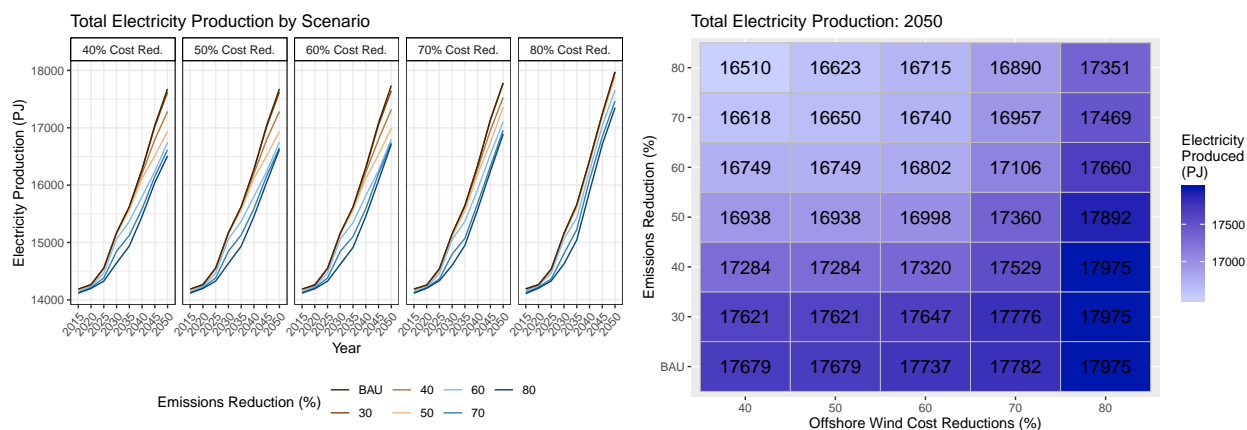




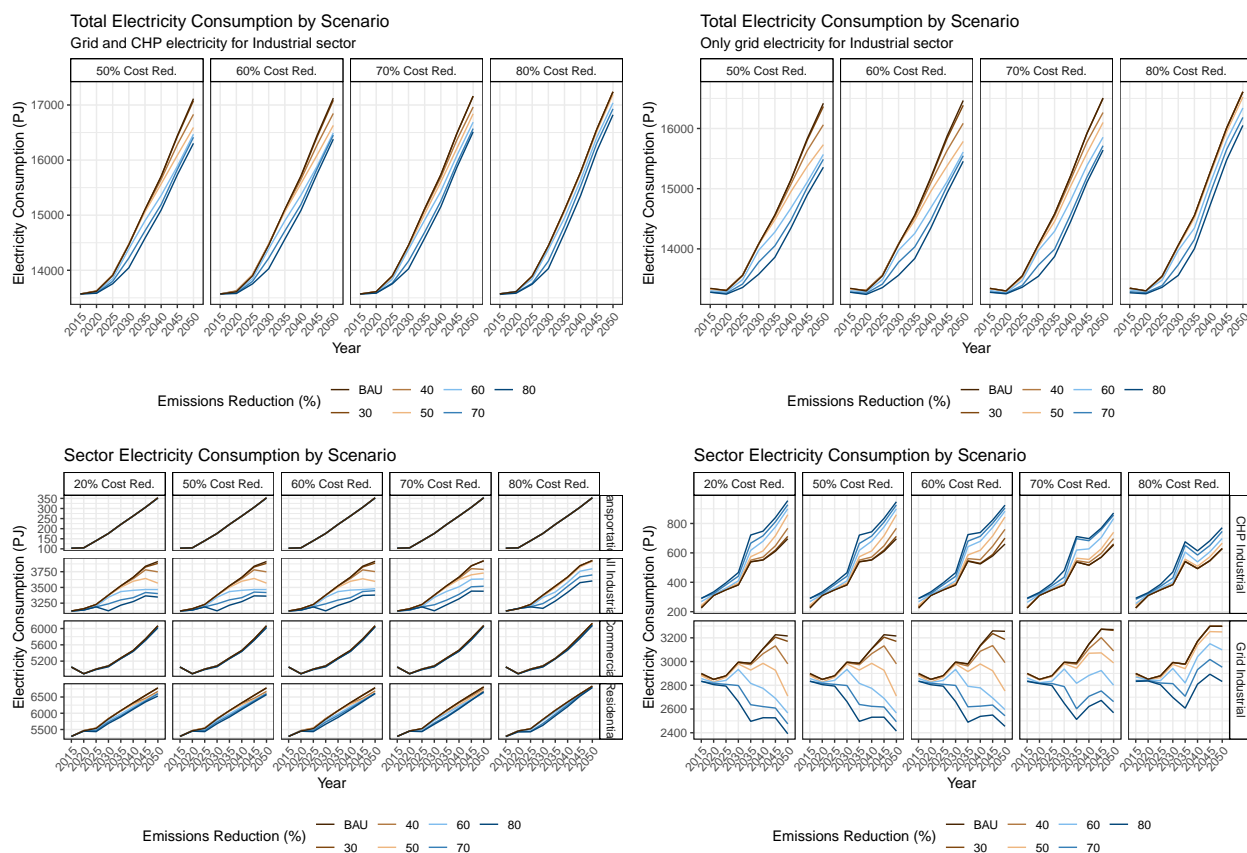
## 7.4 Emissions by Commodity - Percent Reduction

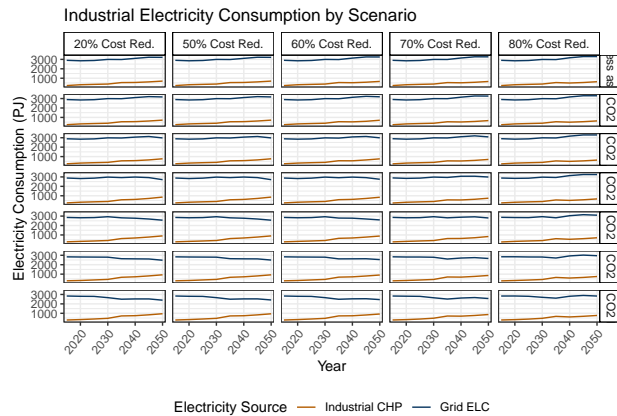
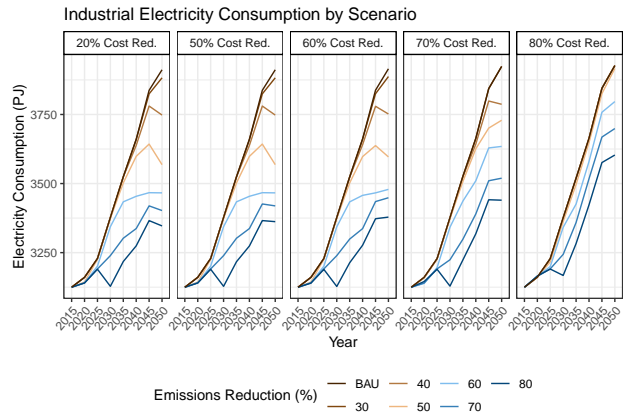
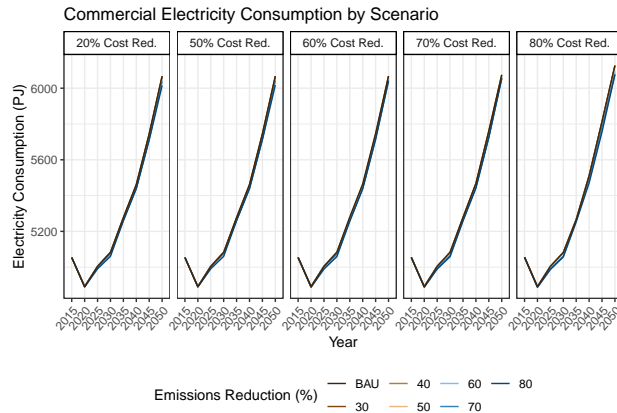
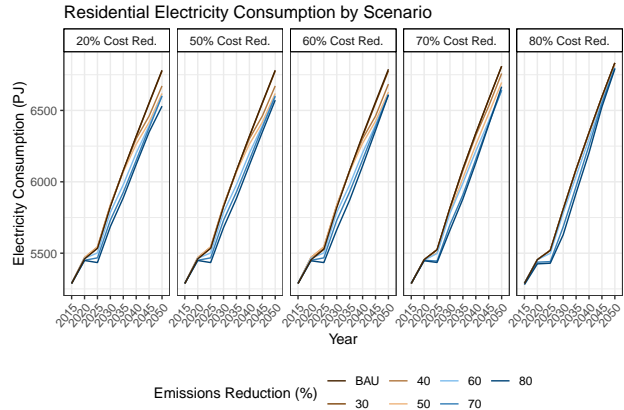
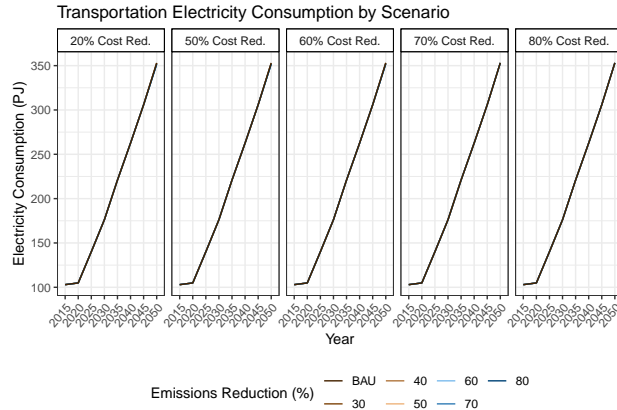


## 8 Total Electricity Production

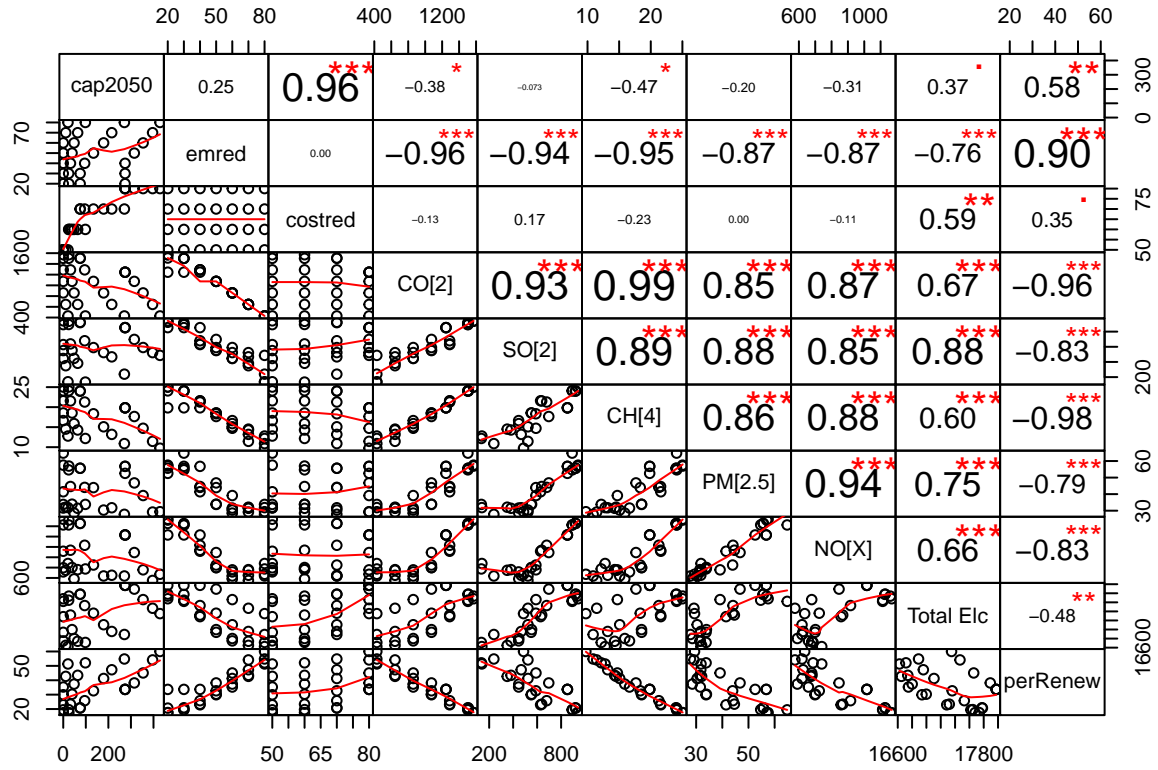


## 9 End Use ELC





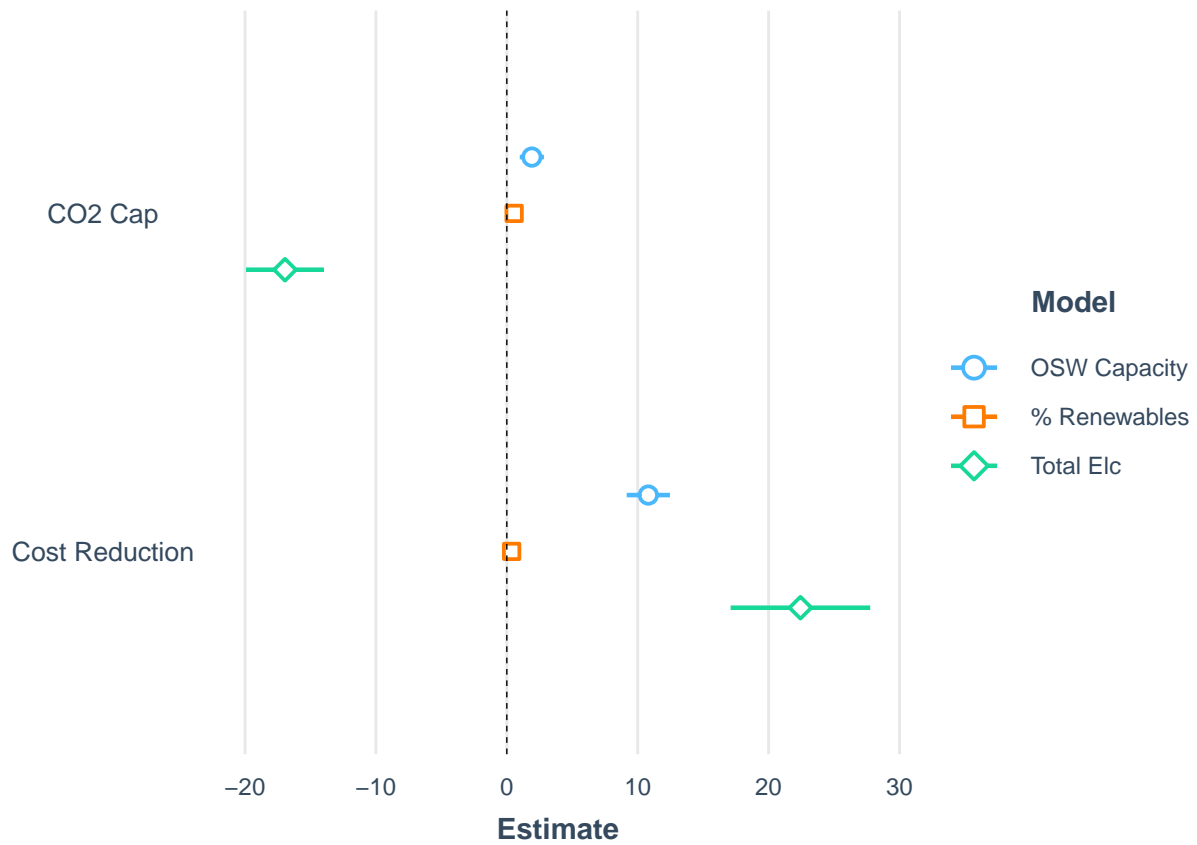
## 10 Correlations



## 11 Regressions

	OSW Capacity	% Renewables	Total Elc
CO2 Cap	1.91 *** (0.45)	0.56 *** (0.03)	-16.94 *** (1.45)
Cost Reduction	10.81 *** (0.80)	0.37 *** (0.06)	22.43 *** (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 *** (0.83)	-11.91 *** (0.66)	-8.96 *** (0.93)	-0.20 *** (0.01)	-0.53 *** (0.05)
OSW Capacity	-0.28 * (0.12)	0.43 *** (0.10)	-0.03 (0.14)	-0.01 *** (0.00)	0.01 (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.



