

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	1
2 Setup	1
3 Scenarios	1
4 LCOE	2
5 Offshore Wind	2
5.1 Capacity Buildout	3
5.2 Total Capacity	3
5.3 Output	3
5.4 Regions	4
6 Grid Mix	9
6.1 Baseline Production	9
6.2 All Scenarios	9
6.3 Regional Mix	12
6.4 Emissions Cap	14
6.5 Cost Reductions	17
6.6 Heatmaps	19
6.7 Market Share	20
6.8 Renewable Contributions	25
6.9 Retirements and Additions	25
6.10 Changes Over Baseline	26
7 Emissions	40
7.1 Baseline	40
7.2 Emissions by Scenario and Commodity	40
7.3 Emissions by Commodity - Values	41
7.4 Emissions by Commodity - Percent Reduction	43
8 Total Electricity Production	44
9 Correlations	44
10 Regressions	44

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

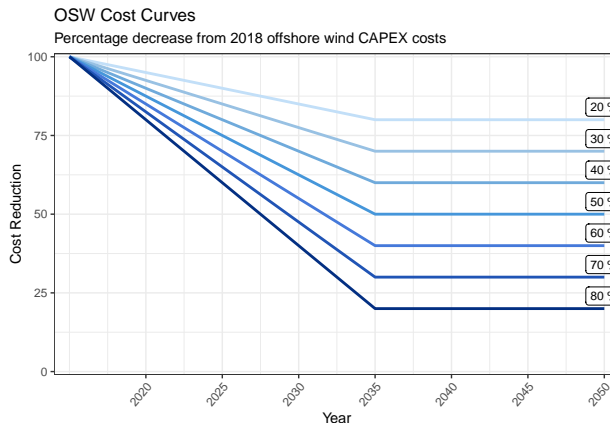
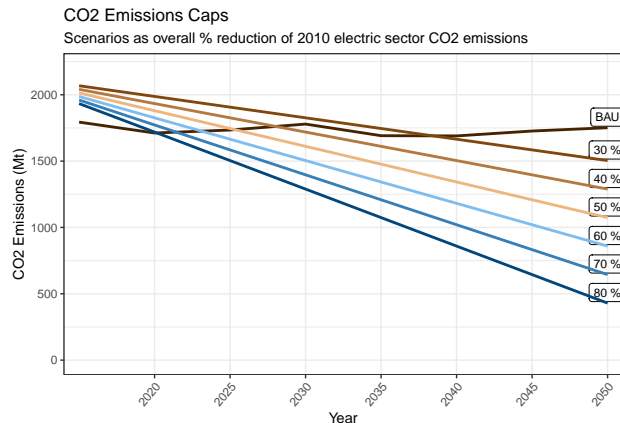
Three scripts are loaded into this markdown document to allow for analysis of the data. The setup script loads the library, creates generalized functions, and creates global variables for color scales and factors. The data script loads an excel spreadsheet with all of the results data and performs the 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 CO₂ 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 CO₂ 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
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:

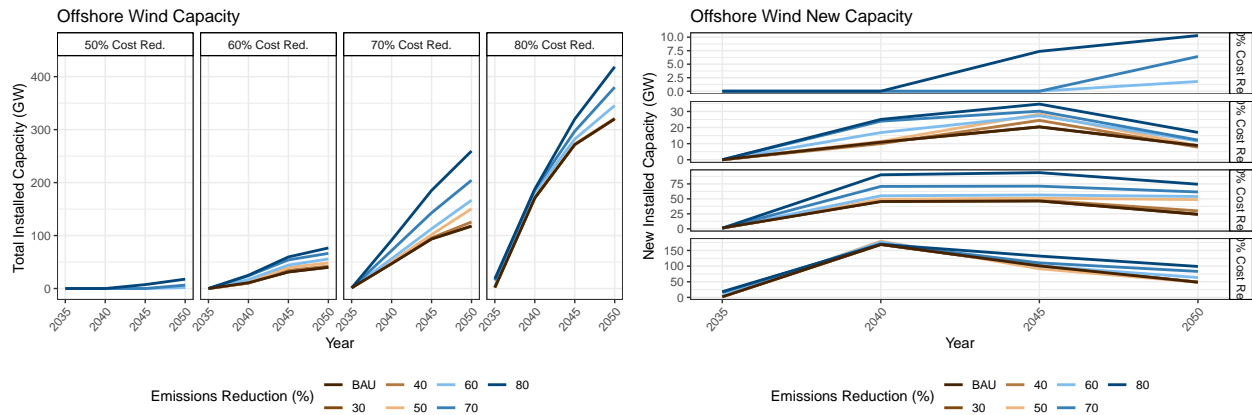
U.S. EIA Annual Energy Outlook 2019

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.

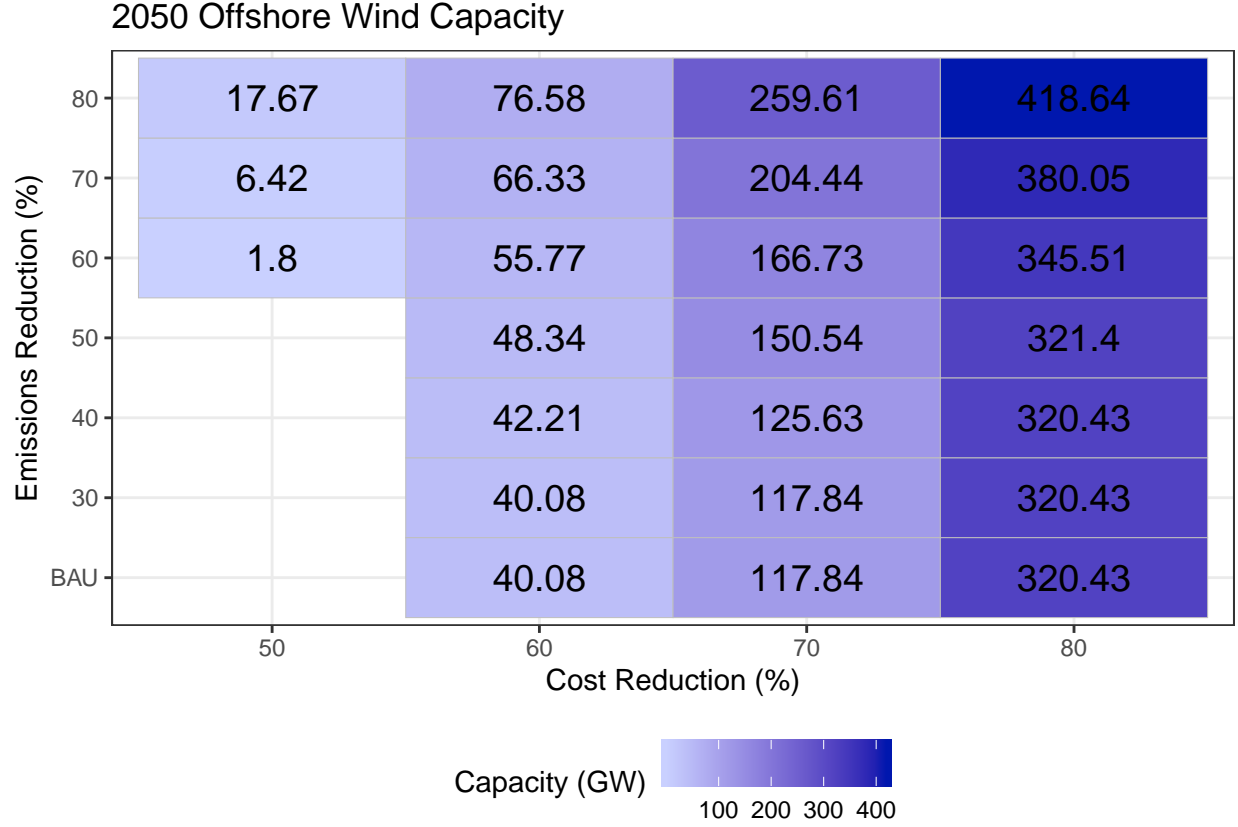


Table 2: Offshore Wind Total Installed Capacity (GW): 2050

CO2 Emissions Reduction (%)	Cost Reduction (%)			
	50	60	70	80
BAU	NA	40.1	117.8	320.4
30	NA	40.1	117.8	320.4
40	NA	42.2	125.6	320.4
50	NA	48.3	150.5	321.4
60	1.8	55.8	166.7	345.5
70	6.4	66.3	204.4	380.1
80	17.7	76.6	259.6	418.6

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.

Offshore Wind Output

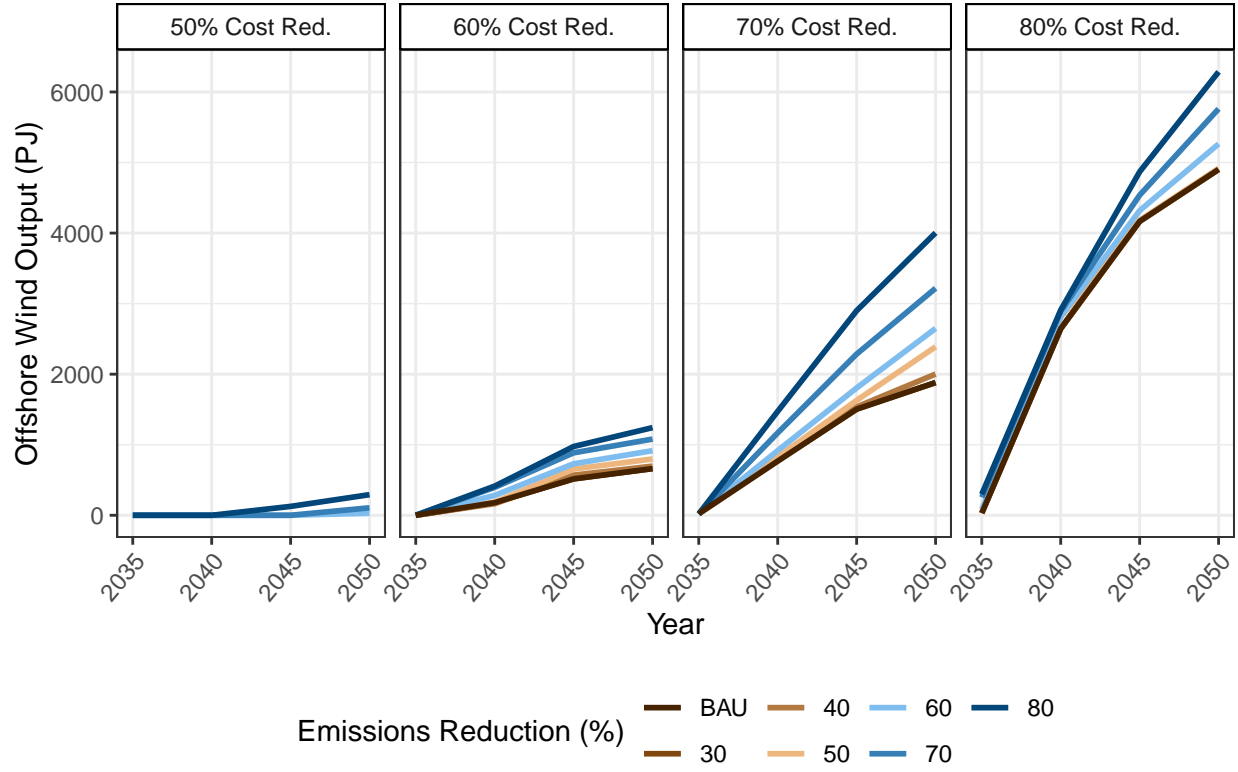
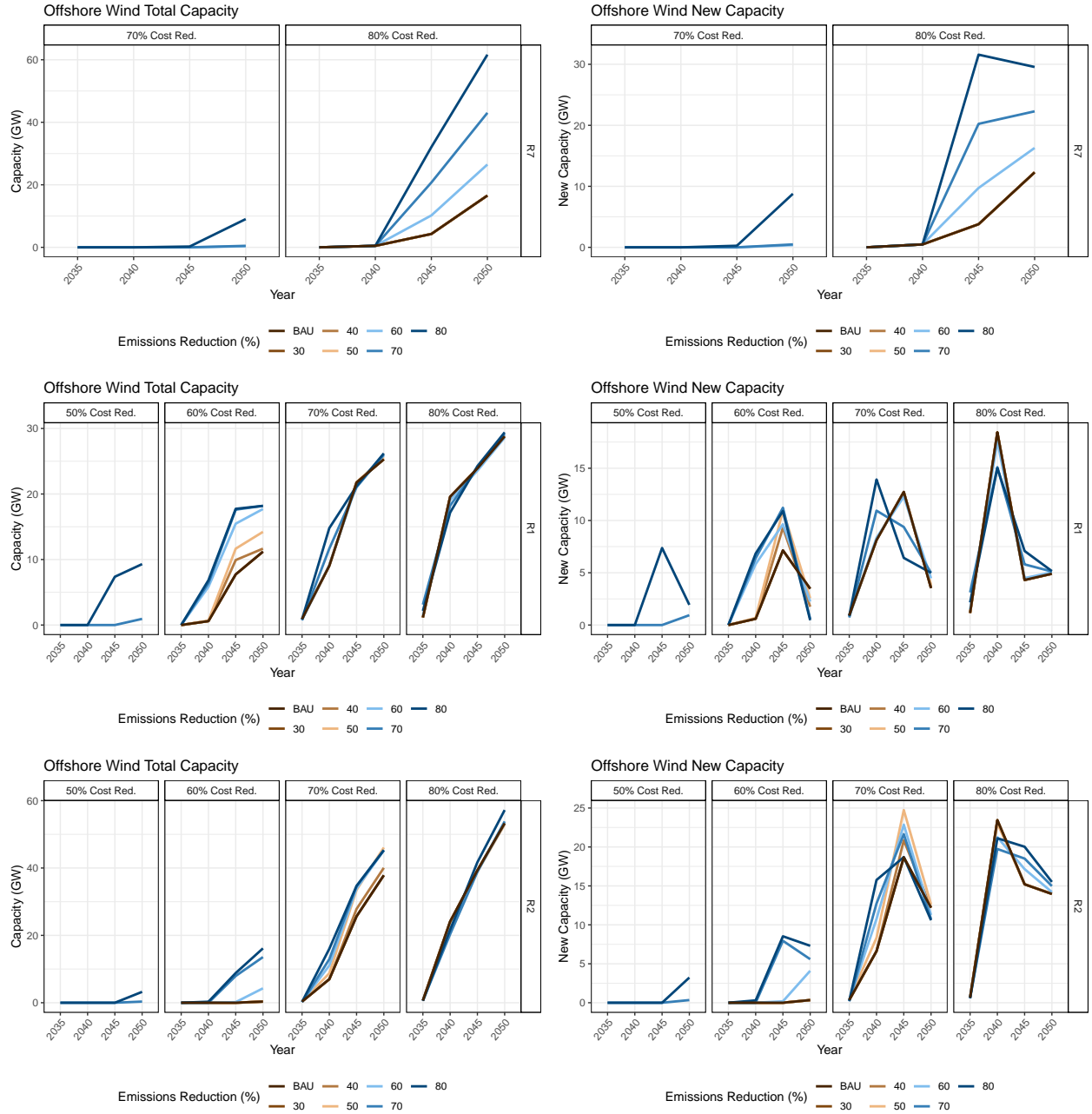


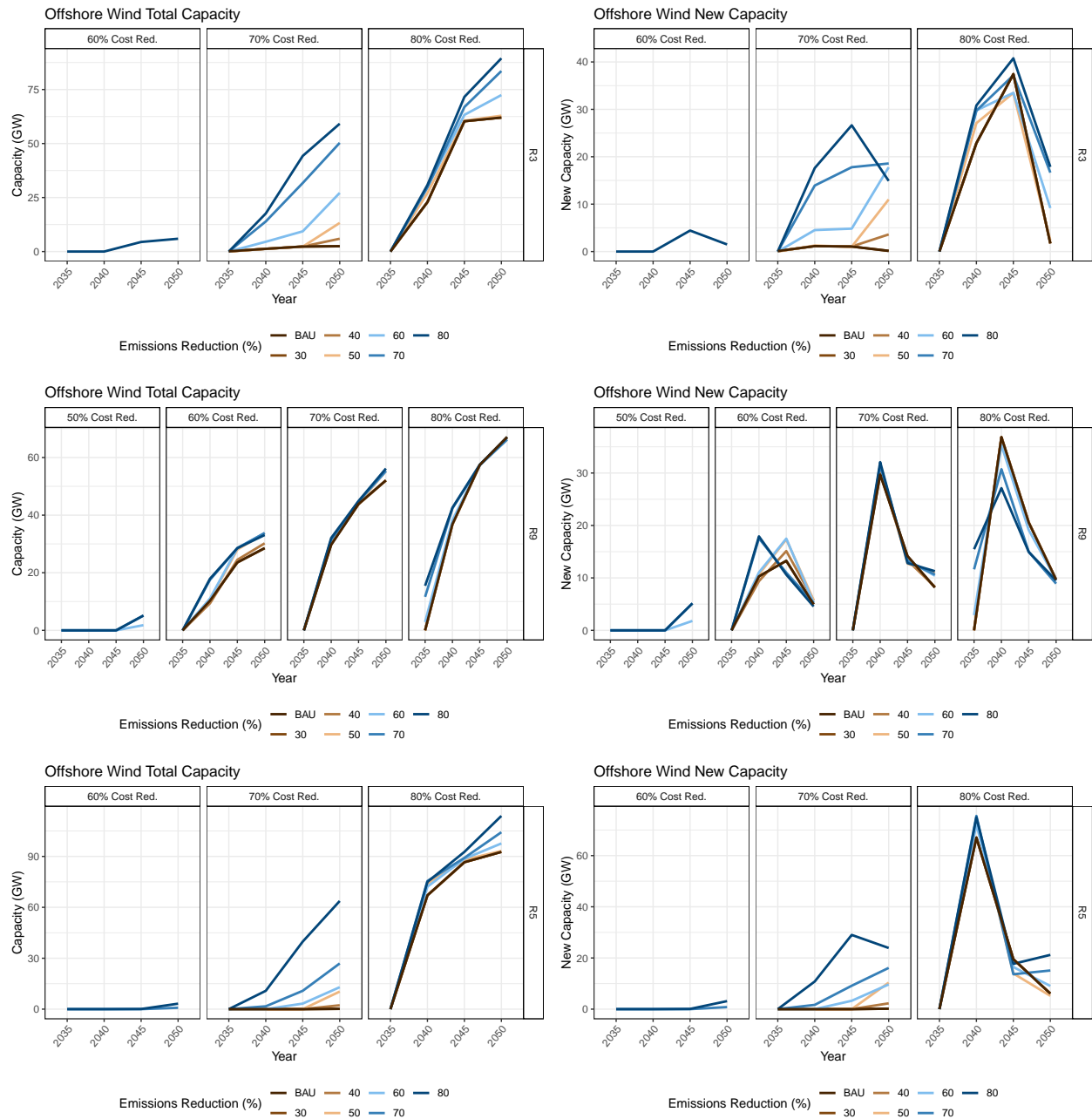
Table 3: Offshore Wind Total Output (PJ): 2050

CO2 Emissions Reduction (%)	Cost Reduction (%)			
	50	60	70	80
BAU	NA	661.5	1881.1	4902.4
30	NA	661.5	1881.1	4902.4
40	NA	696.8	2001.7	4902.4
50	NA	797.6	2387.9	4917.0
60	29.4	915.7	2648.6	5263.3
70	105.9	1079.9	3217.6	5761.1
80	292.3	1242.4	4003.5	6285.8

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.

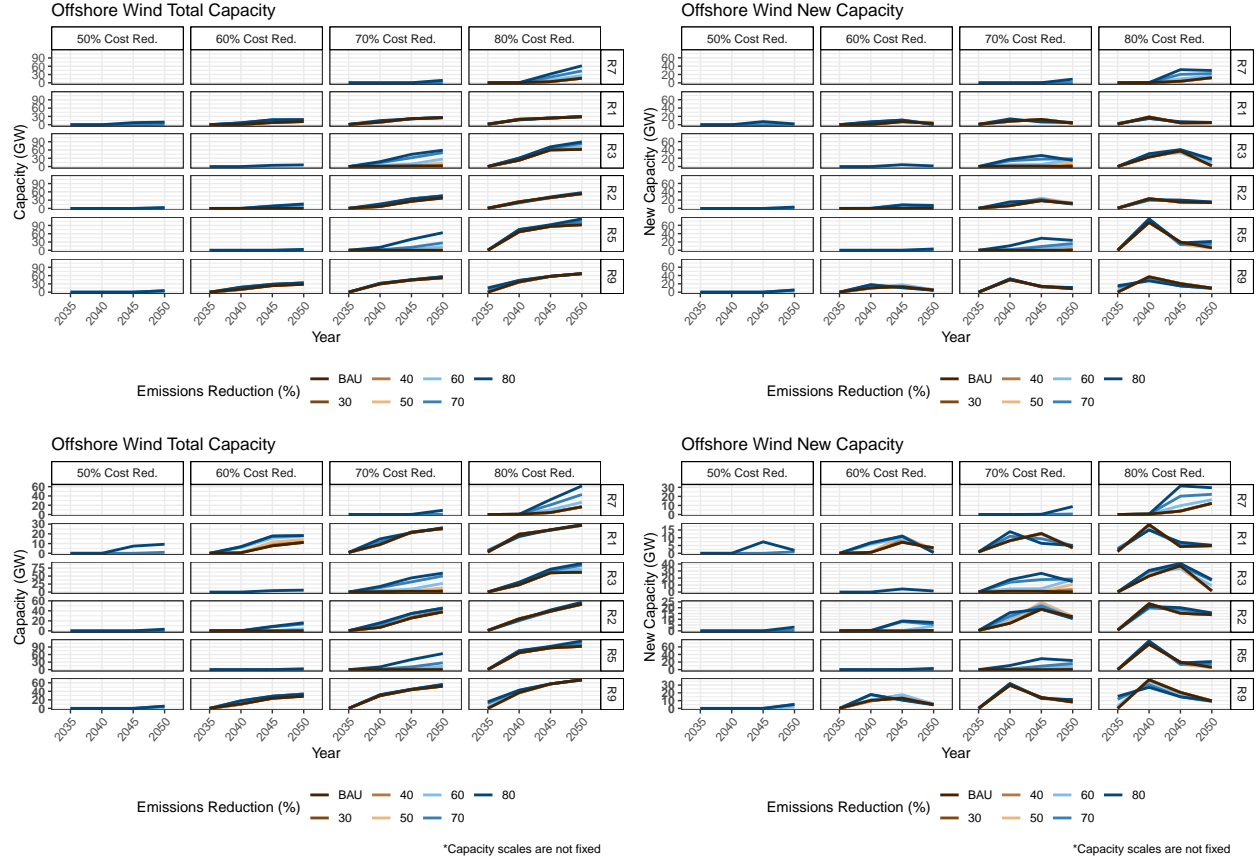


Table 4: Average Installed Capacity (GW)

Region	2050 Total
R7	20.73100
R1	21.50304
R2	31.02391
R3	44.07267
R9	45.02875
R5	50.47438

Note:

Average is across all scenarios

Table 5: Average Electricity Output (PJ)

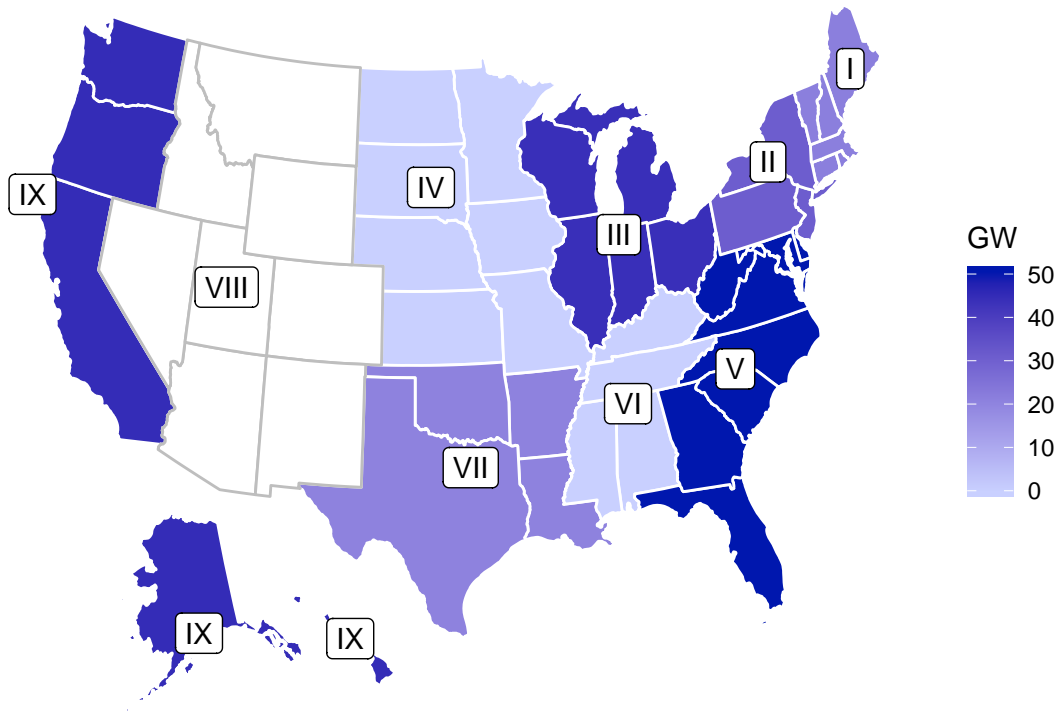
Region	2050 Total
R1	103.8590
R7	120.4272
R2	157.8955
R3	216.6808
R9	251.5586
R5	318.5086

Note:

Average is across all scenarios

Map of average total capacity

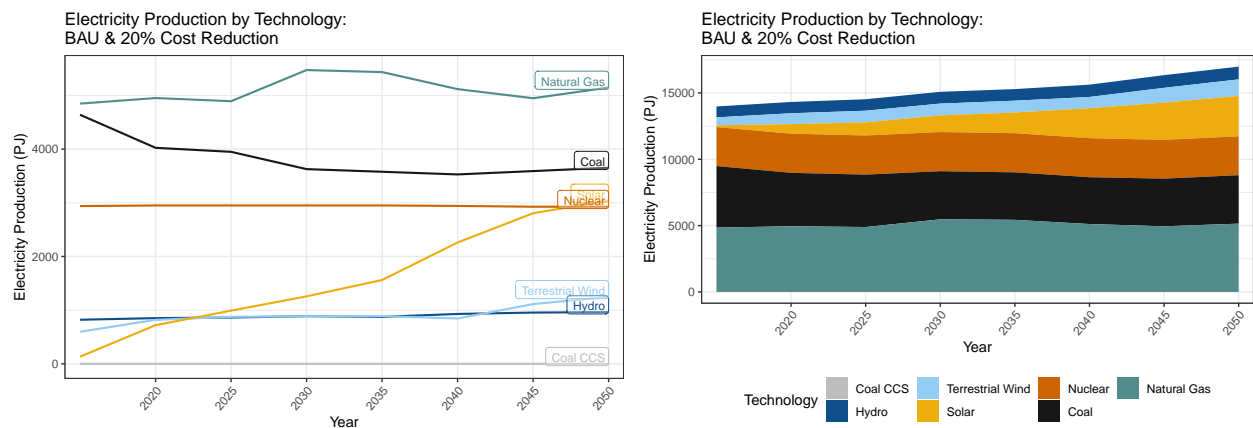
Average Offshore Wind Capacity



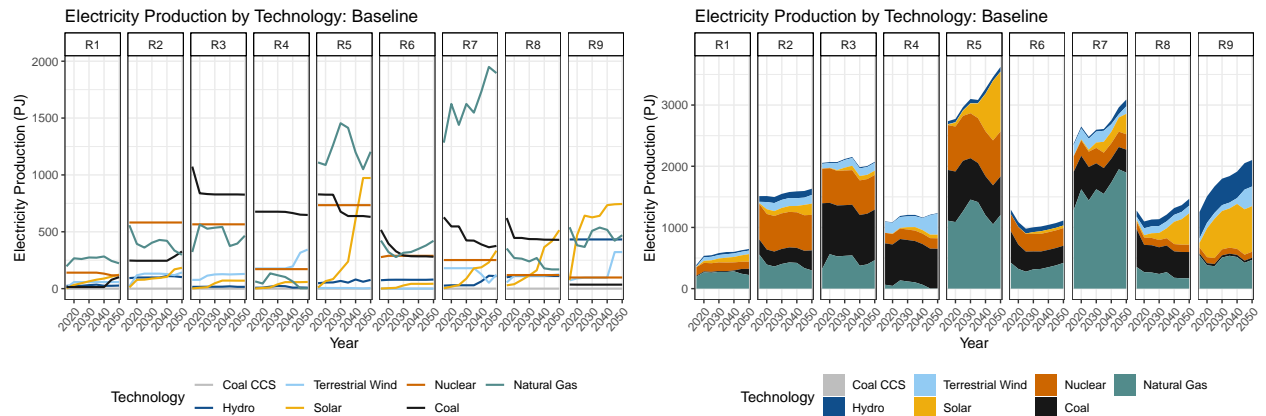
6 Grid Mix

6.1 Baseline Production

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

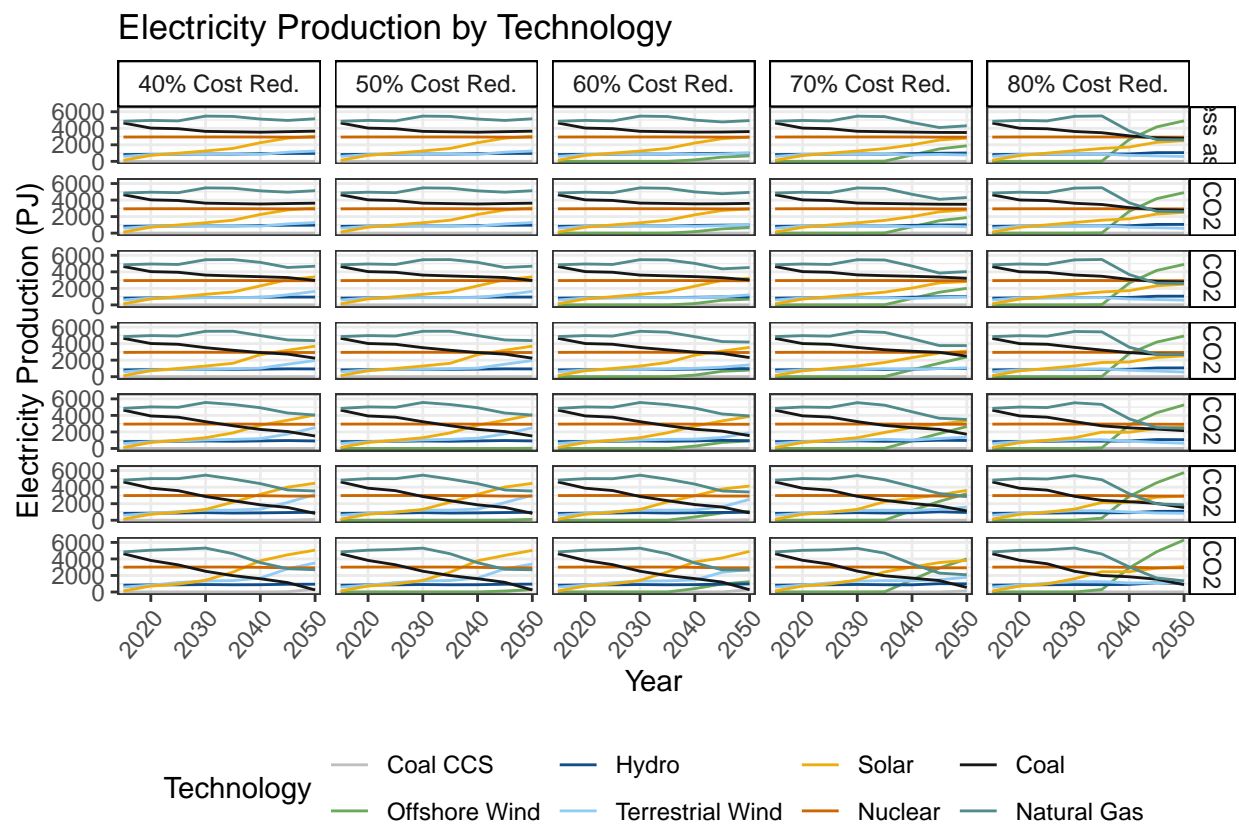


Regional baseline production



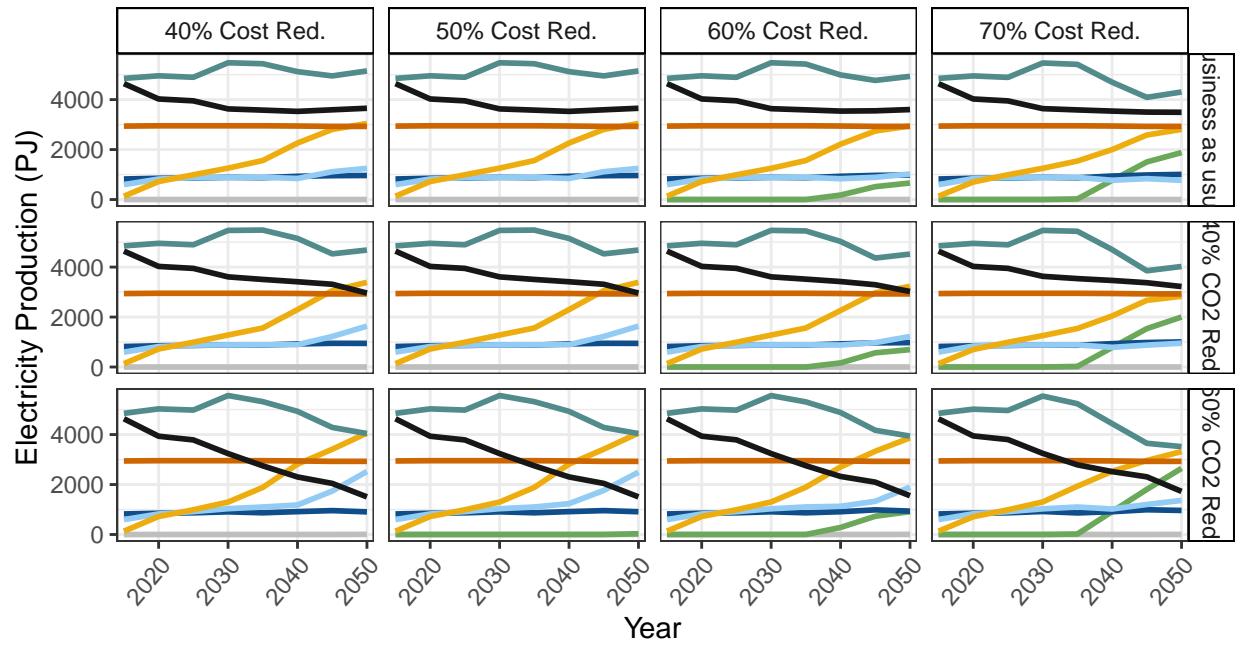
6.2 All Scenarios

Complete Set



Parsed Set

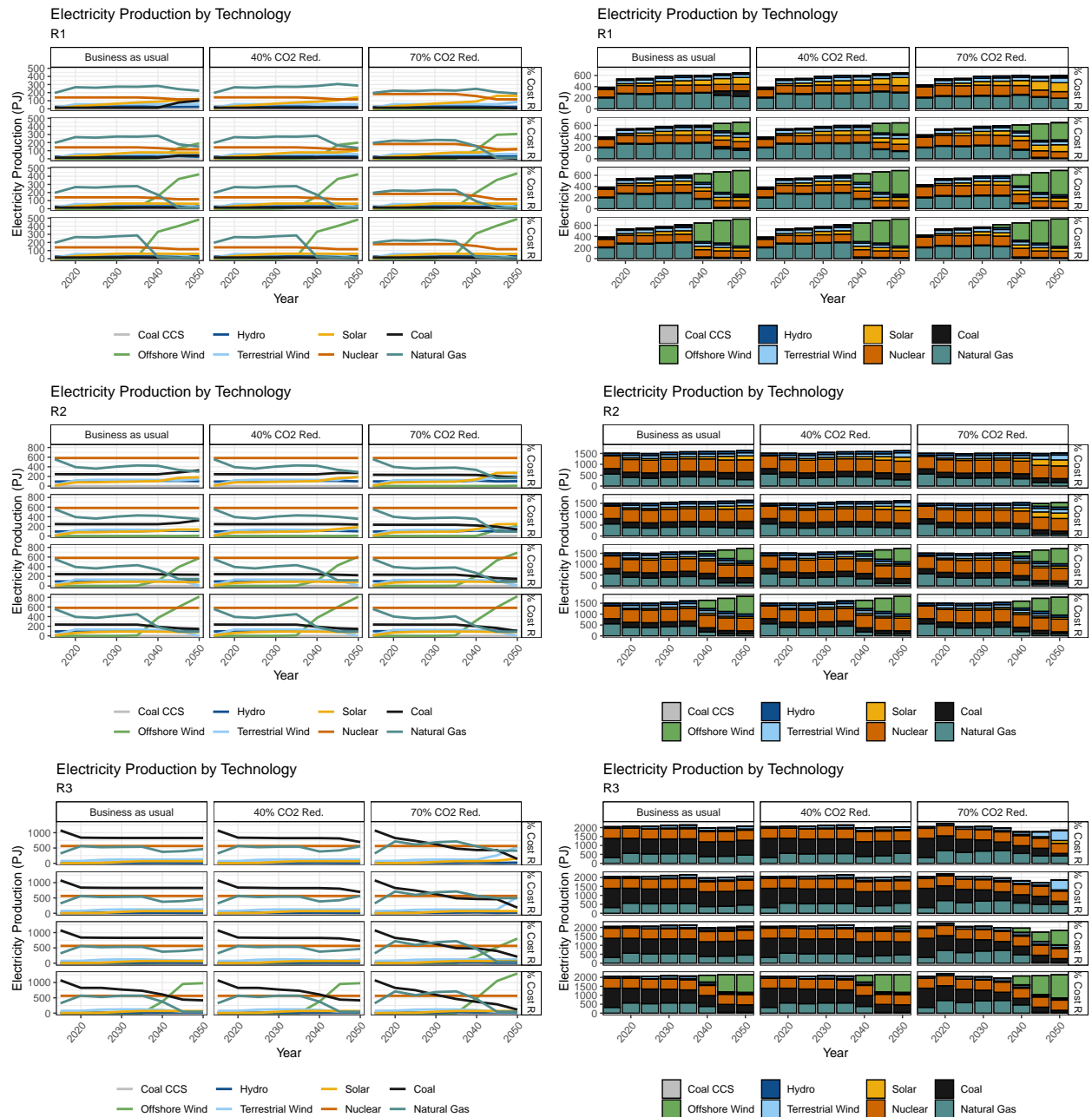
Electricity Production by Technology

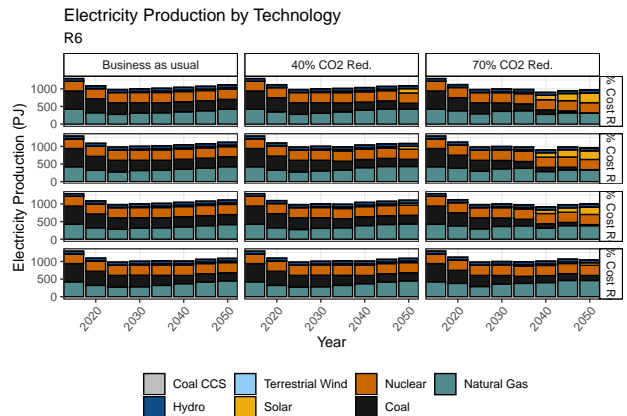
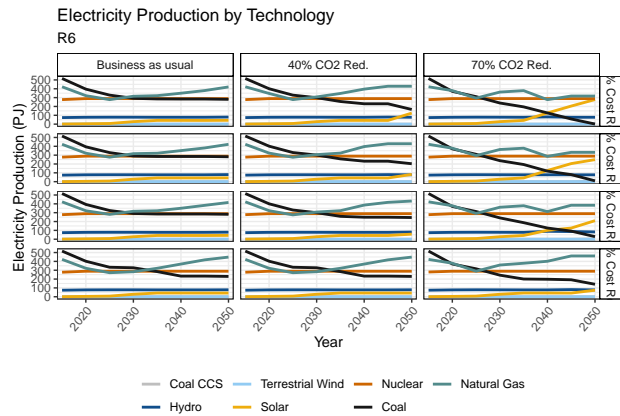
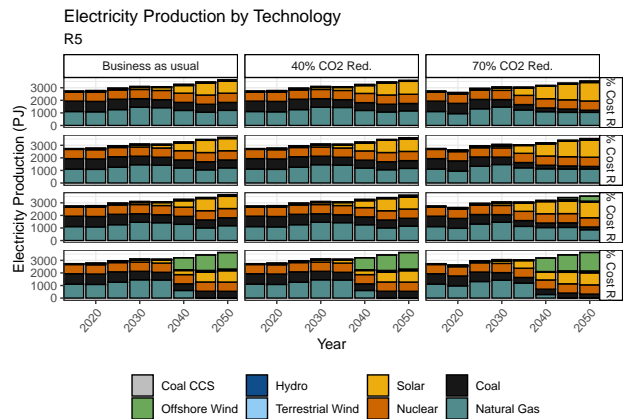
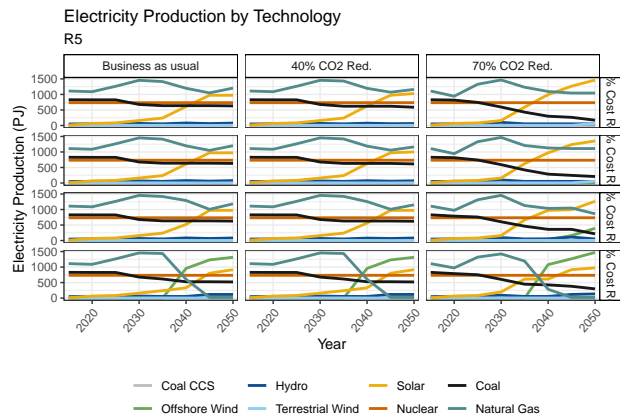
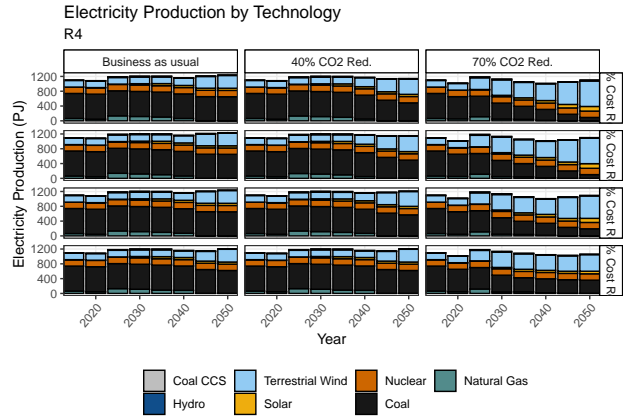
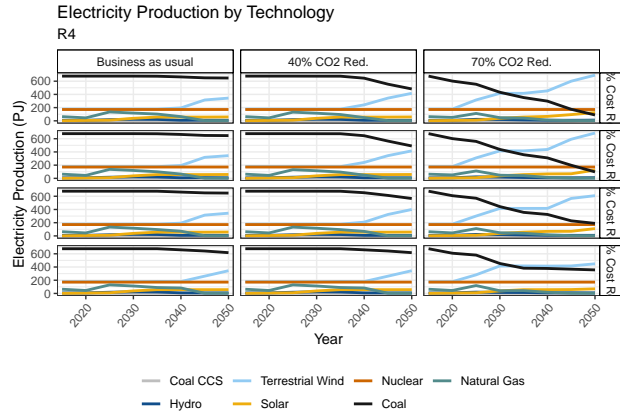


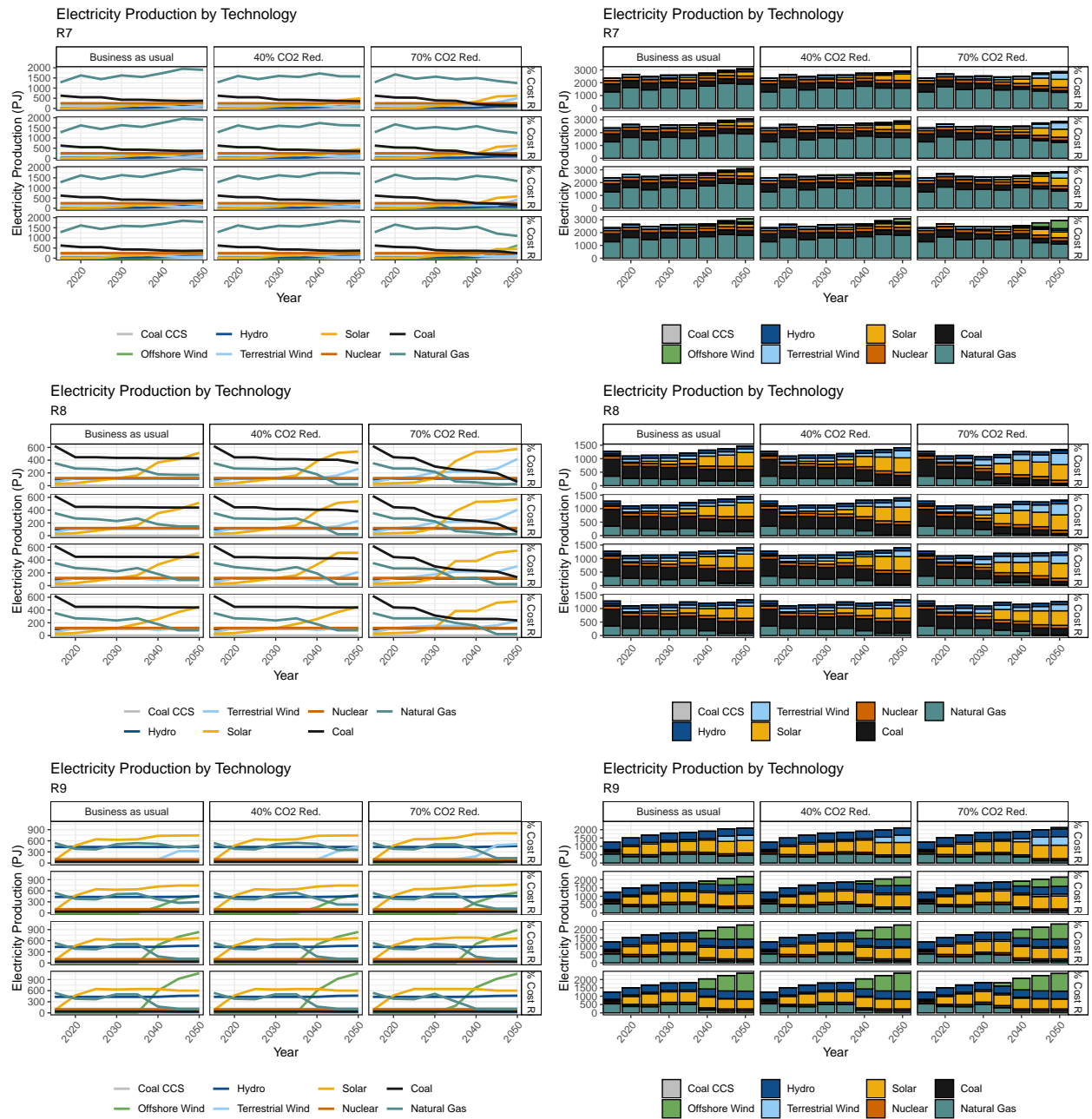
Technology

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

6.3 Regional Mix

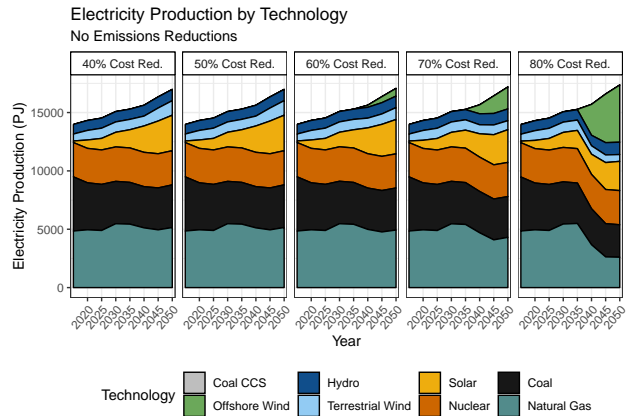
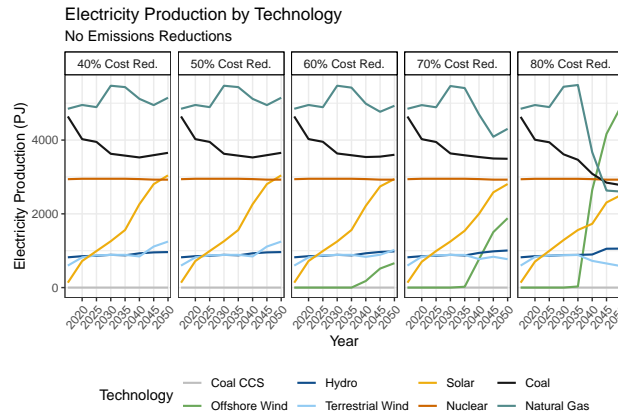




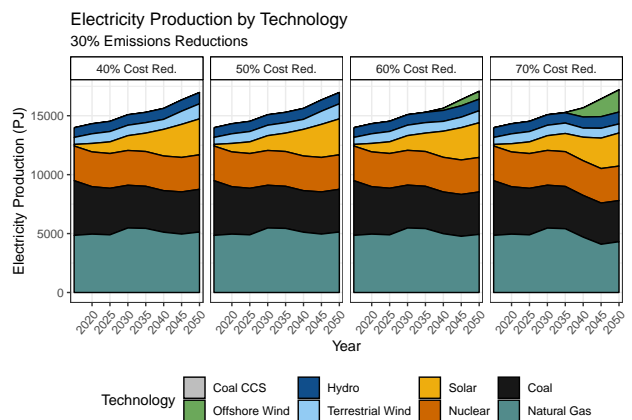
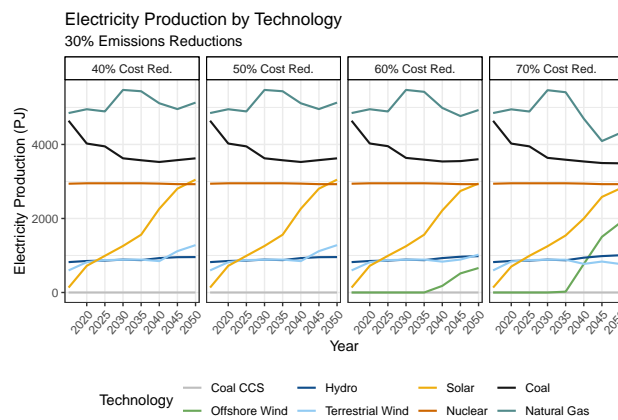


6.4 Emissions Cap

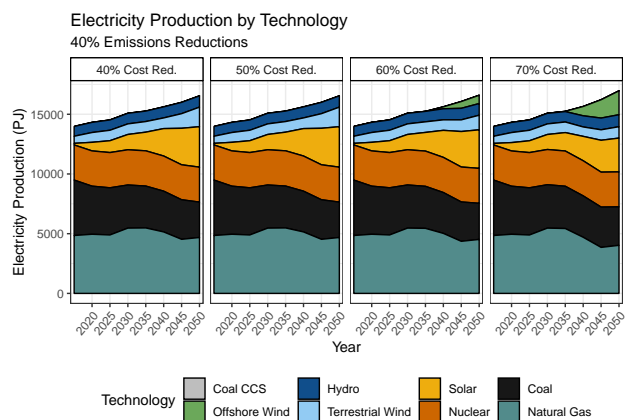
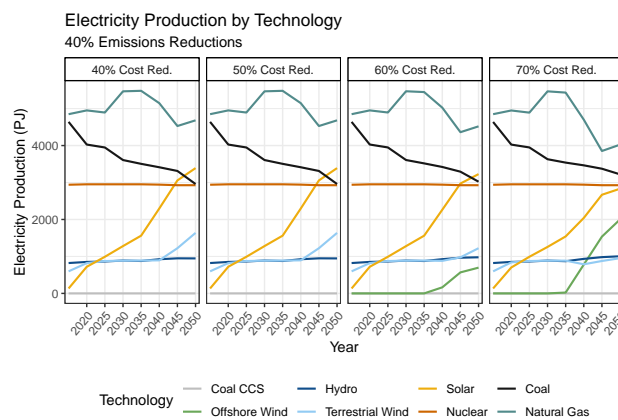
BAU emissions



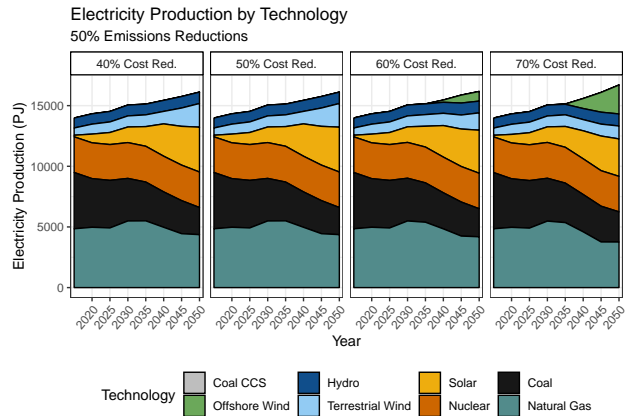
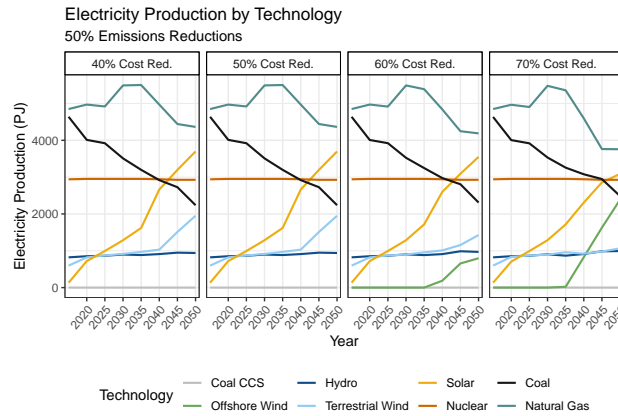
30% emissions reduction



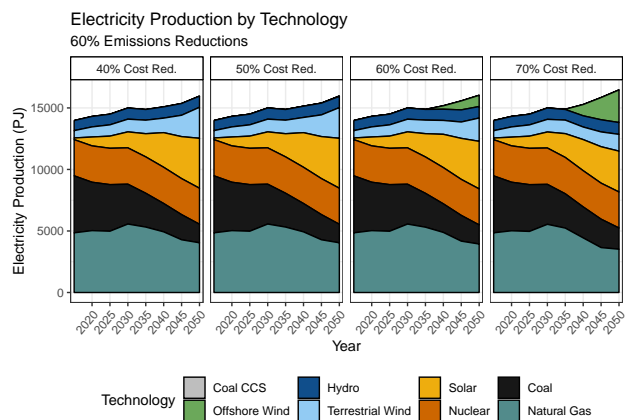
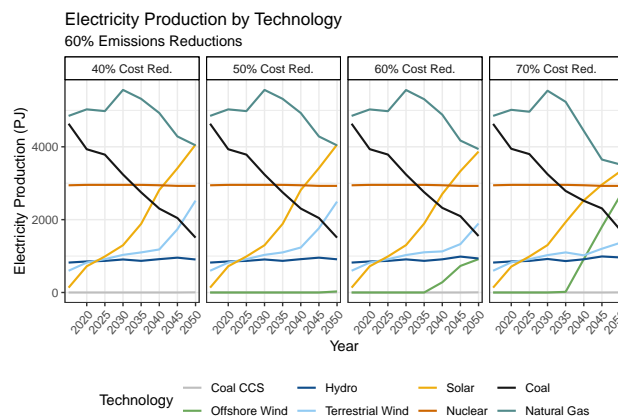
40% emissions reduction



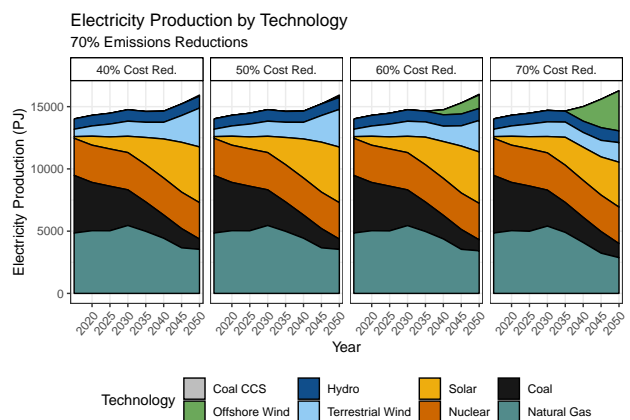
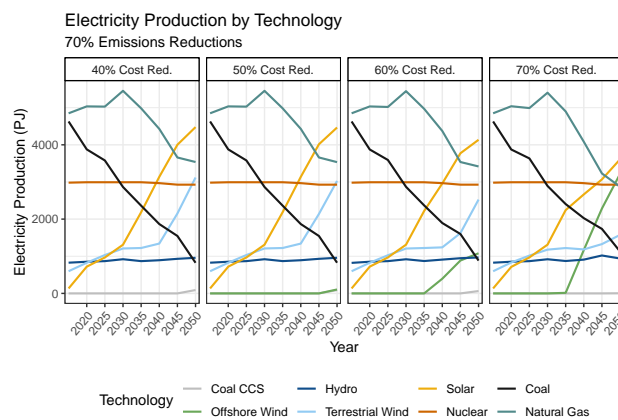
50% emissions reduction



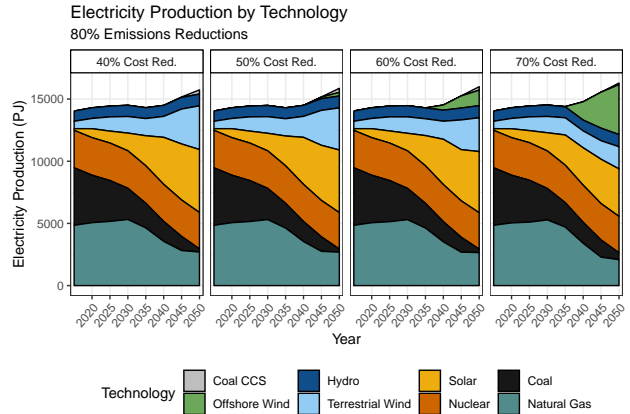
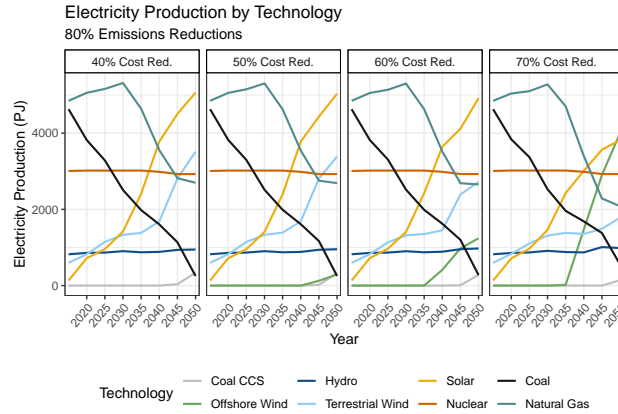
60% emissions reduction



70% emissions reduction

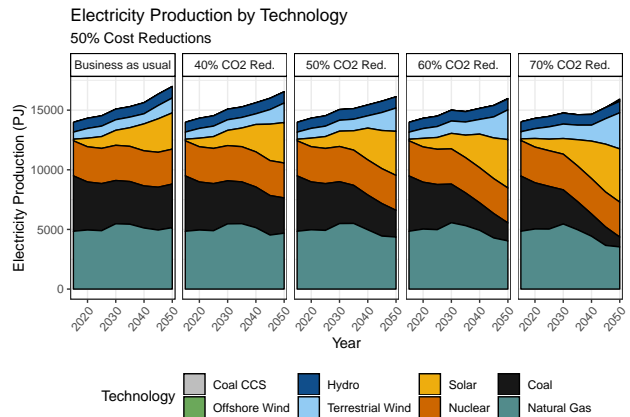
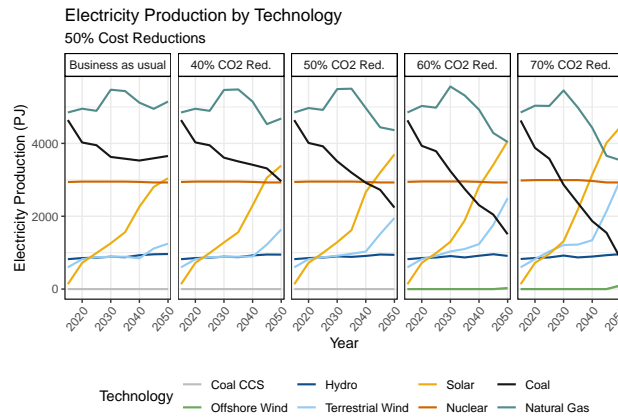


80% emissions reduction

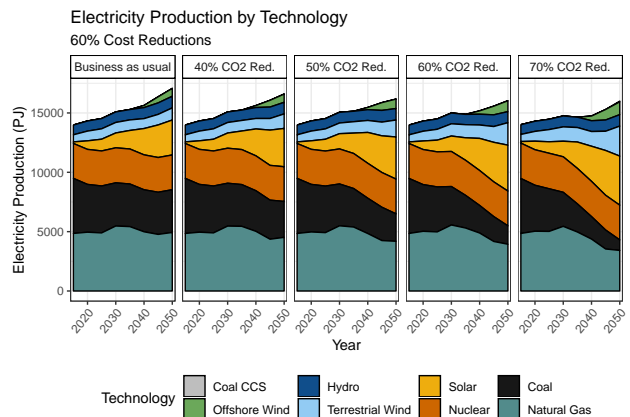
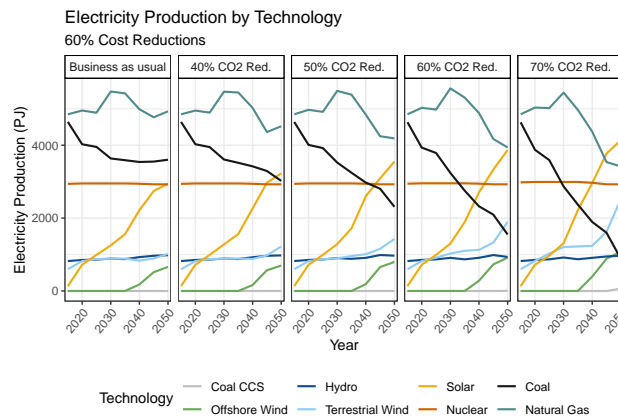


6.5 Cost Reductions

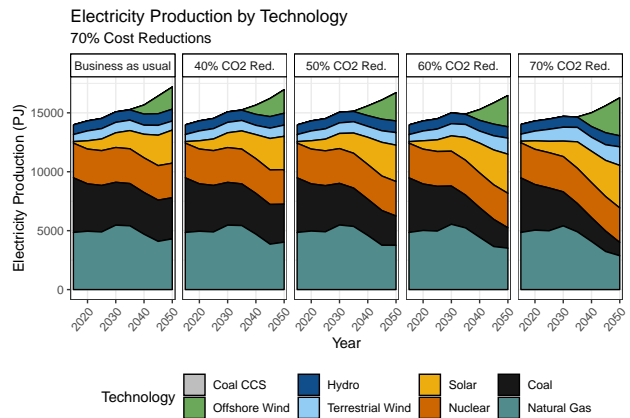
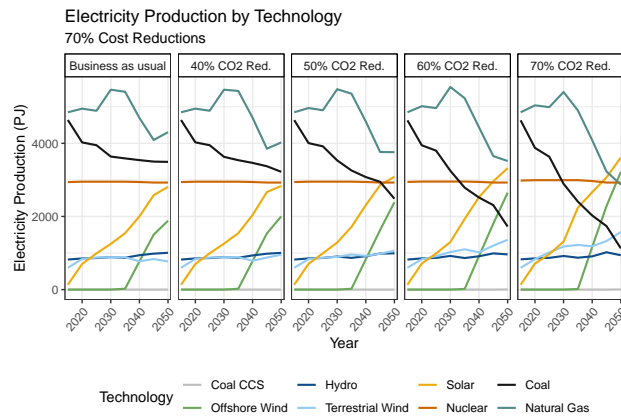
50% cost reduction



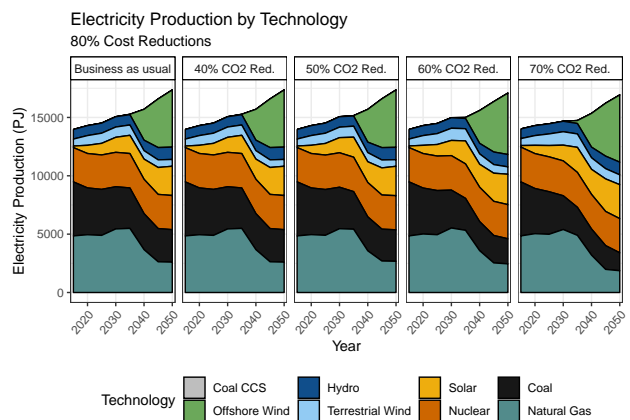
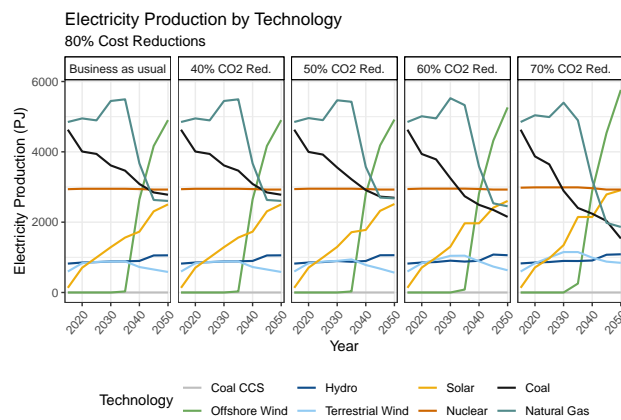
60% cost reduction



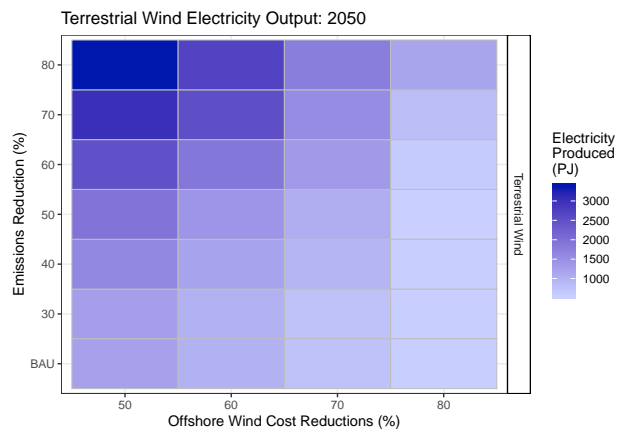
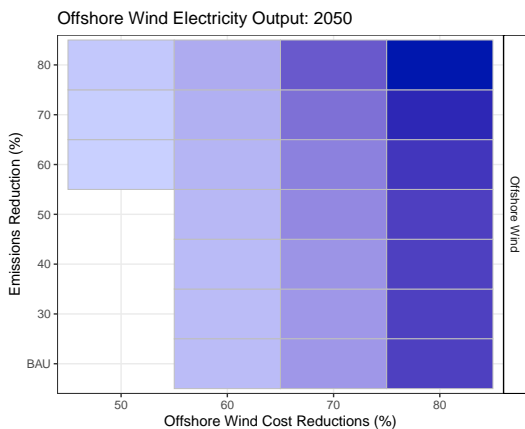
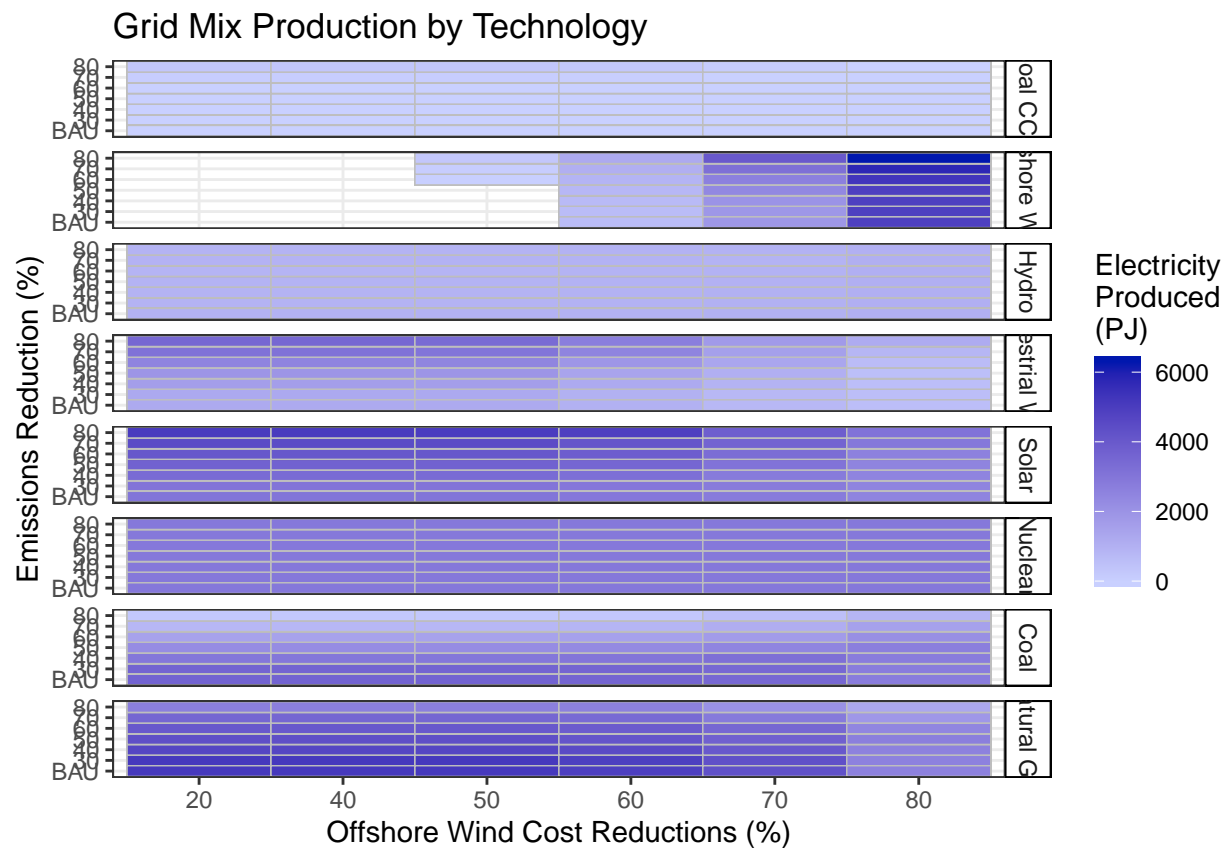
70% cost reduction

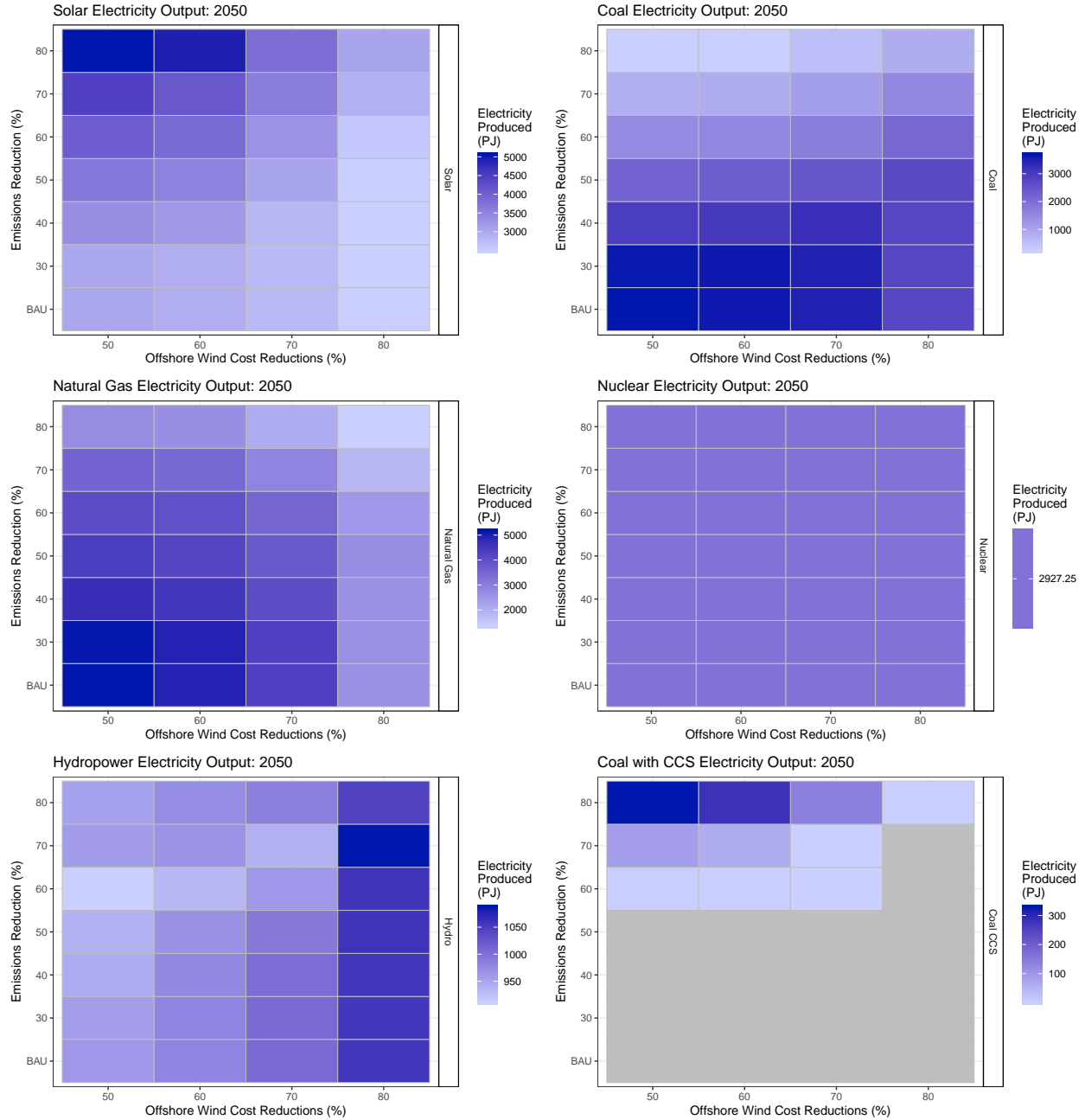


80% cost reduction



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.      : 252.6    Min.      :13967    Min.      : 1.59
## 1st Qu.:2748.5    1st Qu.:14323    1st Qu.:17.31
## Median :3540.3    Median :14993    Median :22.67
## Mean   :3271.2    Mean   :15060    Mean   :21.97
## 3rd Qu.:3940.2    3rd Qu.:15621    3rd Qu.:27.18
## Max.    :4640.4    Max.    :17360    Max.    :33.19
##
##
## $`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.      : 0.000    Min.      :13967    Min.      :0.00000
## 1st Qu.: 0.000    1st Qu.:14323    1st Qu.:0.00000
## Median : 0.000    Median :14993    Median :0.00000
## Mean   : 5.592    Mean   :15060    Mean   :0.03524
## 3rd Qu.: 0.000    3rd Qu.:15621    3rd Qu.:0.00000
## Max.    :335.971    Max.    :17360    Max.    :2.13000
##
##
## $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.      : 821.5    Min.      :13967    Min.      :5.64
## 1st Qu.: 861.3    1st Qu.:14323    1st Qu.:5.88
## Median : 884.4    Median :14993    Median :5.95
## Mean   : 897.6    Mean   :15060    Mean   :5.96
## 3rd Qu.: 930.0    3rd Qu.:15621    3rd Qu.:6.01
## Max.    :1112.8    Max.    :17360    Max.    :6.89
##
##
## $`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.      :1350    Min.      :13967    Min.      : 8.04
## 1st Qu.:4595    1st Qu.:14323    1st Qu.:29.11
## Median :4923    Median :14993    Median :34.42
## Mean   :4689    Mean   :15060    Mean   :31.37
## 3rd Qu.:5131    3rd Qu.:15621    3rd Qu.:35.23
## Max.    :5562    Max.    :17360    Max.    :37.10
##
##
## $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.      :13967    Min.      :16.86
## 1st Qu.:2935    1st Qu.:14323    1st Qu.:18.83
## Median :2951    Median :14993    Median :19.71
## Mean   :2954    Mean   :15060    Mean   :19.68
## 3rd Qu.:2955    3rd Qu.:15621    3rd Qu.:20.64
## Max.    :3020    Max.    :17360    Max.    :21.43
##
##
## $`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.      : 0.0    Min.      :13967    Min.      : 0.000
## 1st Qu.: 0.0    1st Qu.:14323    1st Qu.: 0.000
## Median : 0.0    Median :14993    Median : 0.000
## Mean   : 412.9    Mean   :15060    Mean   : 2.527
## 3rd Qu.: 0.0    3rd Qu.:15621    3rd Qu.: 0.000
## Max.    :6285.8    Max.    :17360    Max.    :37.430
##
##
## $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.      : 133.3    Min.      :13967    Min.      : 0.950
## 1st Qu.: 897.3    1st Qu.:14323    1st Qu.: 6.232
## Median :1541.6    Median :14993    Median :10.095
## Mean   :1767.7    Mean   :15060    Mean   :11.446
## 3rd Qu.:2677.9    3rd Qu.:15621    3rd Qu.:16.920
## Max.    :5064.4    Max.    :17360    Max.    :32.180
##
##
## $`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.      : 565.0    Min.      :13967    Min.      : 3.260
## 1st Qu.: 825.2    1st Qu.:14323    1st Qu.: 5.720
## Median : 888.4    Median :14993    Median : 5.990
## Mean   :1062.2    Mean   :15060    Mean   : 7.015
## 3rd Qu.:1181.4    3rd Qu.:15621    3rd Qu.: 7.595
## Max.    :3514.2    Max.    :17360    Max.    :22.330
##
##

```

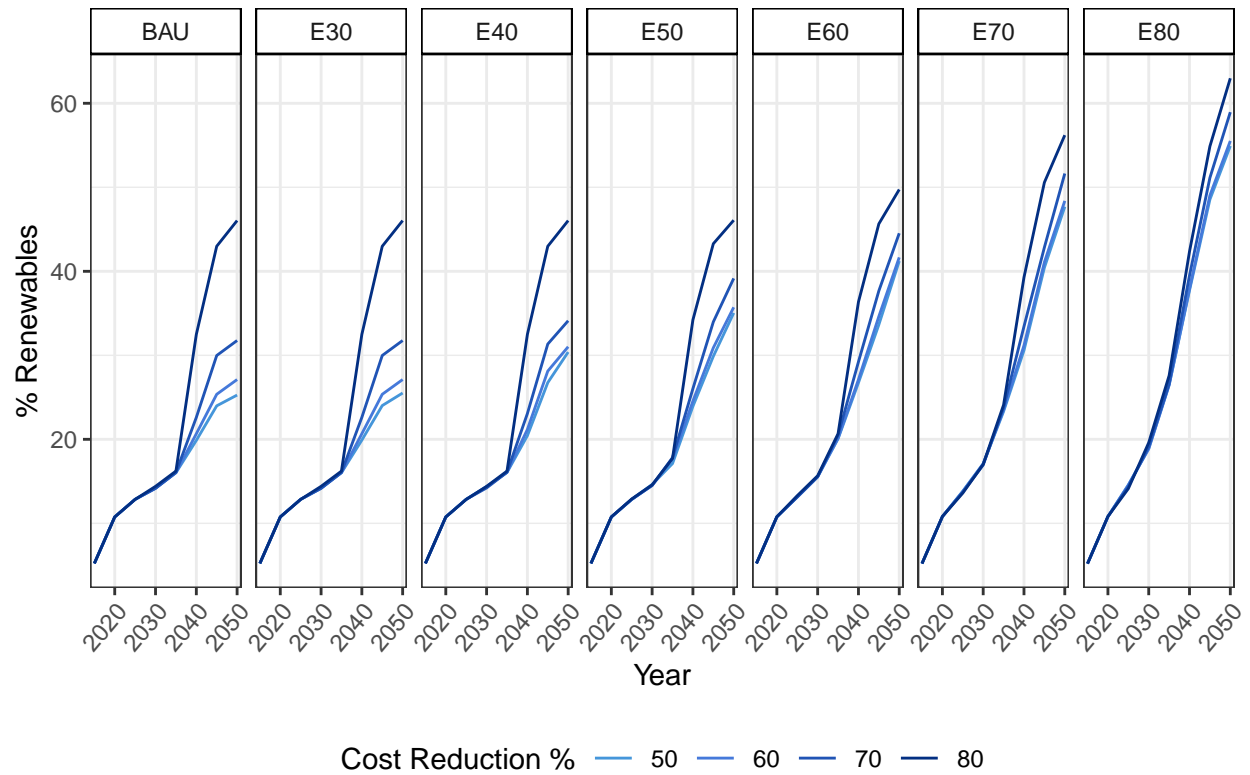
Table 6: 2050 Percent Market Share by Technology

Technology	CO2 Cap	Cost Reduction (%)					
		20	40	50	60	70	80
Coal	BAU	21.5	21.5	21.5	21.1	20.3	16.0
	30	21.4	21.4	21.4	21.1	20.3	16.0
	40	17.9	17.9	17.9	18.2	19.0	16.0
	50	13.9	13.9	13.9	14.3	14.9	15.5
	60	9.4	9.4	9.4	9.7	10.5	12.6
	70	5.2	5.2	5.2	5.5	6.9	9.1
	80	1.6	1.6	1.6	1.7	3.4	5.3
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	0.0	0.0	0.0	0.0	0.0	0.0
	70	0.6	0.6	0.6	0.4	0.0	0.0
	80	2.1	2.1	2.1	1.8	0.8	0.0
Hydro	BAU	5.7	5.7	5.7	5.8	5.8	6.1
	30	5.6	5.6	5.6	5.8	5.8	6.1
	40	5.7	5.7	5.7	5.9	5.9	6.1
	50	5.8	5.8	5.8	6.0	5.9	6.1
	60	5.7	5.7	5.7	5.8	5.8	6.2
	70	6.0	6.0	6.0	6.0	5.8	6.4
	80	6.0	6.0	6.0	6.1	6.0	6.2
BAU		30.3	30.3	30.3	28.9	25.0	15.0

	30	30.2	30.2	30.2	28.9	25.1	15.0
	40	28.3	28.3	28.3	27.2	23.7	15.0
Natural Gas	50	27.1	27.1	27.1	25.9	22.5	15.4
	60	25.3	25.3	25.3	24.6	21.4	14.3
	70	22.2	22.2	22.2	21.4	17.6	11.0
	80	17.1	17.1	16.9	16.6	12.8	8.0
<hr/>							
	BAU	17.2	17.2	17.2	17.1	17.0	16.9
	30	17.2	17.2	17.2	17.1	17.0	16.9
	40	17.7	17.7	17.7	17.6	17.3	16.9
Nuclear	50	18.2	18.2	18.2	18.1	17.5	16.9
	60	18.3	18.3	18.3	18.3	17.8	17.1
	70	18.4	18.4	18.4	18.3	18.0	17.3
	80	18.6	18.6	18.4	18.3	18.0	17.4
<hr/>							
	BAU	0.0	0.0	0.0	3.9	10.9	28.2
	30	0.0	0.0	0.0	3.9	10.9	28.2
	40	0.0	0.0	0.0	4.2	11.8	28.2
Offshore Wind	50	0.0	0.0	0.0	4.9	14.3	28.3
	60	0.0	0.0	0.2	5.7	16.1	30.8
	70	0.0	0.0	0.7	6.8	19.8	34.0
	80	0.0	0.0	1.8	7.8	24.6	37.4
<hr/>							
	BAU	17.9	17.9	17.9	17.2	16.3	14.4
	30	18.0	18.0	18.0	17.2	16.3	14.4
	40	20.5	20.5	20.5	19.4	16.7	14.4
Solar	50	22.9	22.9	22.9	21.9	18.5	14.5
	60	25.4	25.4	25.4	24.1	20.2	15.2
	70	28.1	28.1	28.0	25.9	22.2	17.2
	80	32.2	32.2	31.7	30.8	23.4	18.4
<hr/>							
	BAU	7.3	7.3	7.3	6.0	4.5	3.4
	30	7.5	7.5	7.5	6.0	4.5	3.4
	40	9.9	9.9	9.9	7.4	5.6	3.4
Terrestrial Wind	50	12.1	12.1	12.1	8.8	6.4	3.3
	60	15.8	15.8	15.6	11.8	8.3	3.7
	70	19.6	19.6	19.0	15.8	9.7	5.0
	80	22.3	22.3	21.3	17.0	10.9	7.2

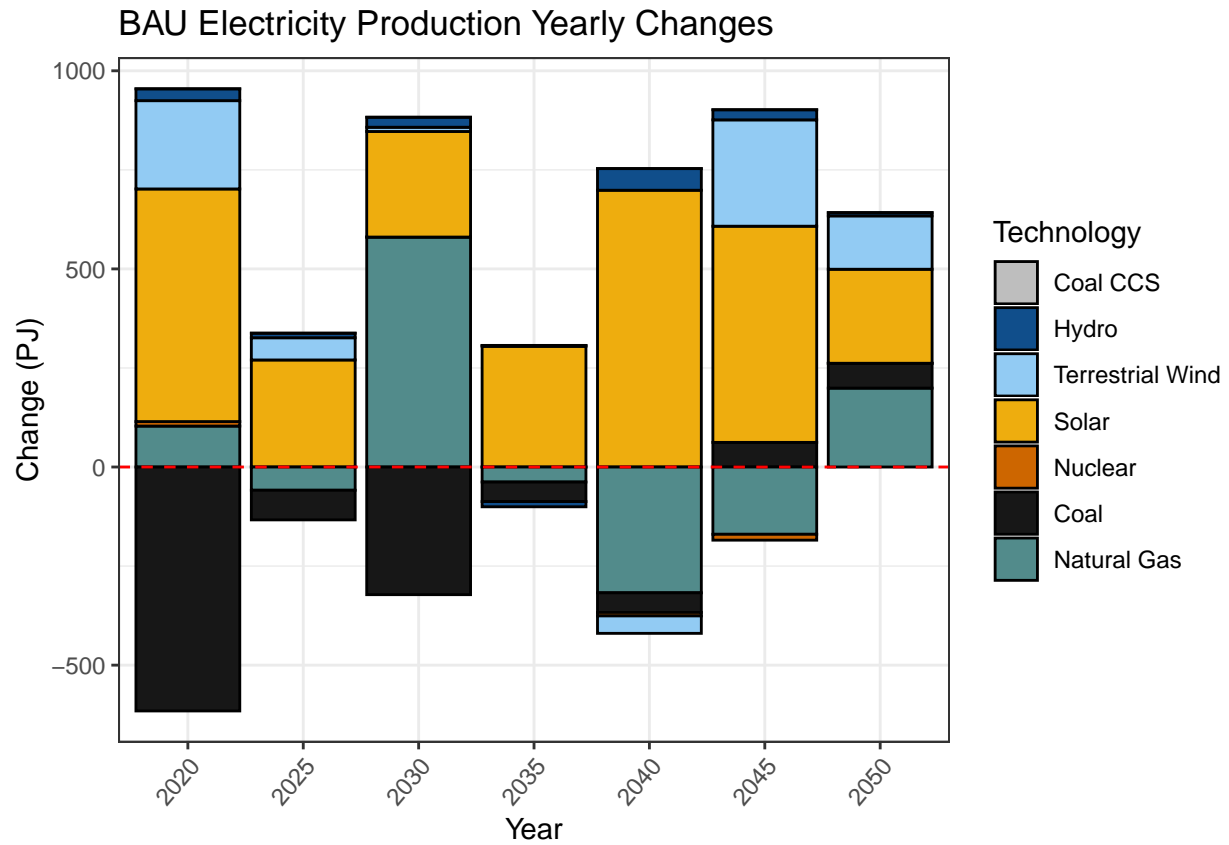
6.8 Renewable Contributions

Renewable Technology Contribution to Electricity Production



6.9 Retirements and Additions

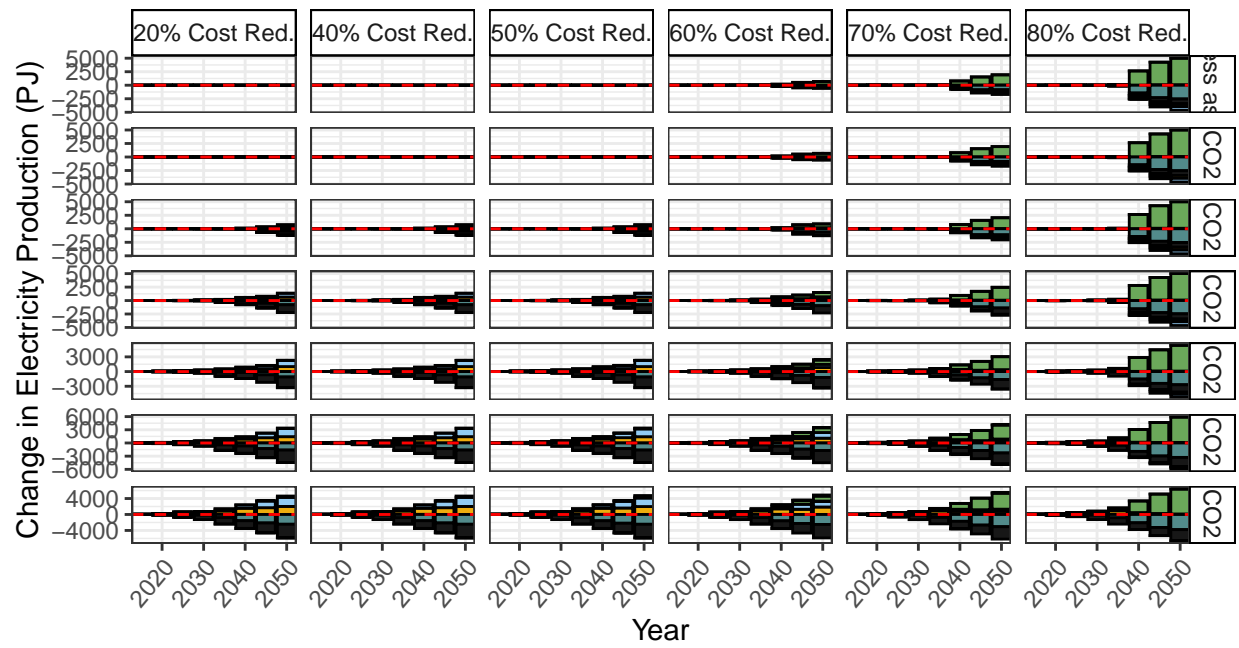
Basecase year-on-year changes in the grid mix. Shows the modeled fluctuations in generation. All following quantifications of grid mix changes are as compared to these changes in the basecase.



6.10 Changes Over Baseline

Summary Graph

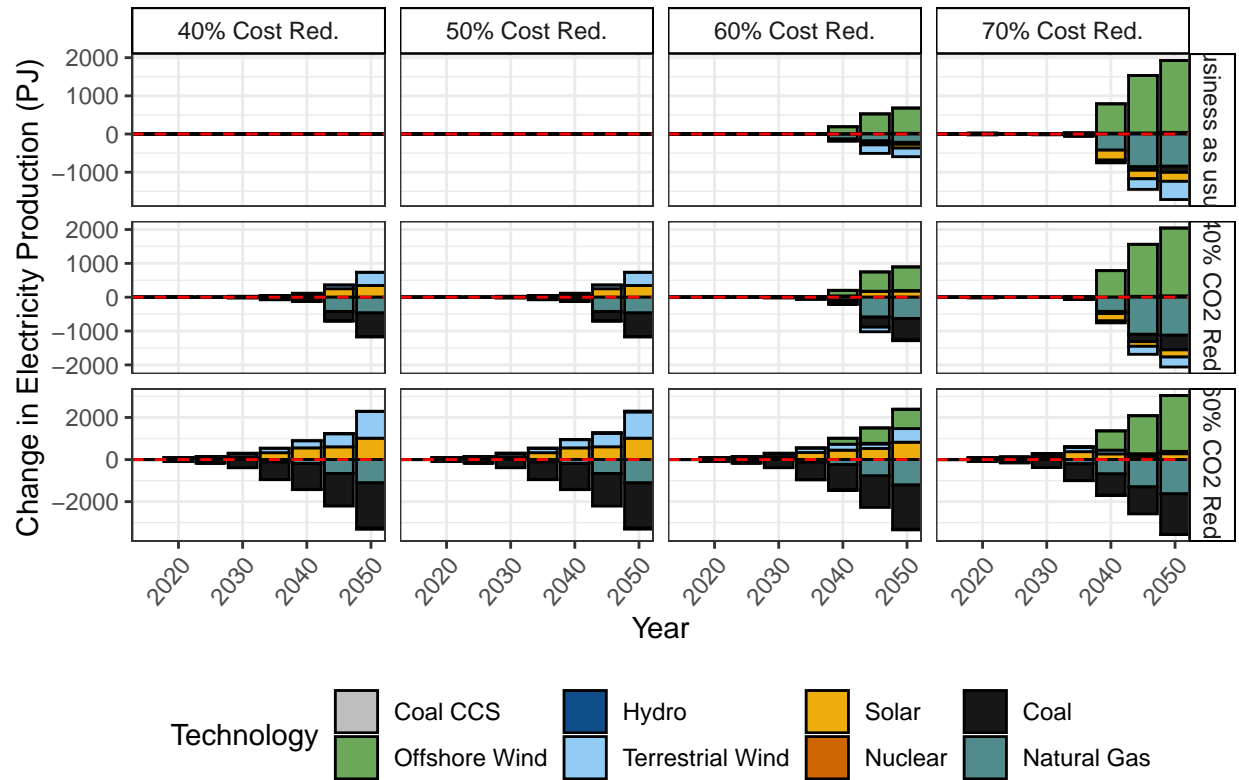
Changes in Grid Mix over Baseline



Technology

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

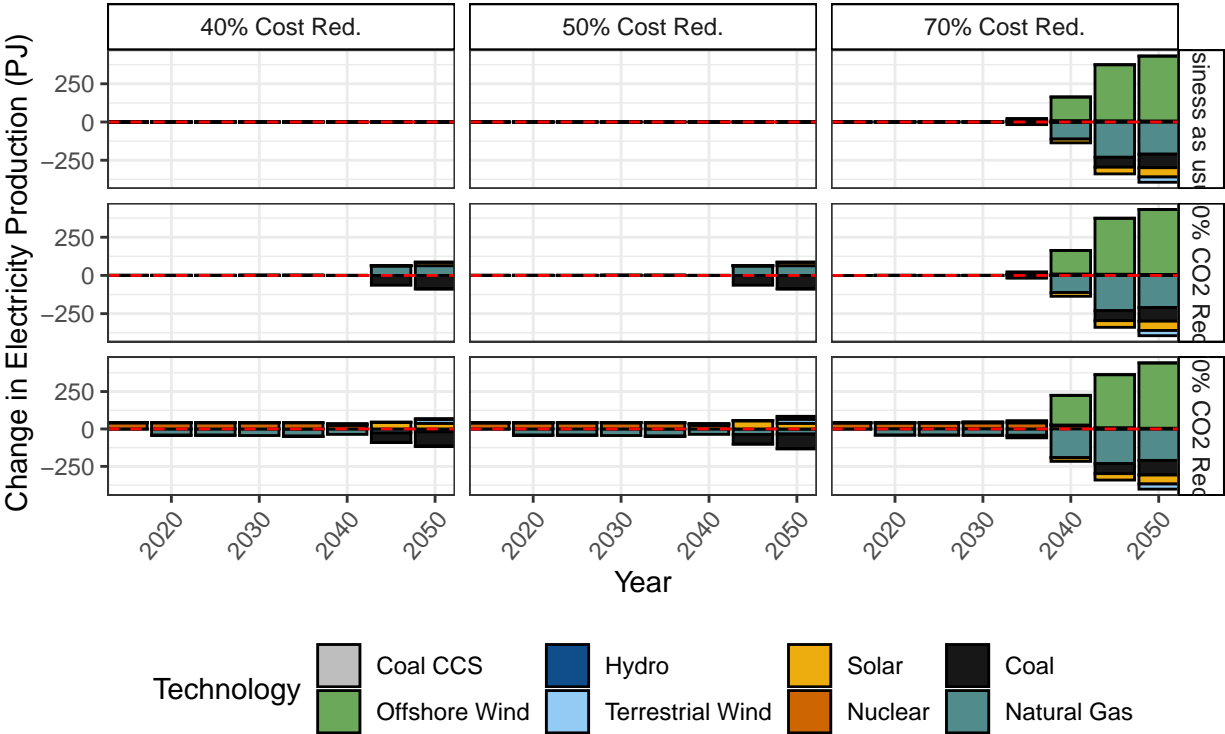
Changes in Grid Mix over Baseline



Regional Summary Graphs

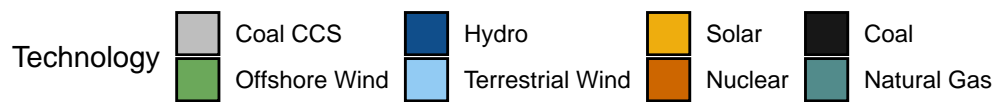
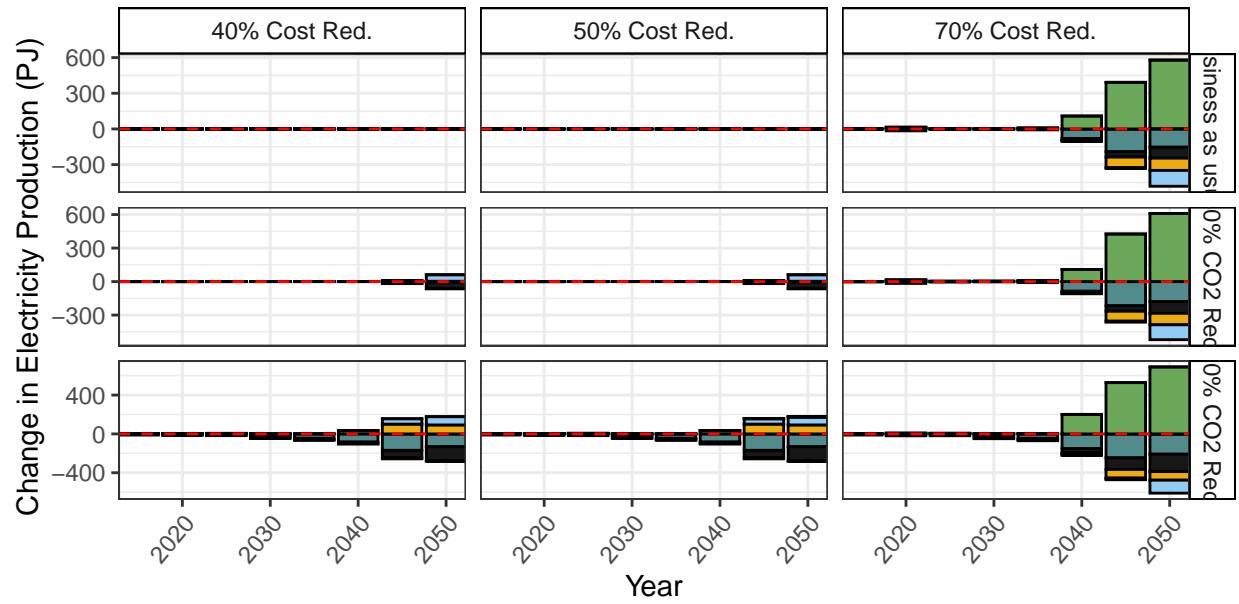
Changes in Grid Mix over Baseline

R1



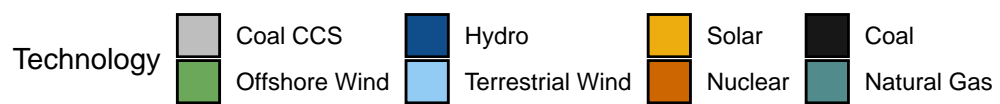
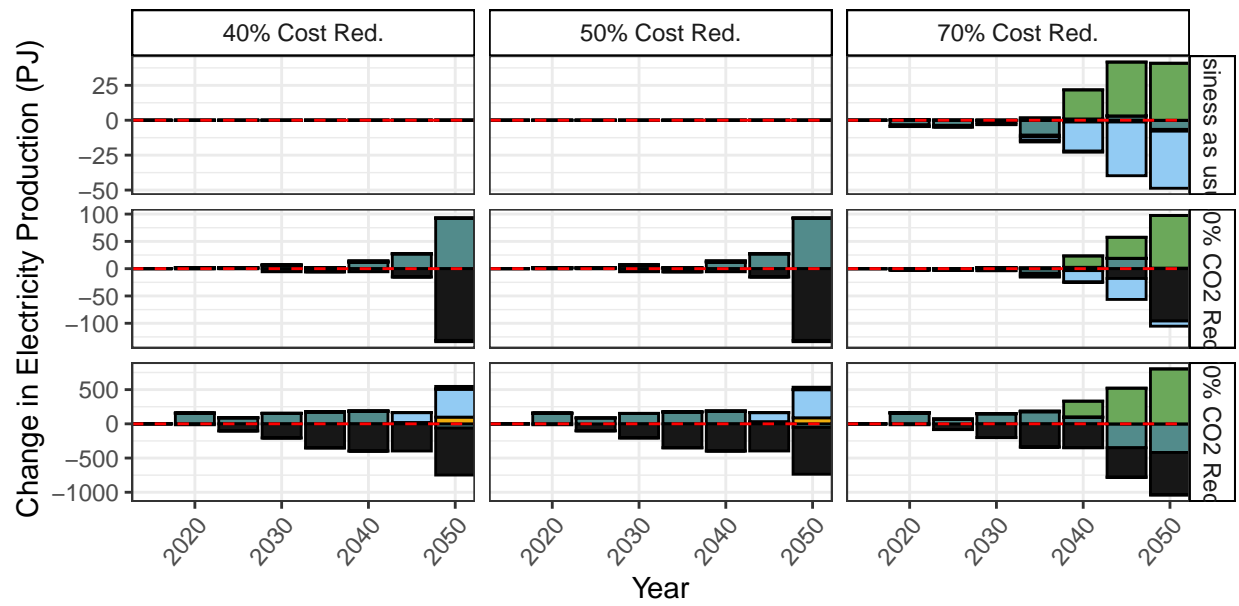
Changes in Grid Mix over Baseline

R2



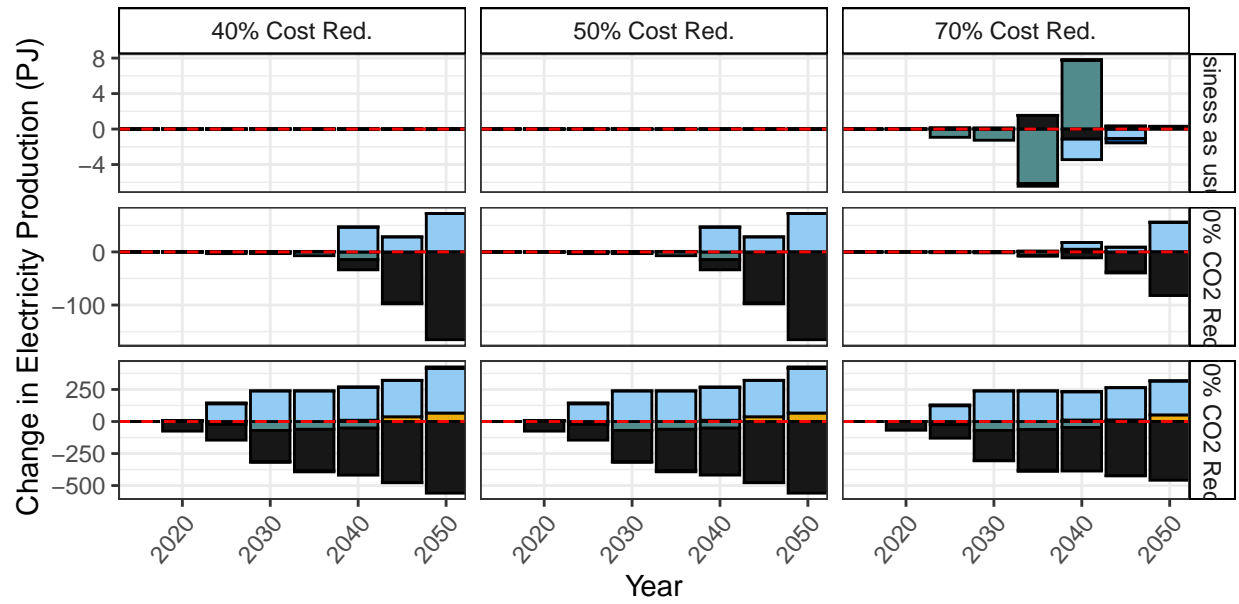
Changes in Grid Mix over Baseline

R3



Changes in Grid Mix over Baseline

R4

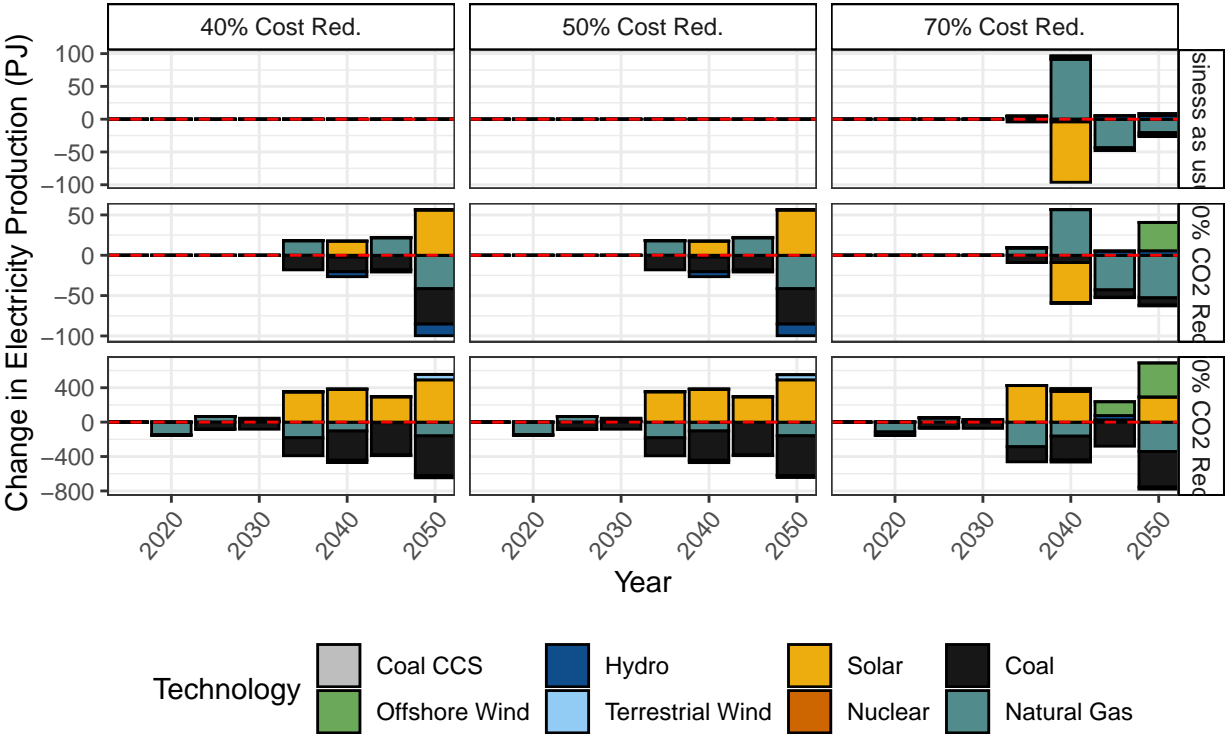


Technology

Coal CCS	Terrestrial Wind	Nuclear	Natural Gas
Hydro	Solar	Coal	

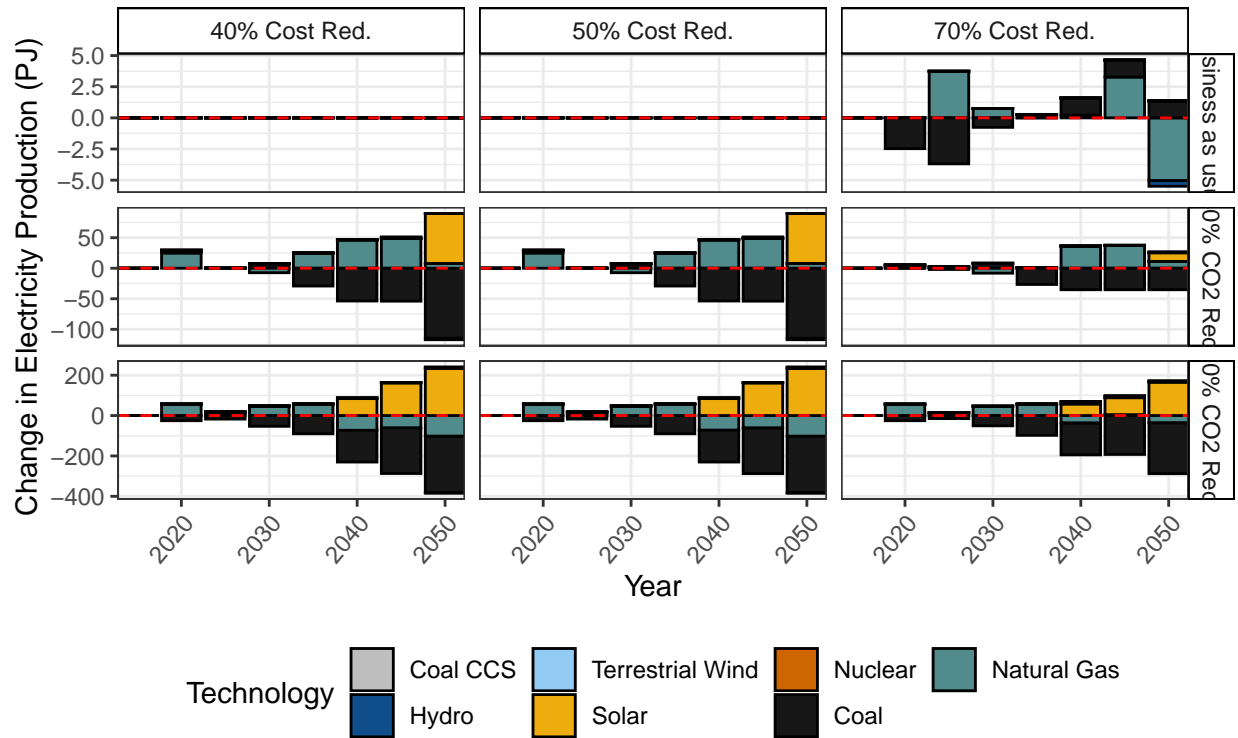
Changes in Grid Mix over Baseline

R5



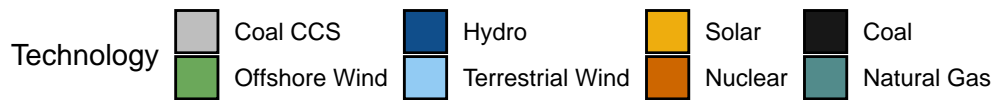
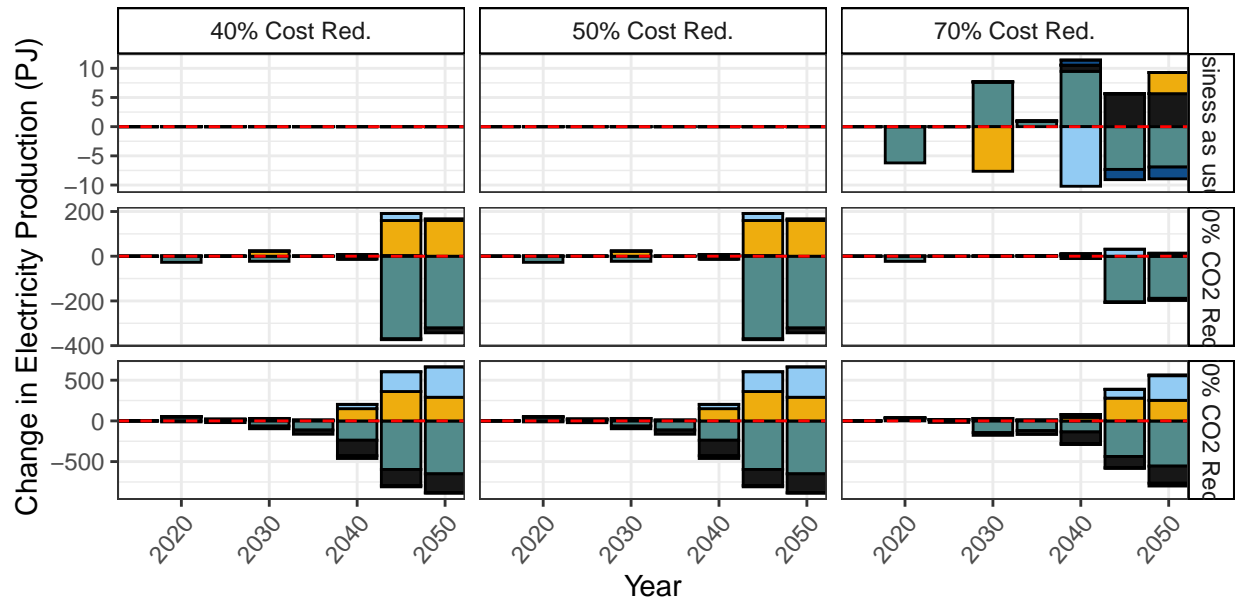
Changes in Grid Mix over Baseline

R6



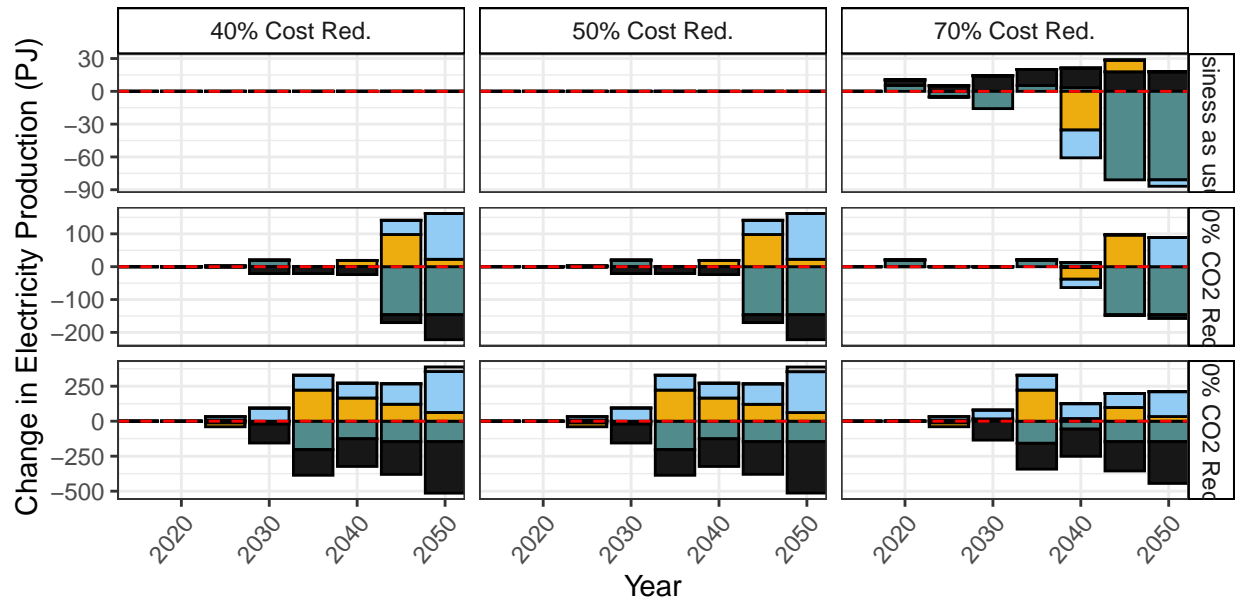
Changes in Grid Mix over Baseline

R7



Changes in Grid Mix over Baseline

R8

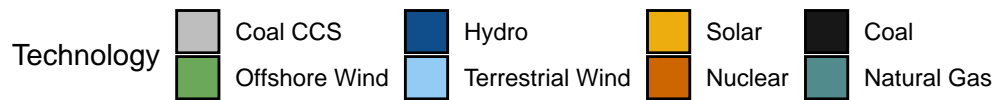
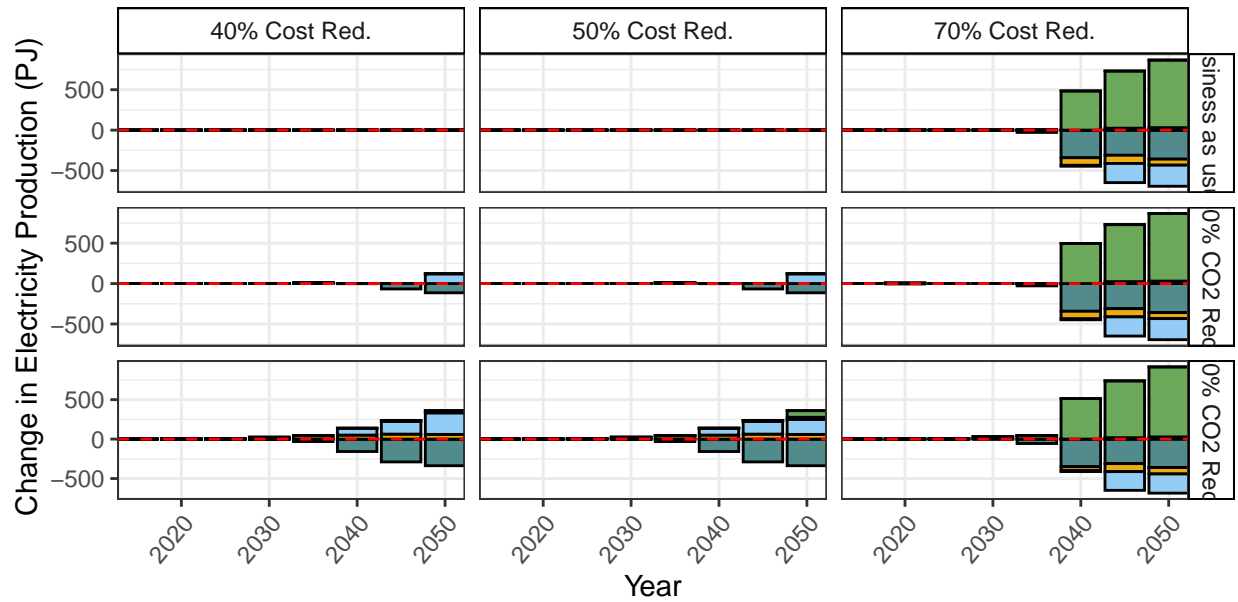


Technology

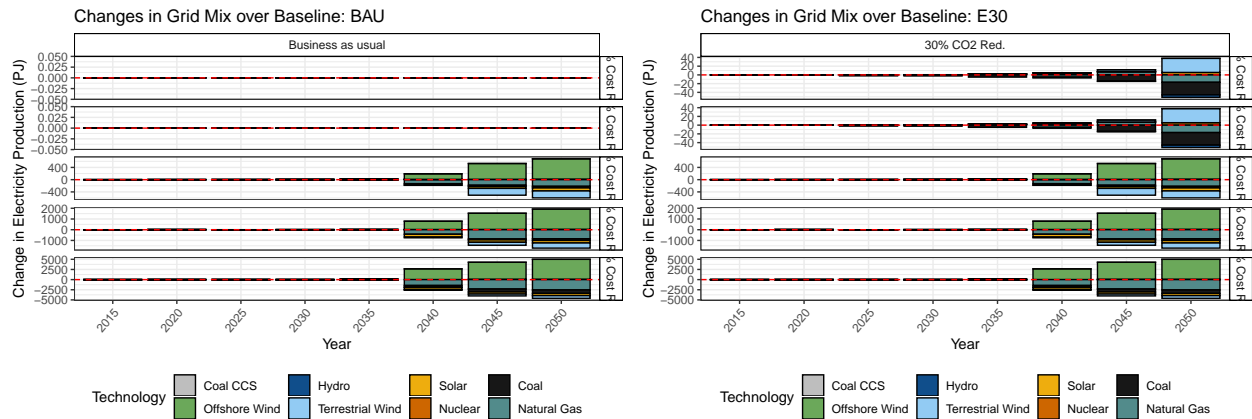
Coal CCS	Terrestrial Wind	Nuclear	Natural Gas
Hydro	Solar	Coal	

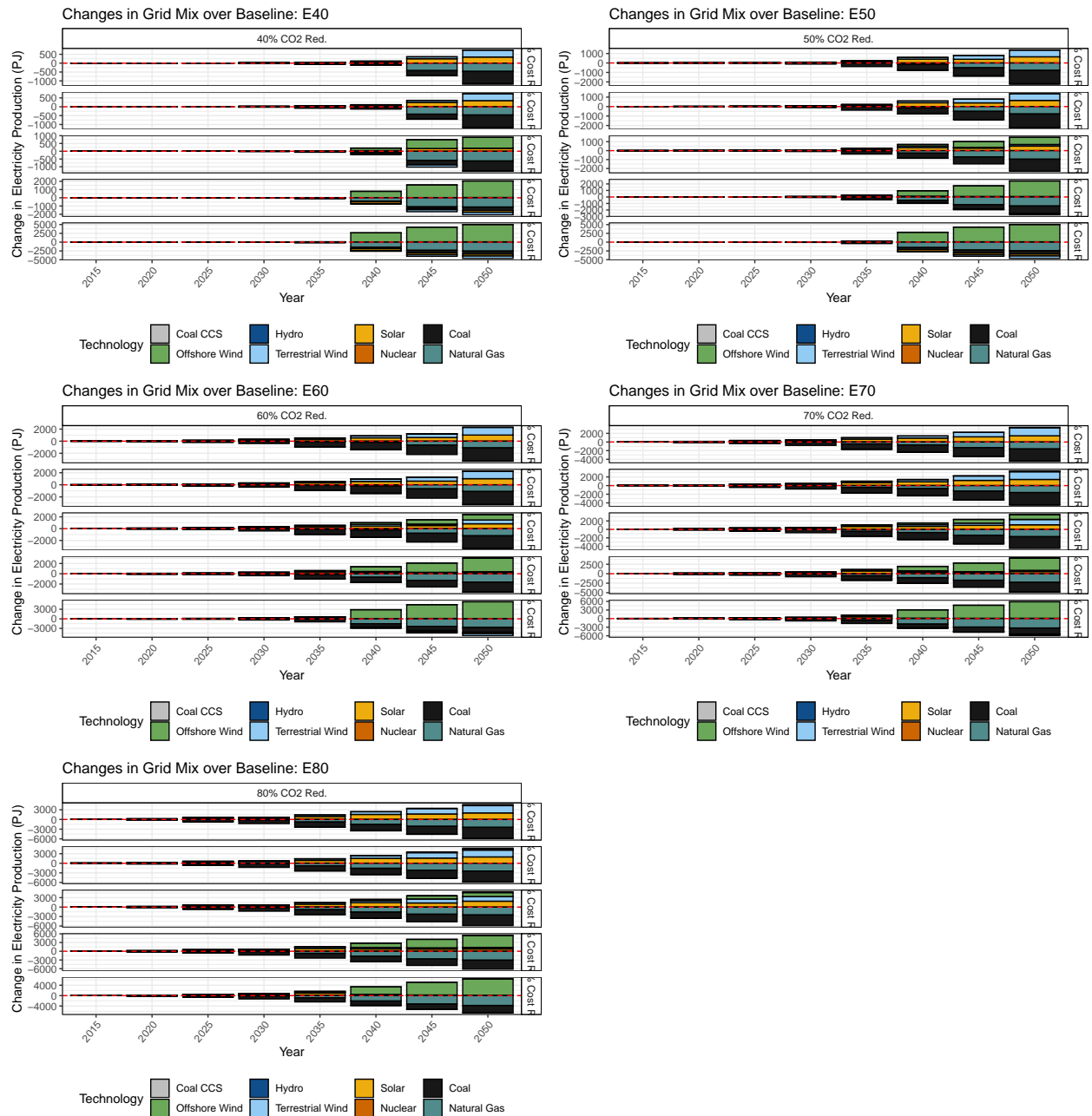
Changes in Grid Mix over Baseline

R9

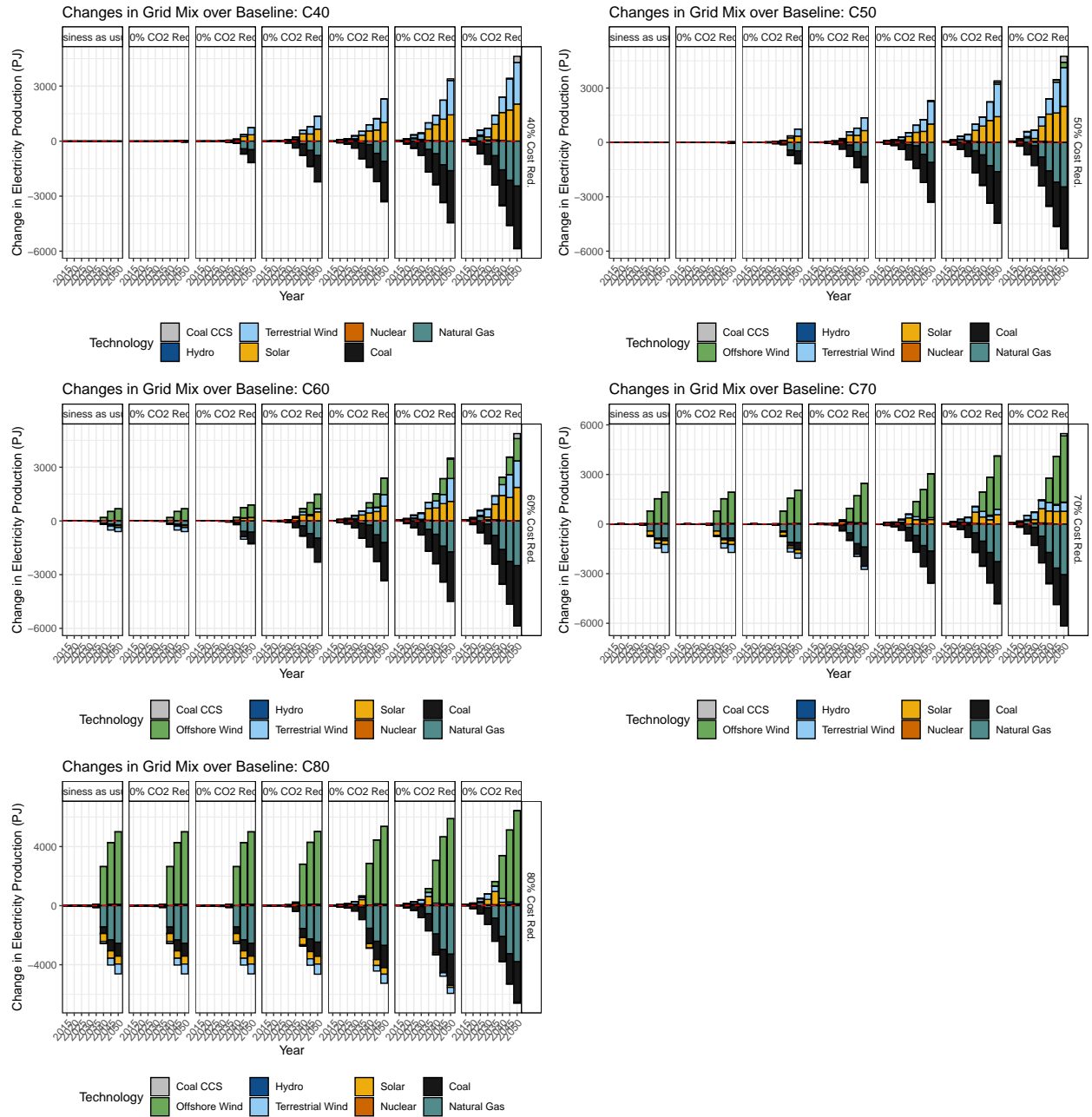


By Emissions Reduction %



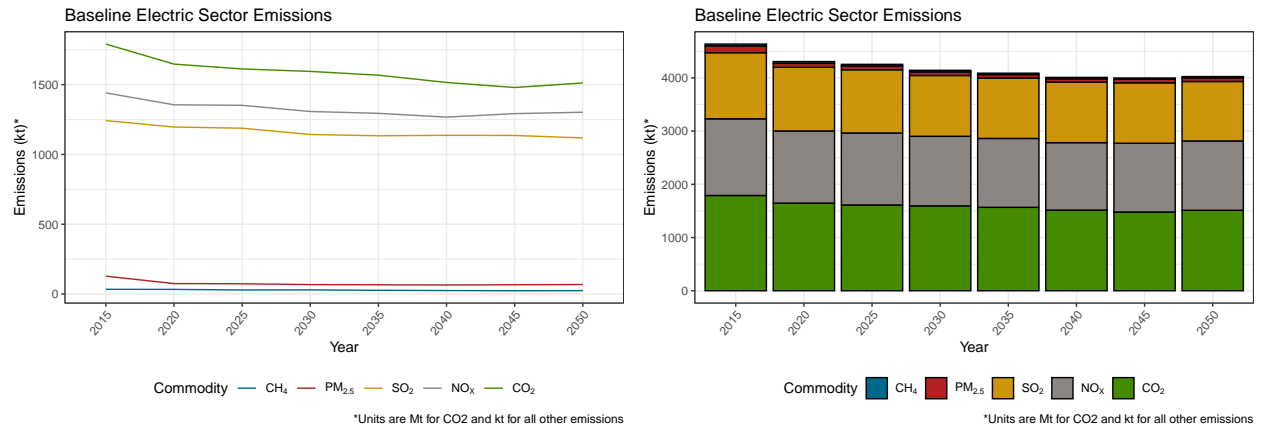


By Cost Reduction %

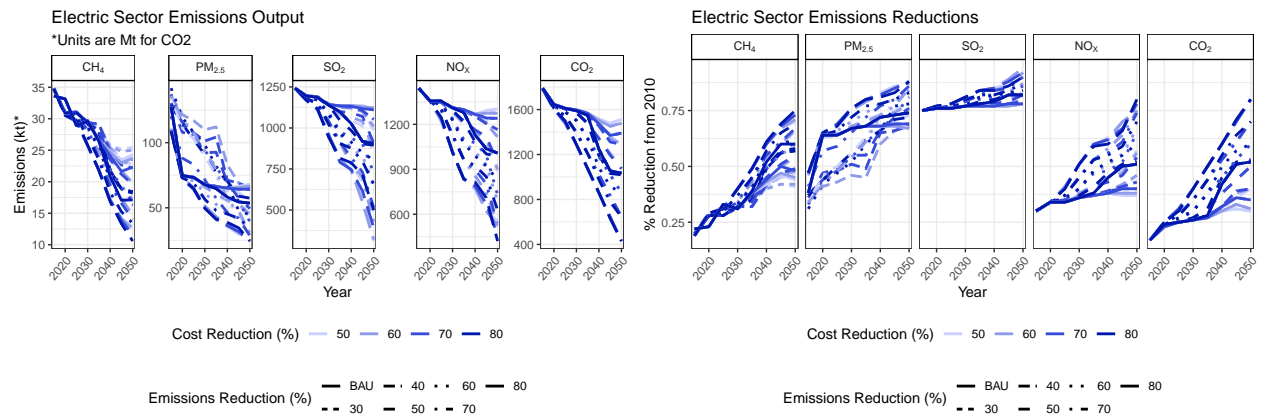


7 Emissions

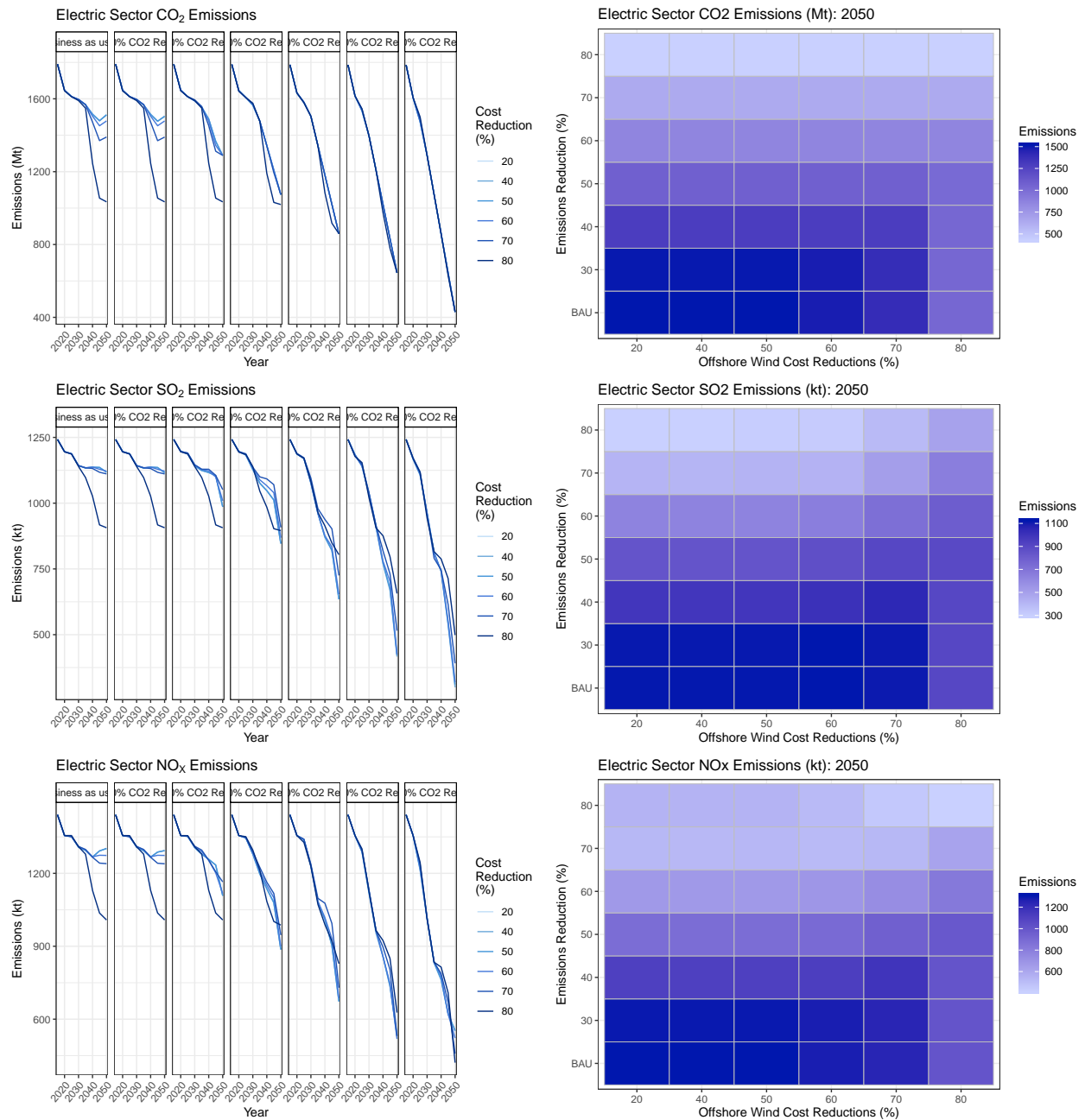
7.1 Baseline

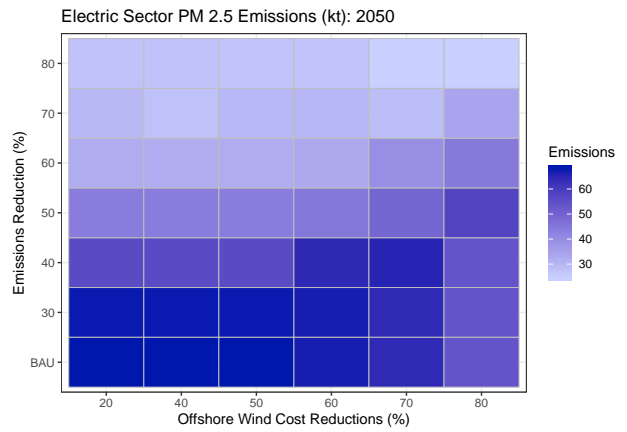
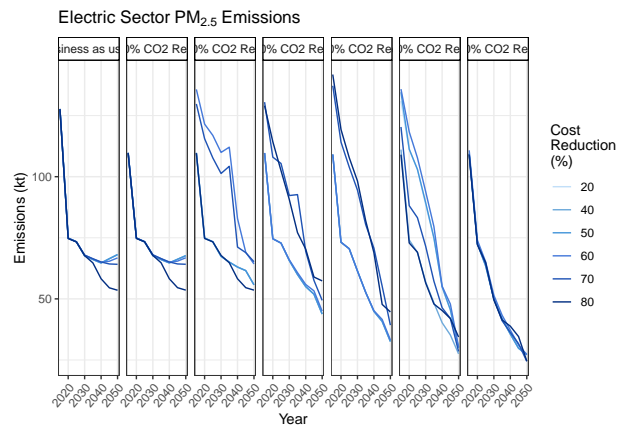
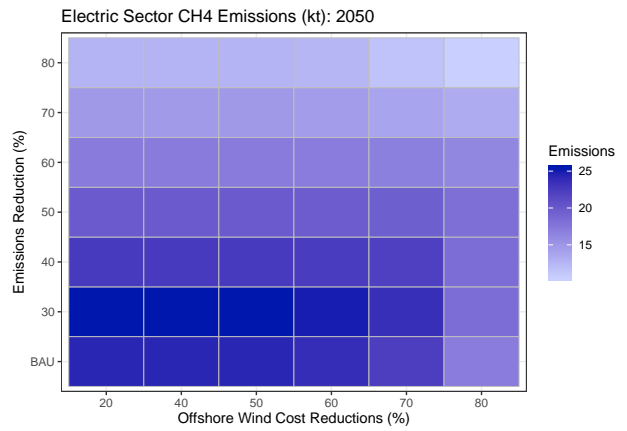
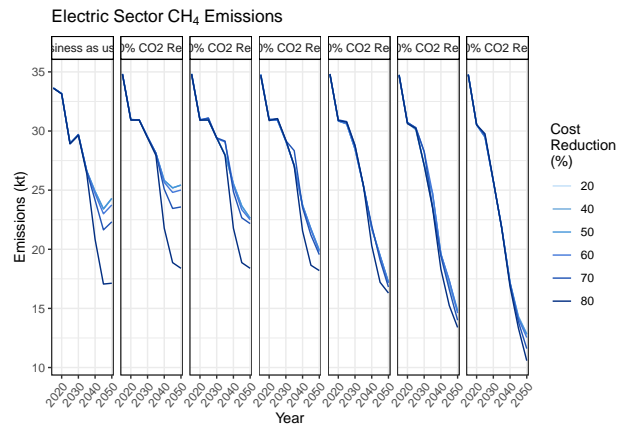


7.2 Emissions by Scenario and Commodity

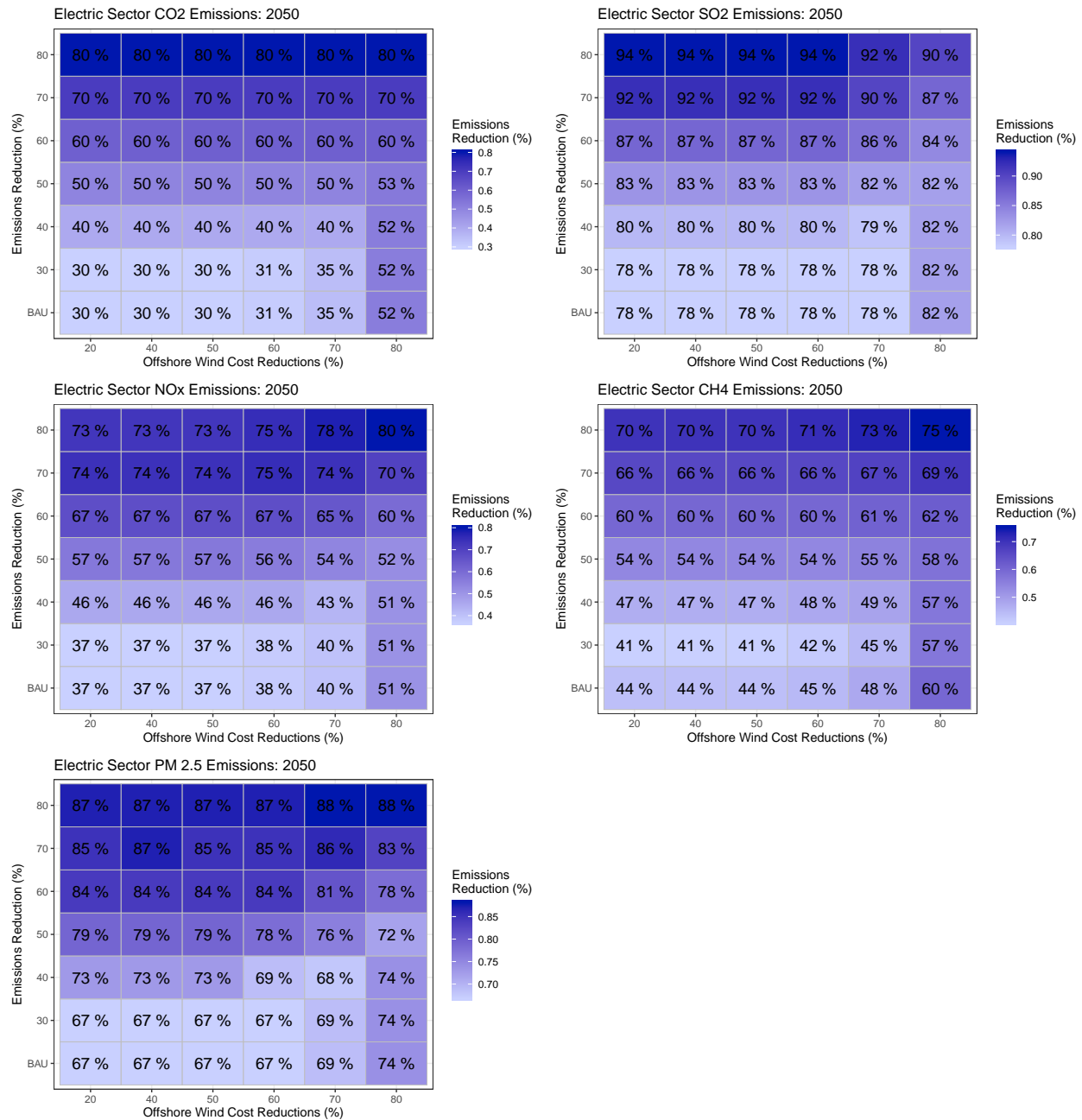


7.3 Emissions by Commodity - Values

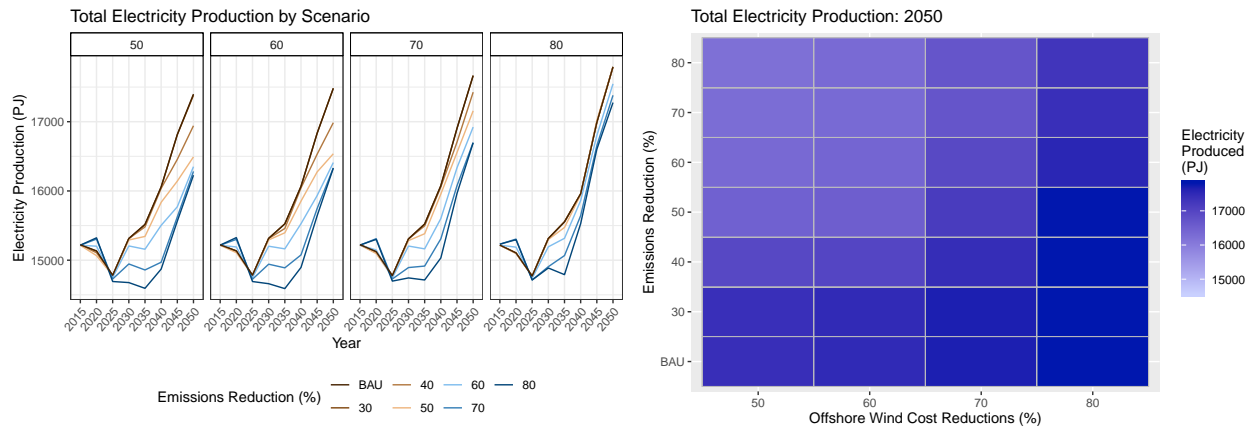




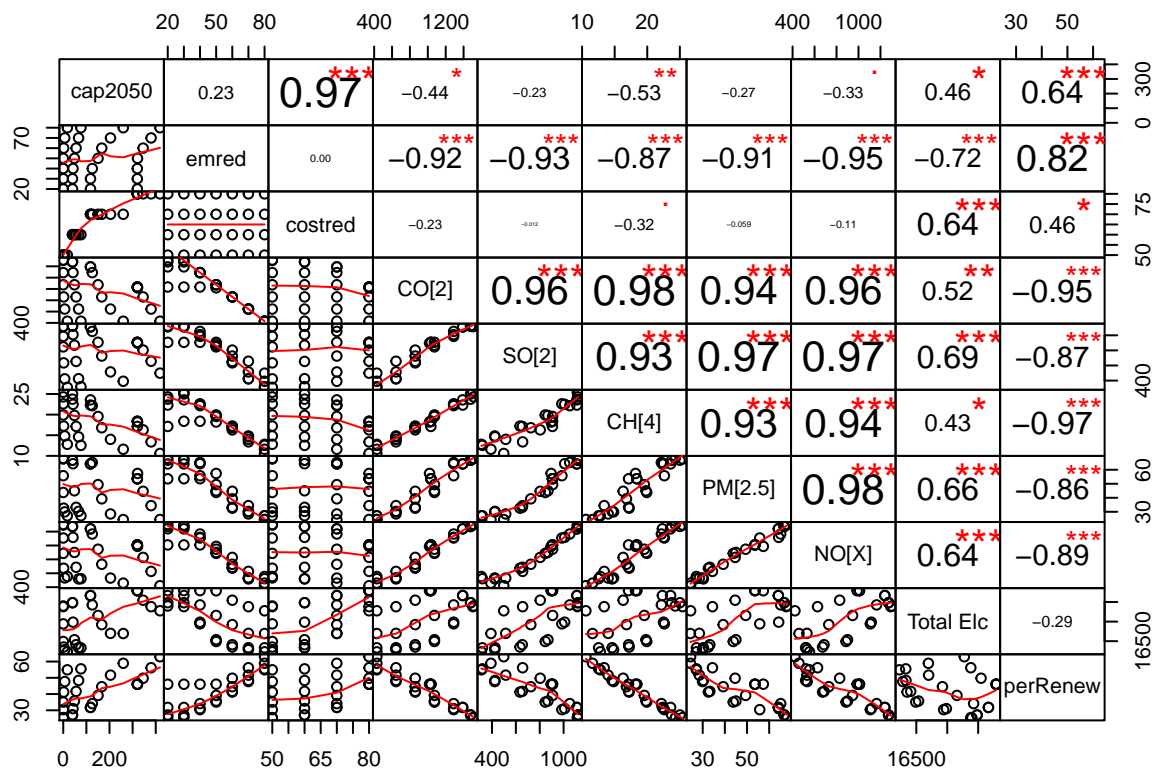
7.4 Emissions by Commodity - Percent Reduction



8 Total Electricity Production



9 Correlations



10 Regressions

	OSW Capacity	% Renewables	Total Elc
CO2 Cap	24.04 ** (8.00)	8.89 *** (0.77)	-374.63 *** (39.33)
Cost Reduction	129.73 *** (8.00)	4.95 *** (0.77)	350.49 *** (39.33)
N	28	28	28
R2	0.92	0.88	0.87

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

	CO[2]	SO[2]	NO[X]	PM[2.5]	CH[4]
CO2 Cap	-318.36 *** (22.49)	-252.57 *** (20.14)	-273.35 *** (18.65)	-3.55 *** (0.31)	-14.38 *** (1.17)
OSW Capacity	-73.17 ** (22.49)	7.26 (20.14)	-27.54 (18.65)	-1.45 *** (0.31)	-0.49 (1.17)
N	28	28	28	28	28
R2	0.90	0.87	0.90	0.88	0.86

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