

# 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

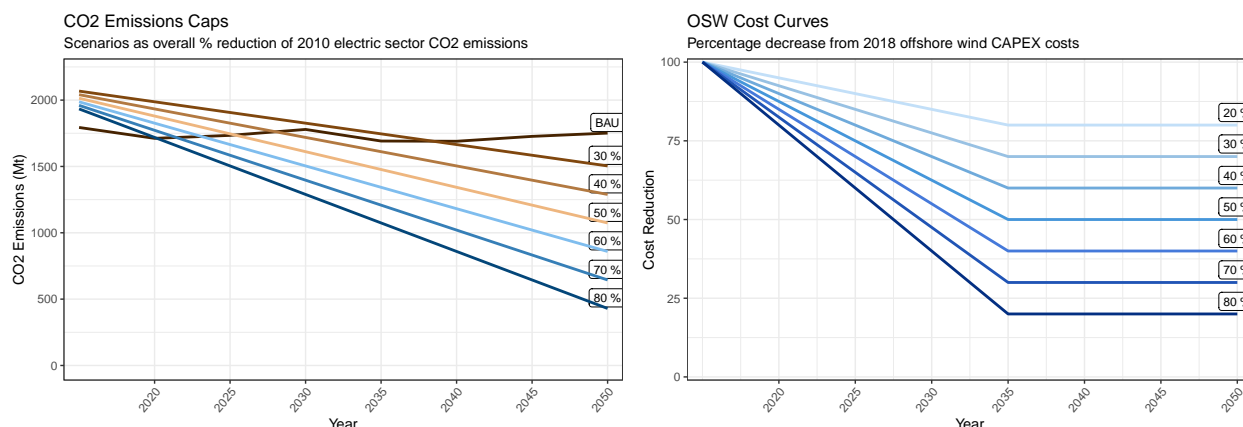
Three scripts are loaded into this markdown document to allow for analysis of the data. The setup script loads the library, creates generalized functions, and creates global variables for color scales and factors. The data script loads an excel spreadsheet with all of the results data and performs the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

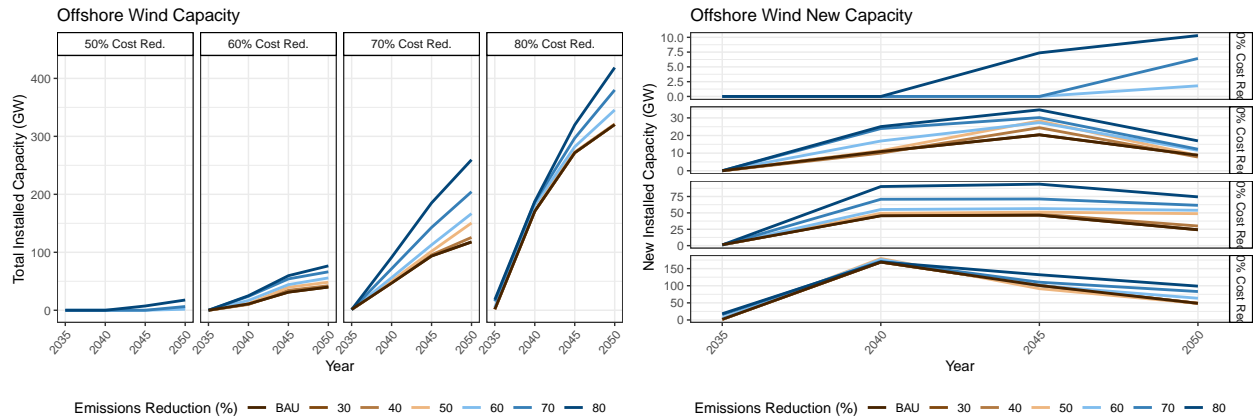
U.S. EIA Annual Energy Outlook 2019

## 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.

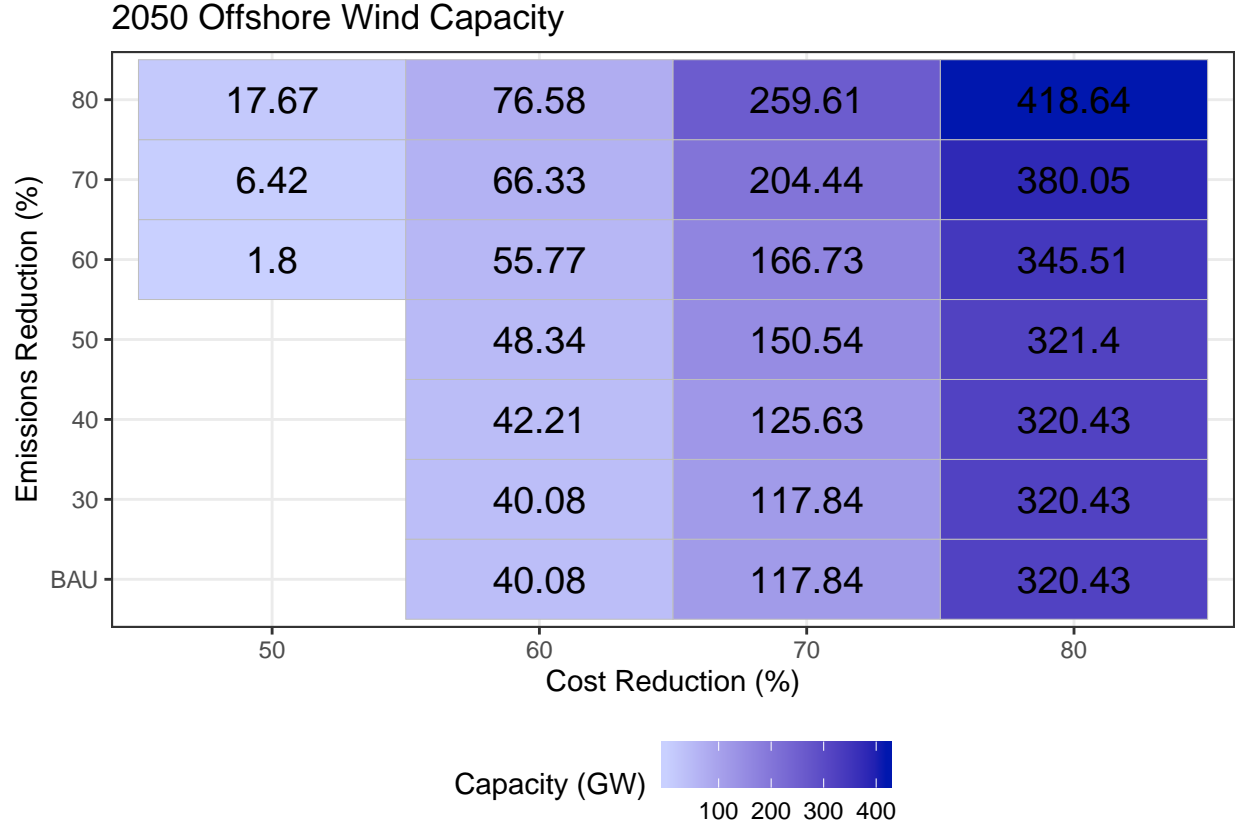


Table 2: Offshore Wind Total Installed Capacity (GW): 2050

CO2 Emissions Reduction (%)	Cost Reduction (%)			
	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

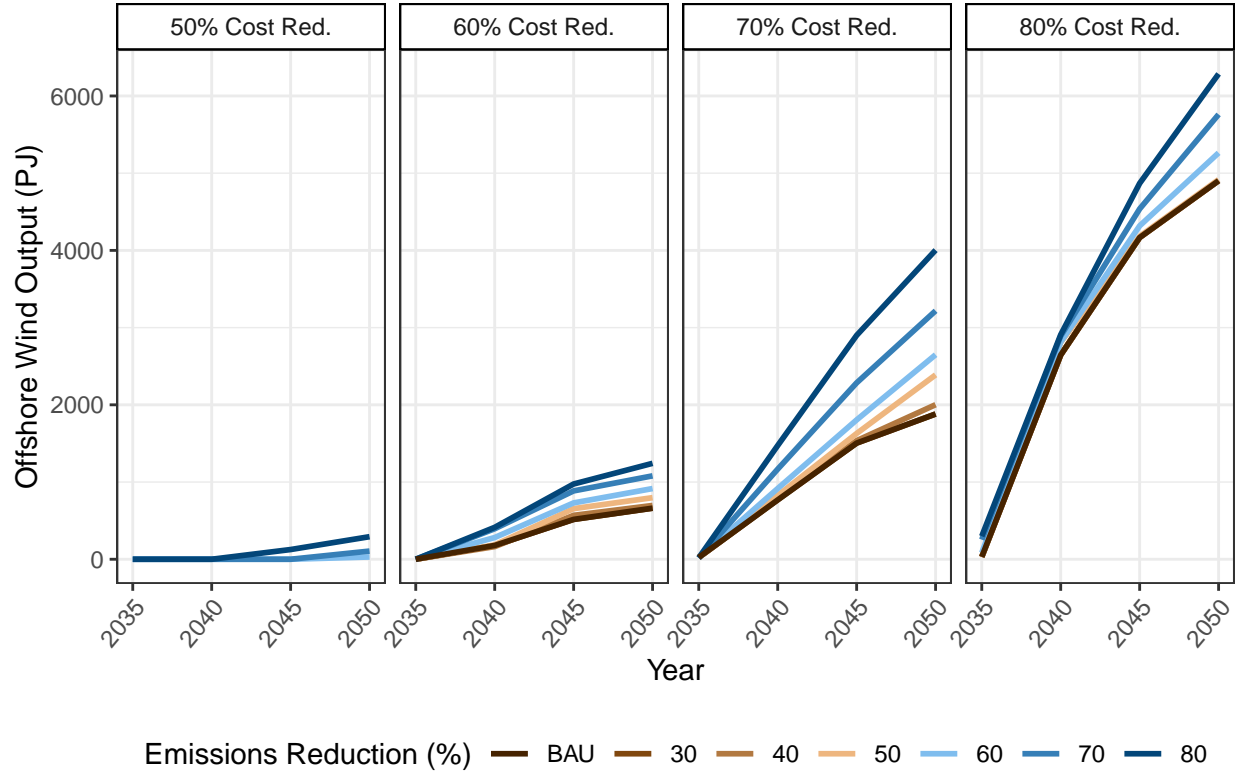
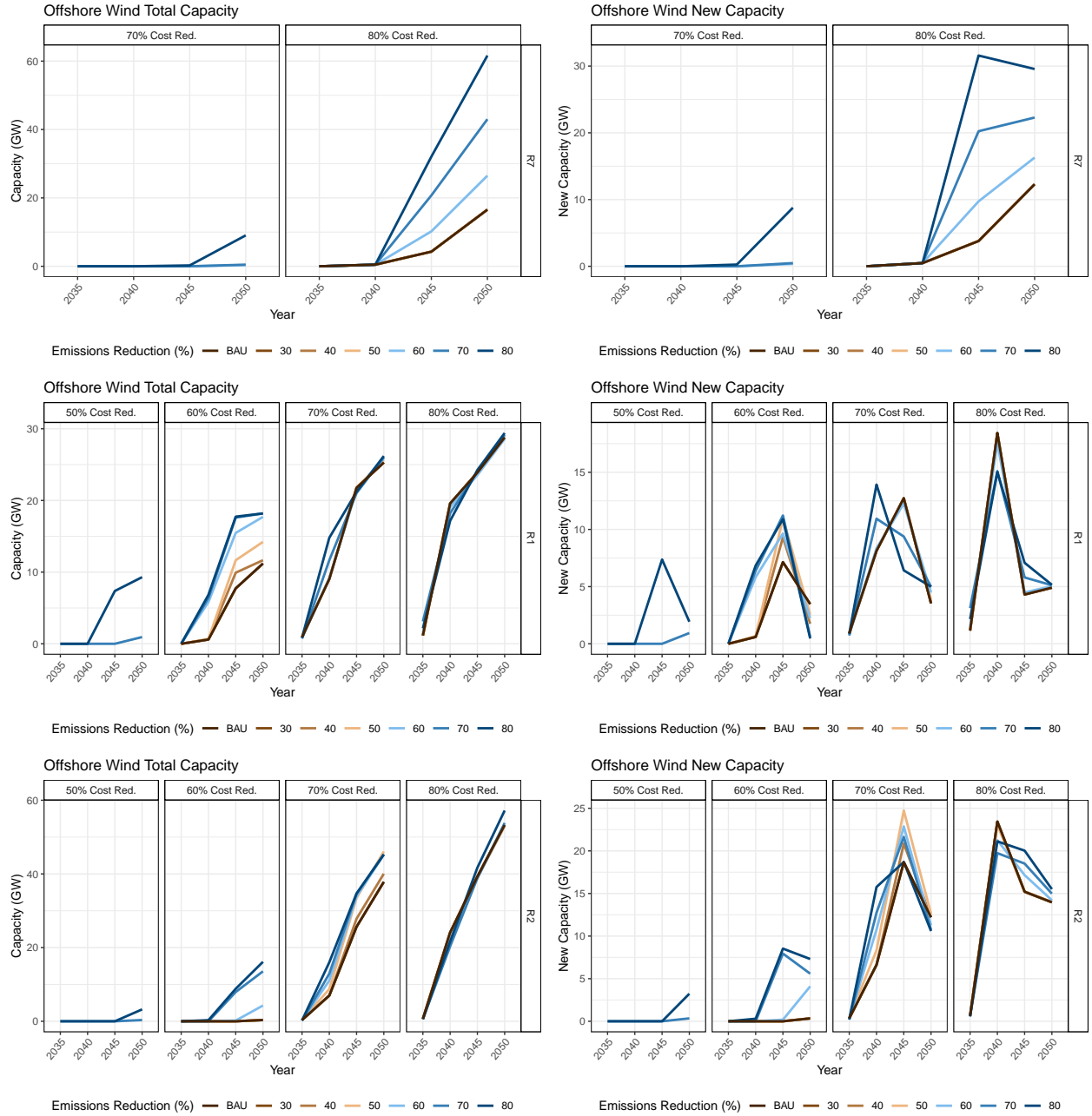


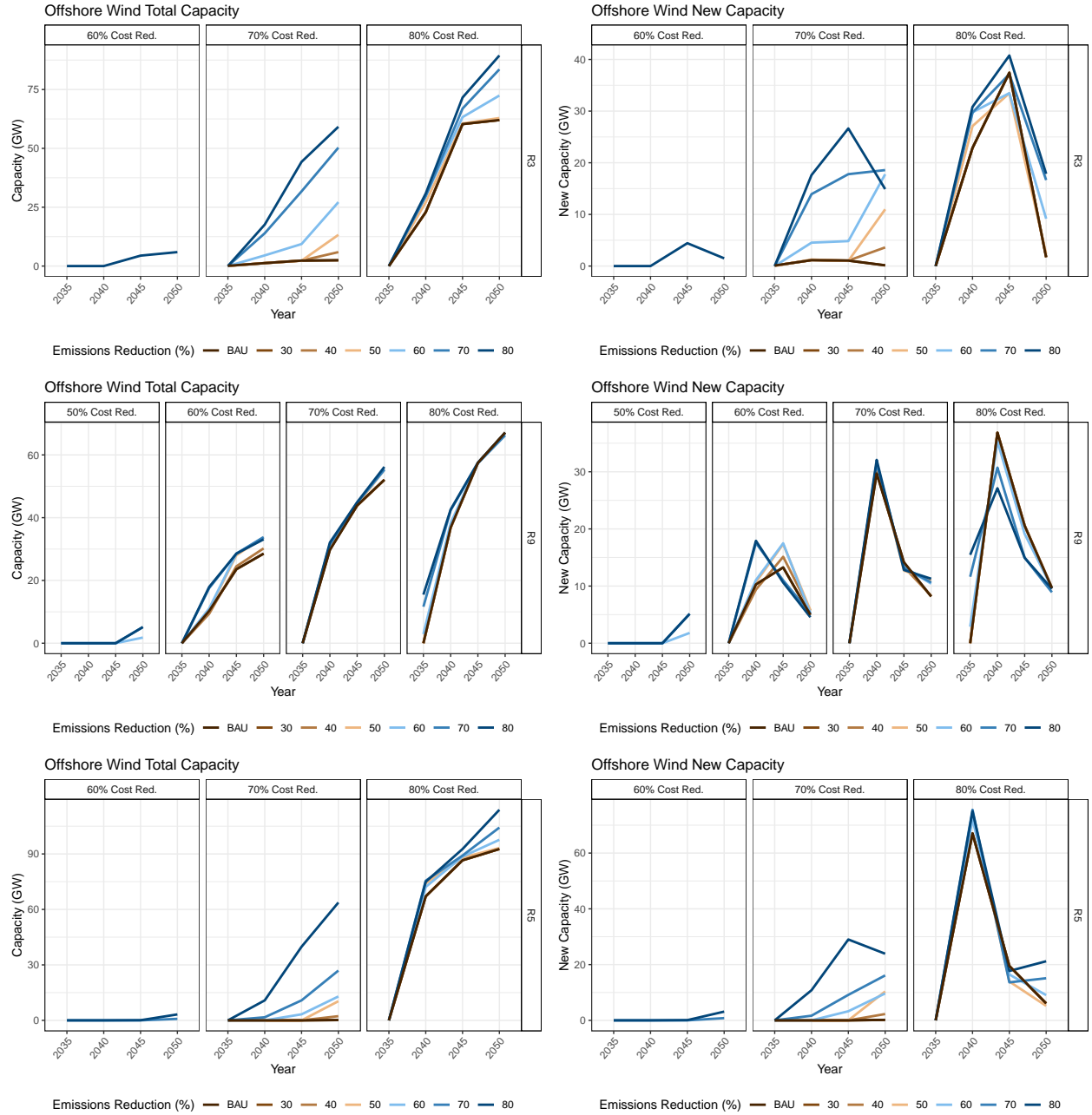
Table 3: Offshore Wind Total Output (PJ): 2050

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.

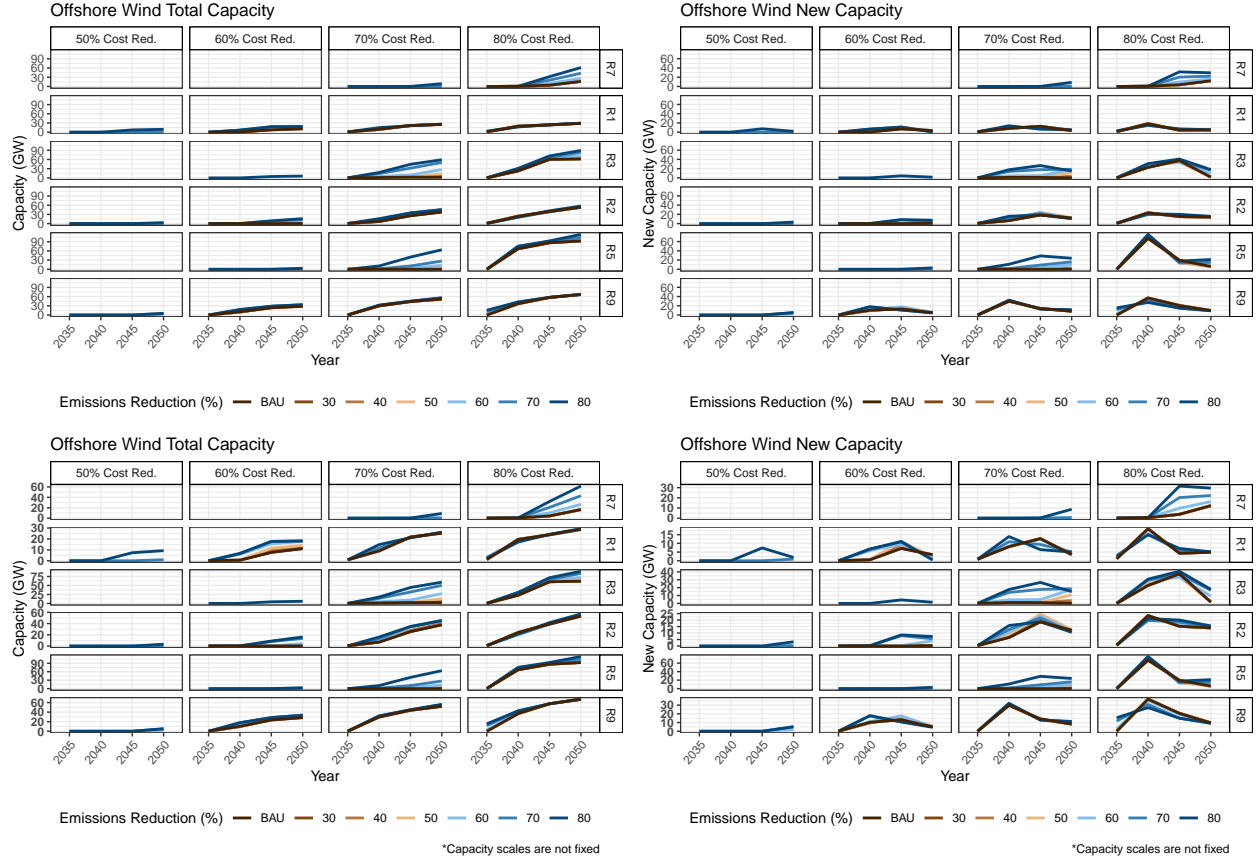


Table 4: Average Installed Capacity (GW)

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

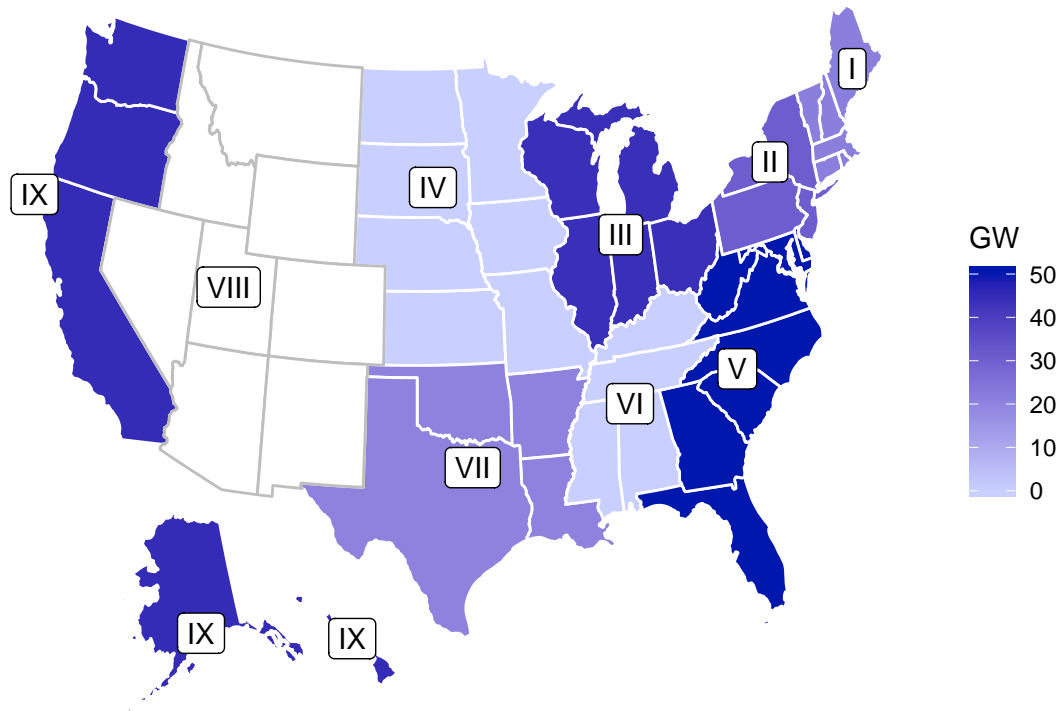
*Note:*

Average is across all scenarios



Map of average total capacity

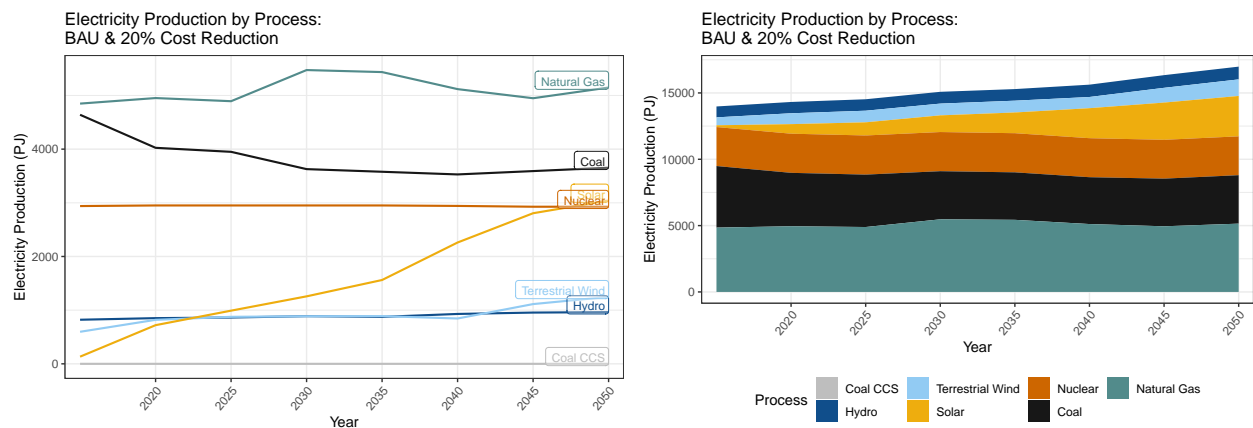
## Average Offshore Wind Capacity



## 6 Grid Mix

### 6.1 Baseline Production

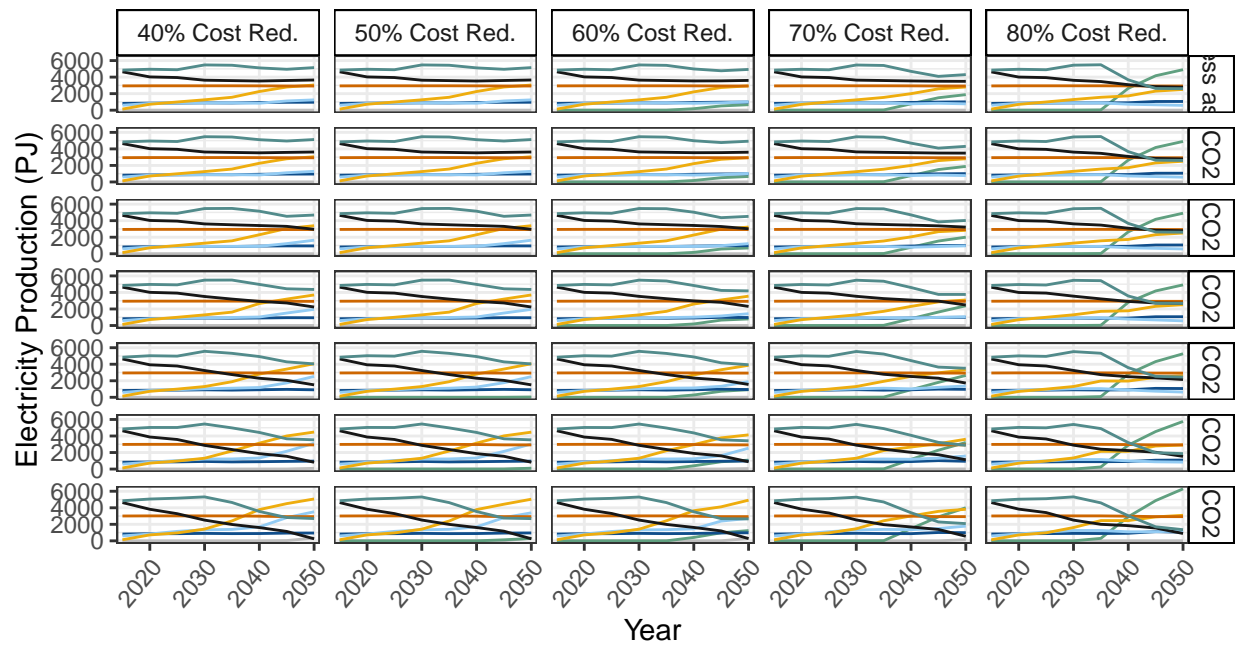
Grid mix without any offshore wind cost reduction or emissions cap.



### 6.2 All Scenarios

Complete Set

## Electricity Production by Process

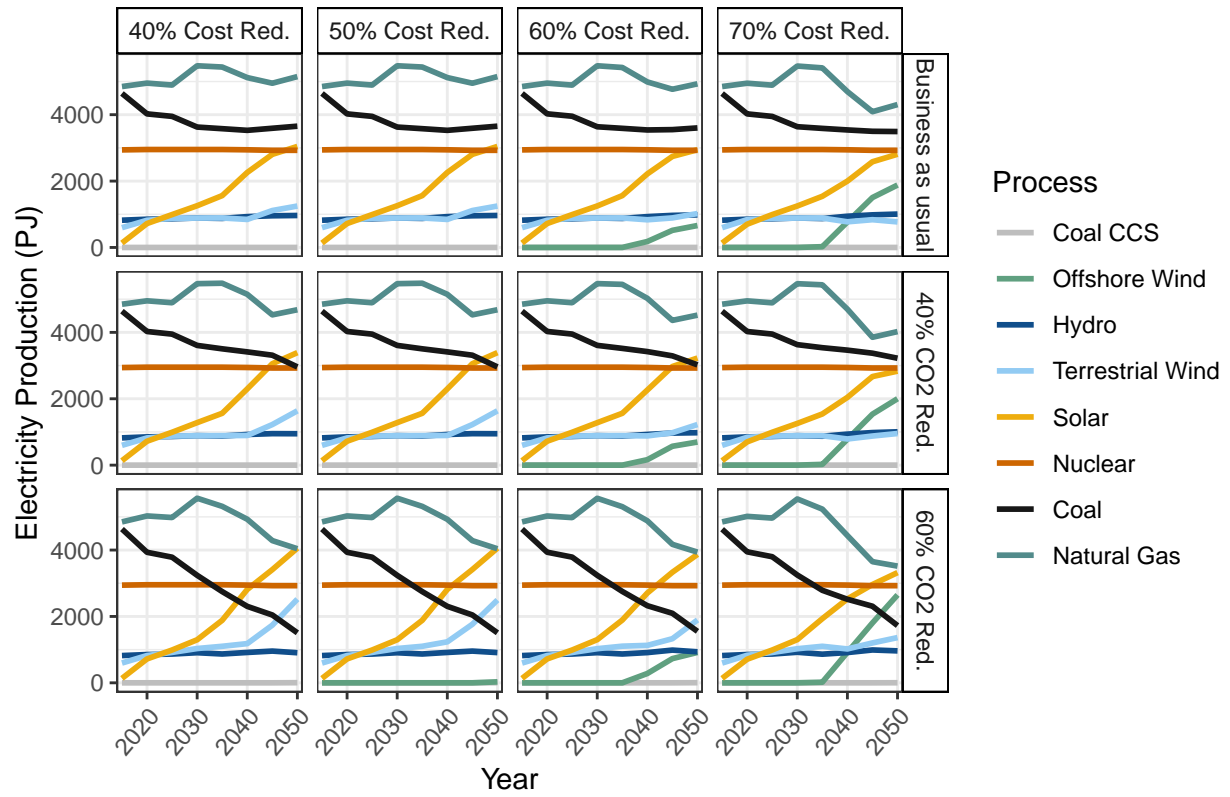


Process

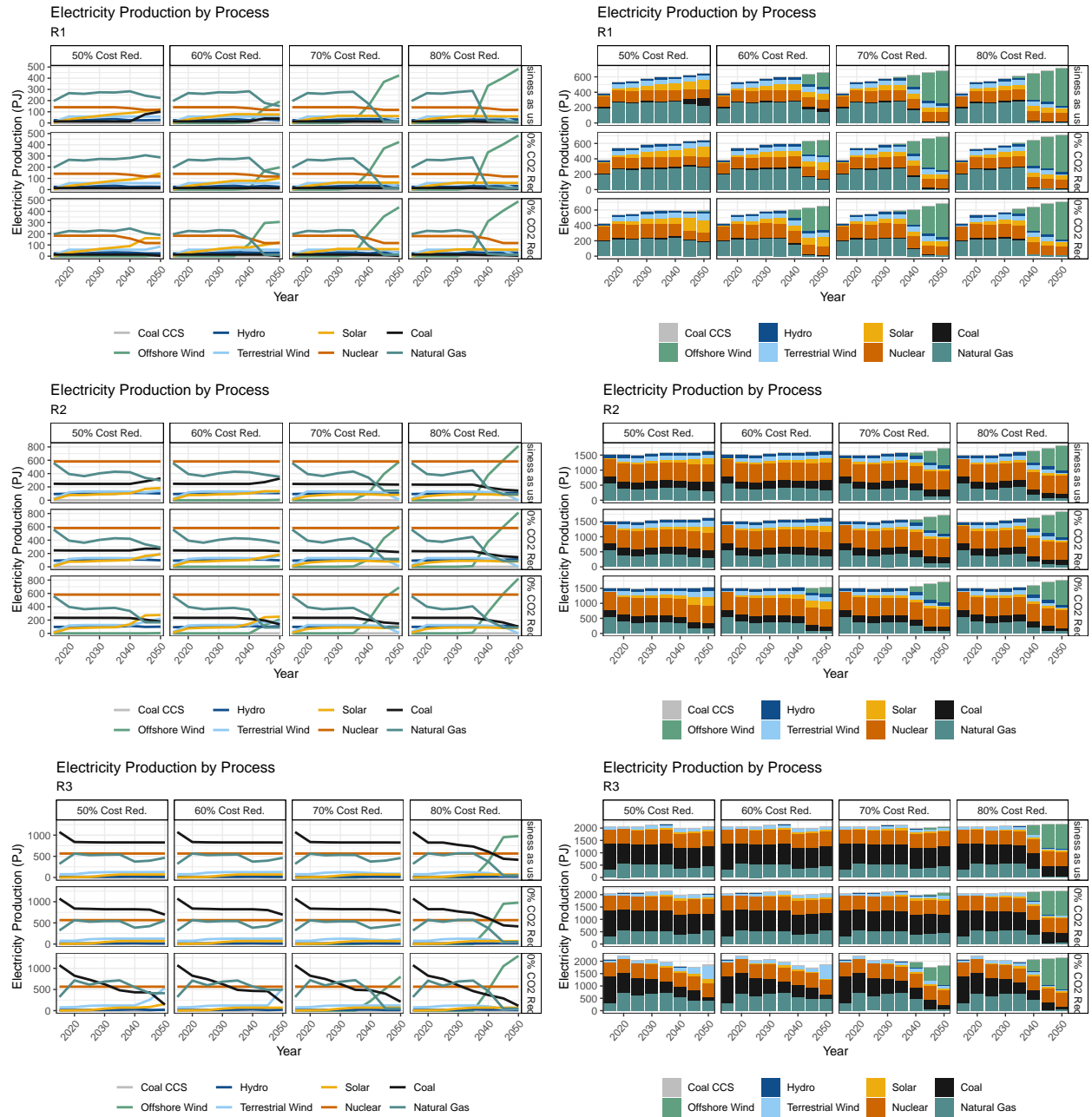
- Coal CCS
- Hydro
- Solar
- Coal
- Offshore Wind
- Terrestrial Wind
- Nuclear
- Natural Gas

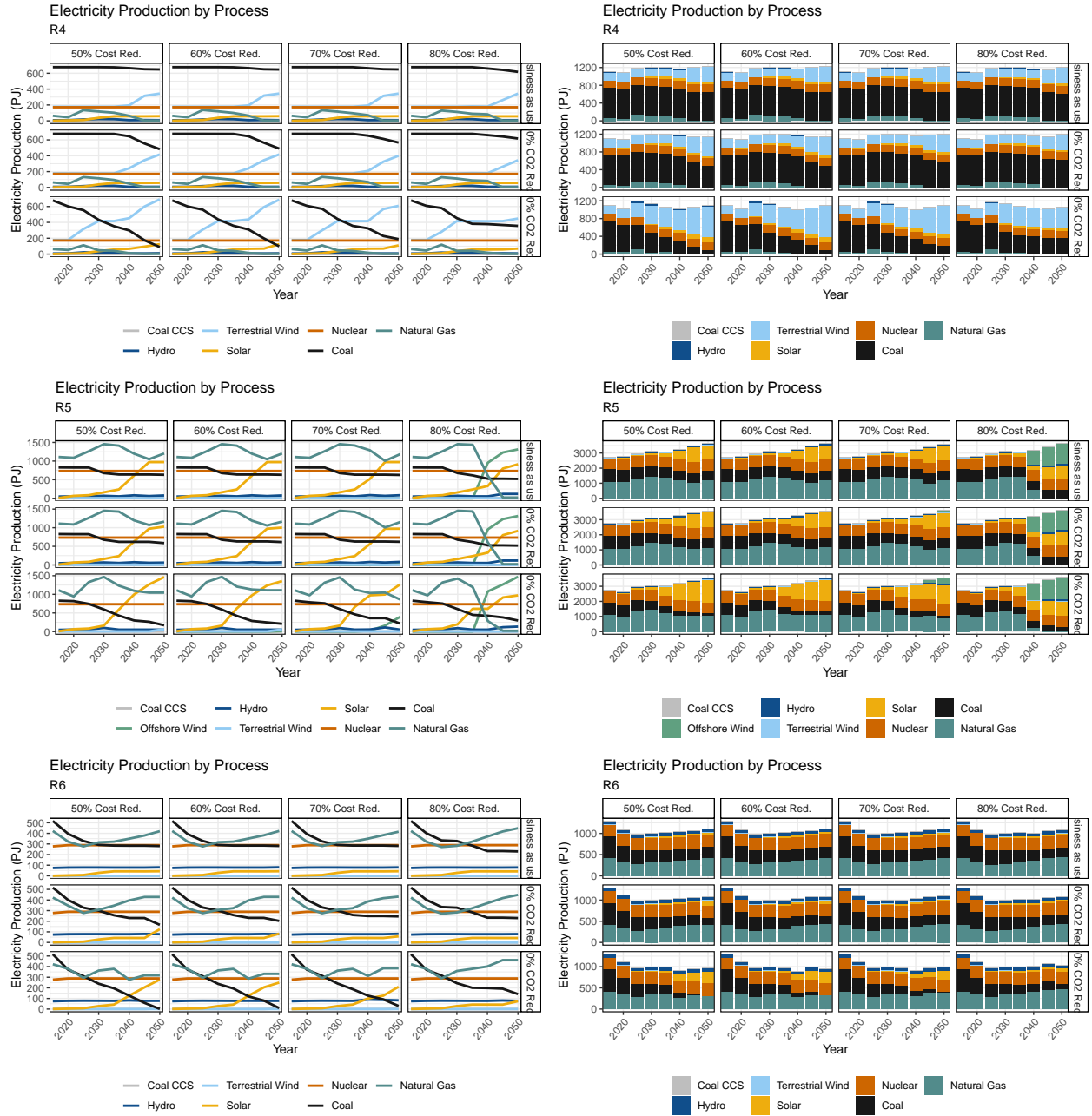
Parsed Set

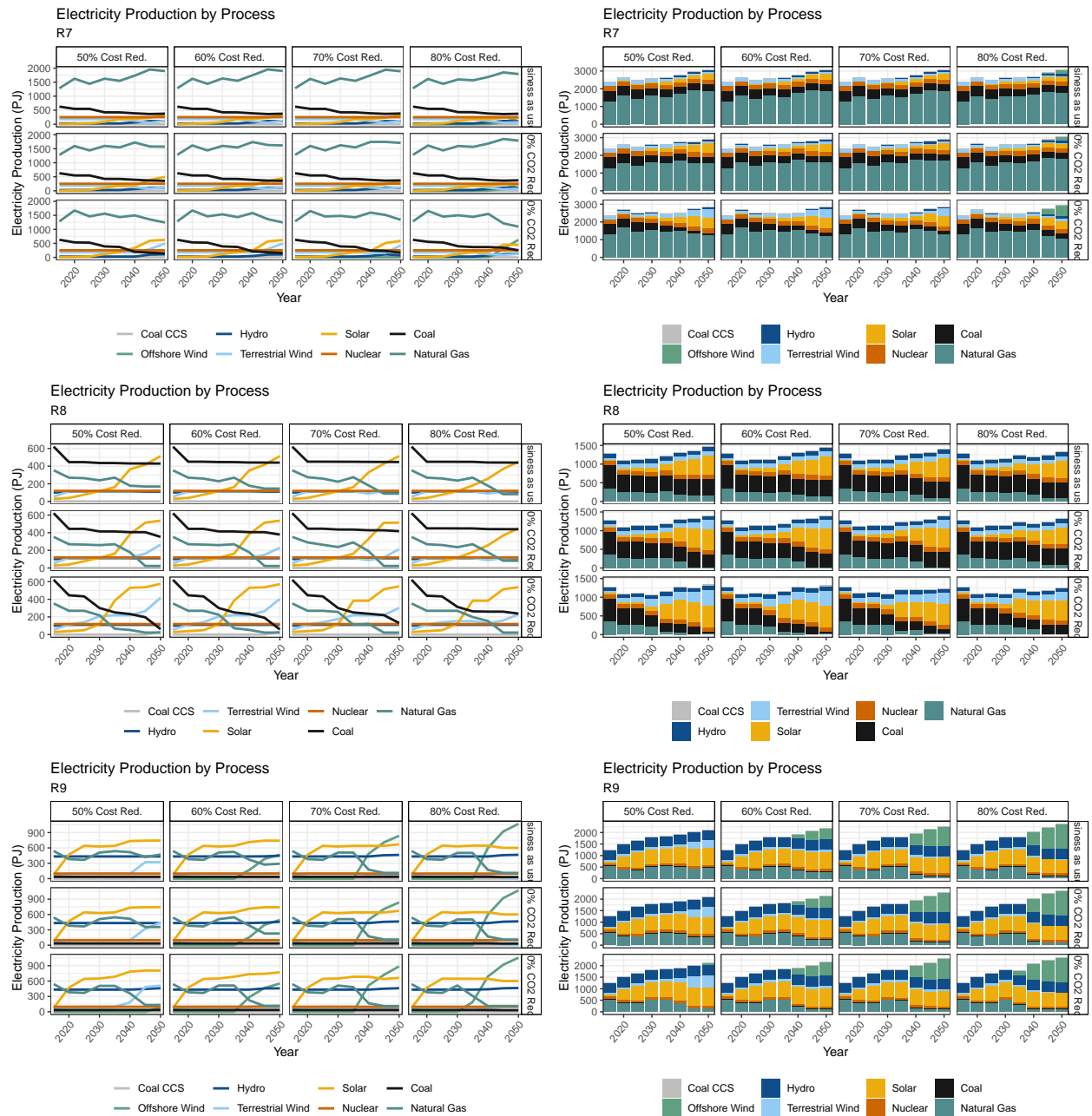
# Electricity Production by Process



## 6.3 Regional Mix

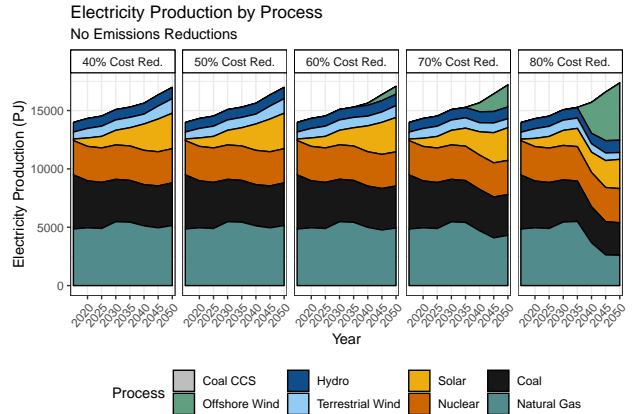
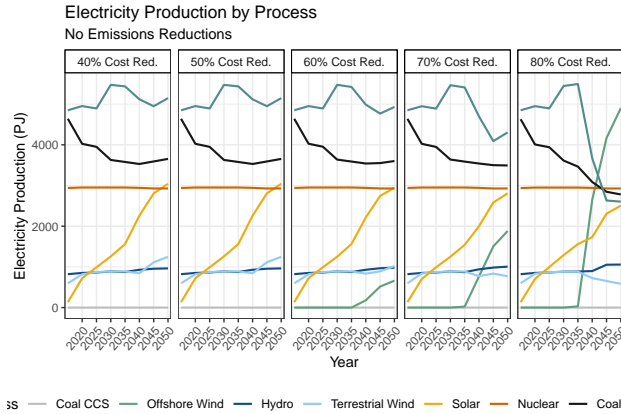




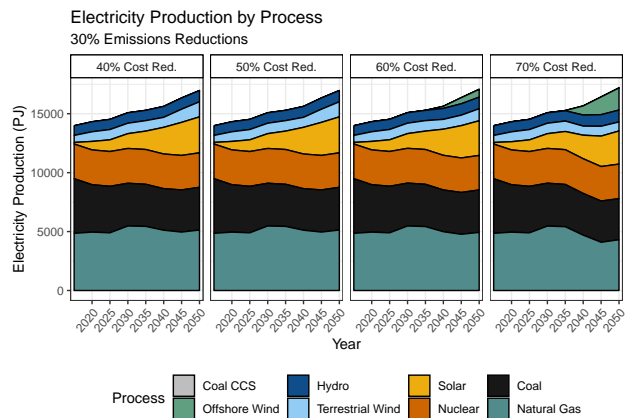
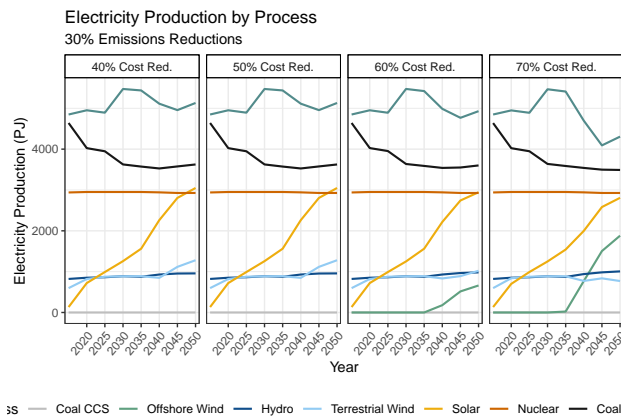


## 6.4 Emissions Cap

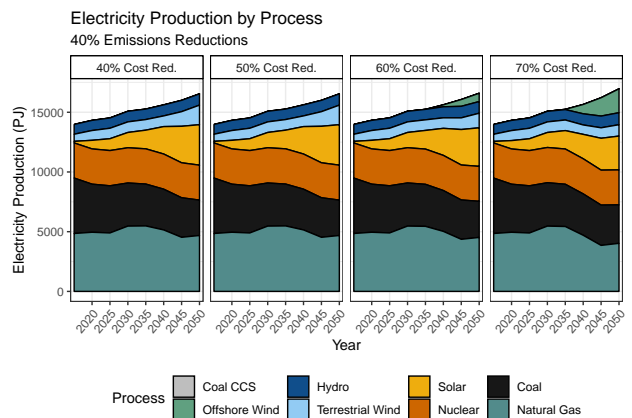
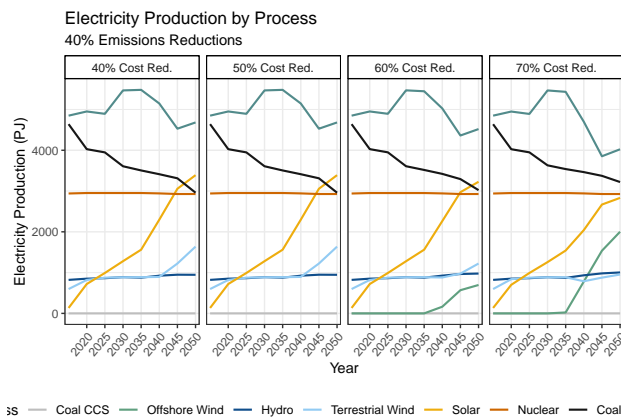
BAU emissions



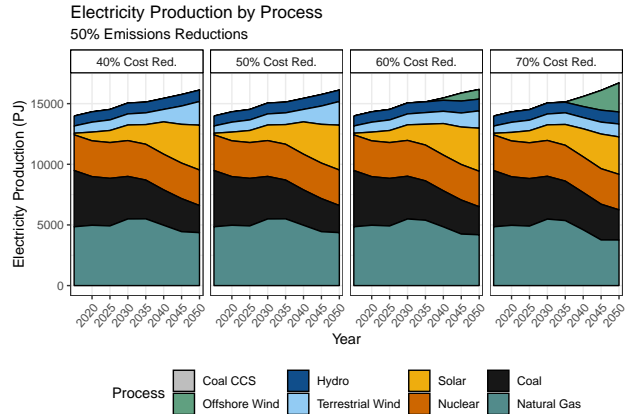
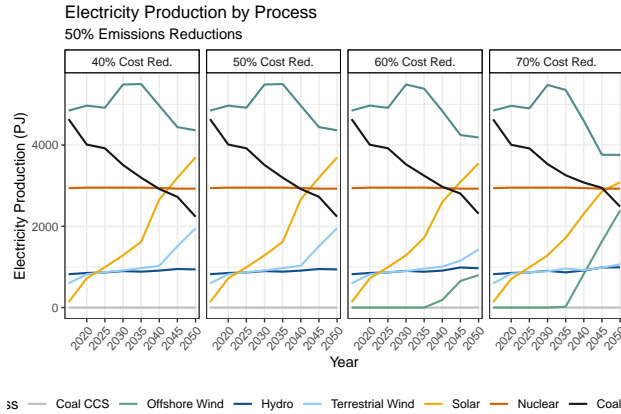
### 30% emissions reduction



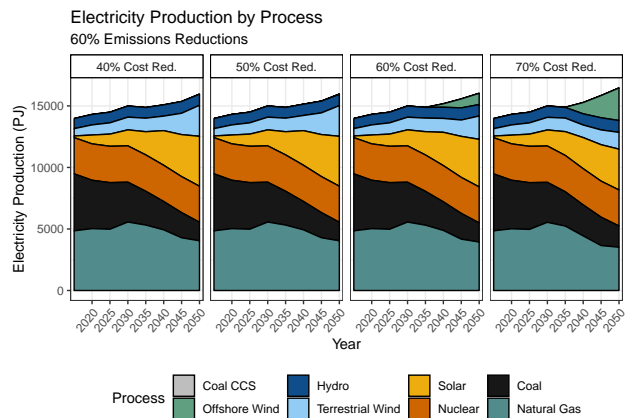
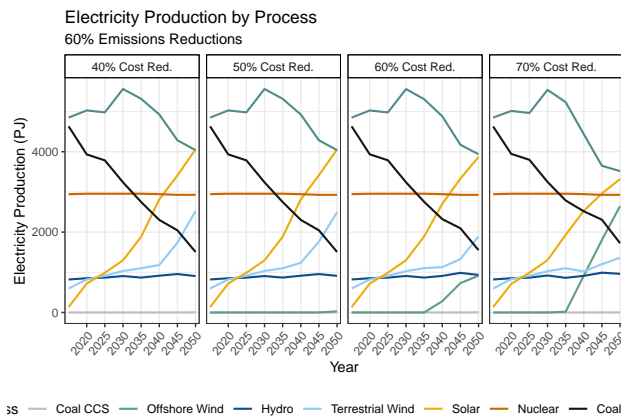
### 40% emissions reduction



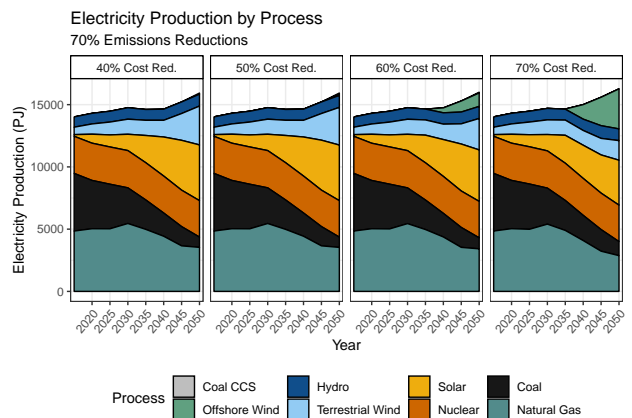
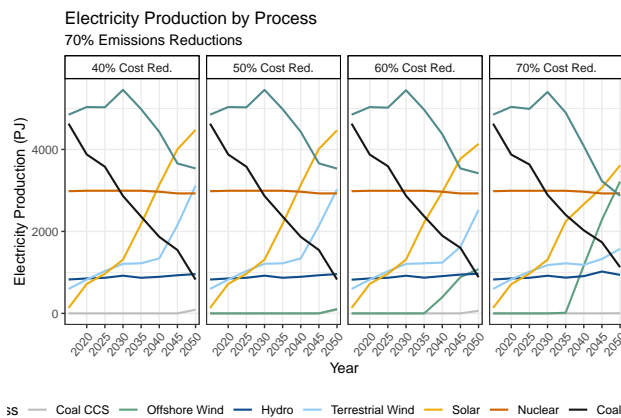
### 50% emissions reduction



## 60% emissions reduction

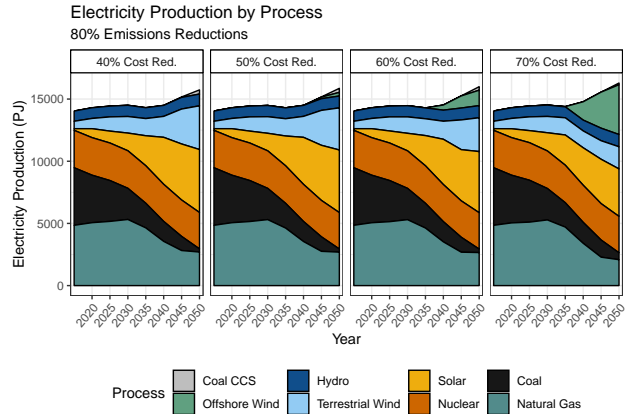
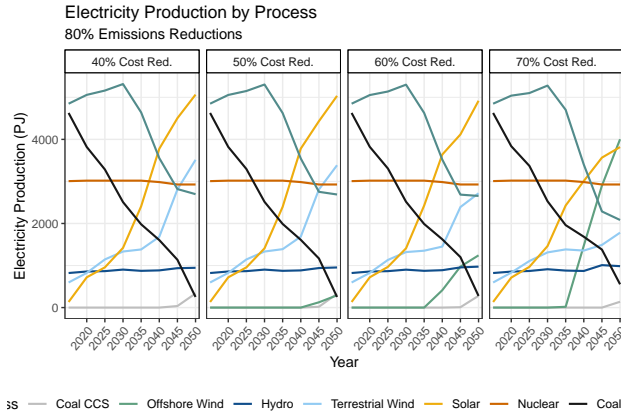


## 70% emissions reduction



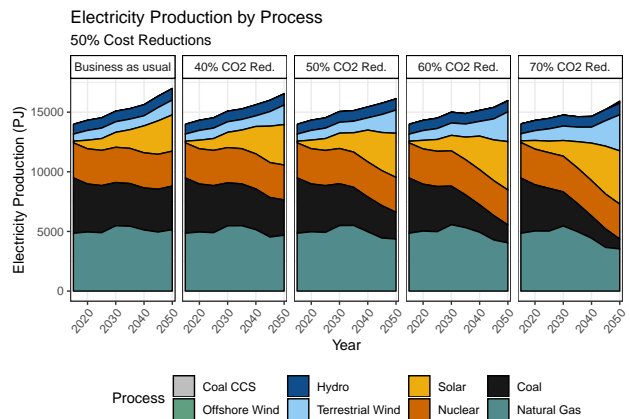
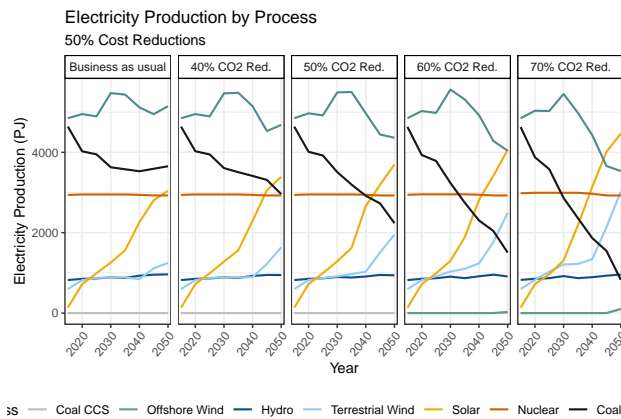
## 80% emissions reduction



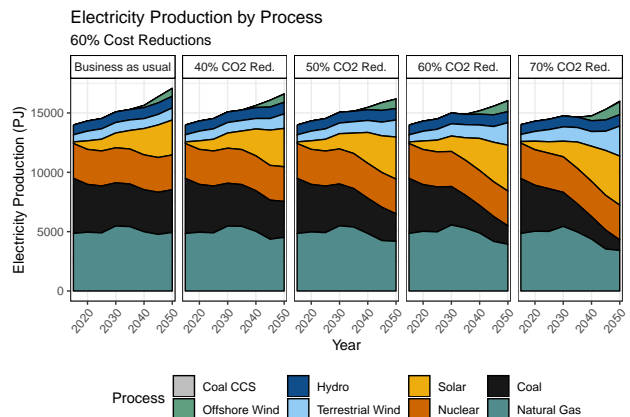
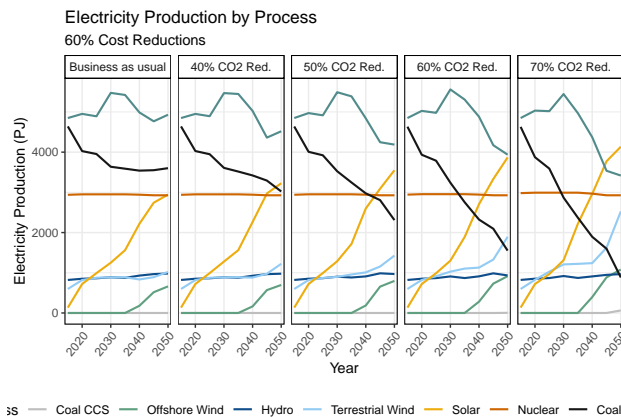


## 6.5 Cost Reductions

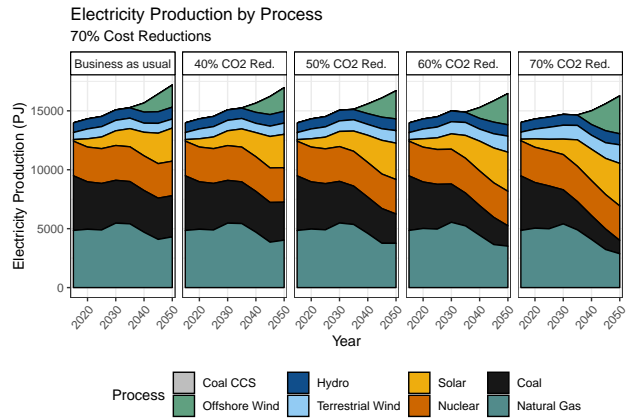
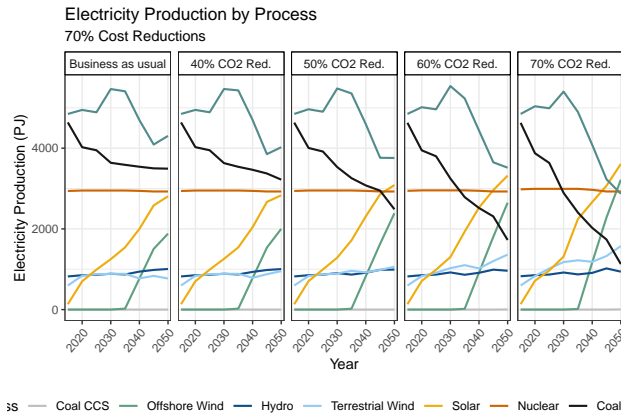
50% cost reduction



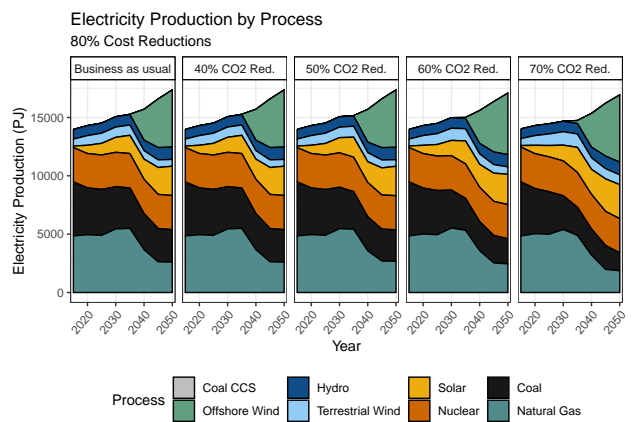
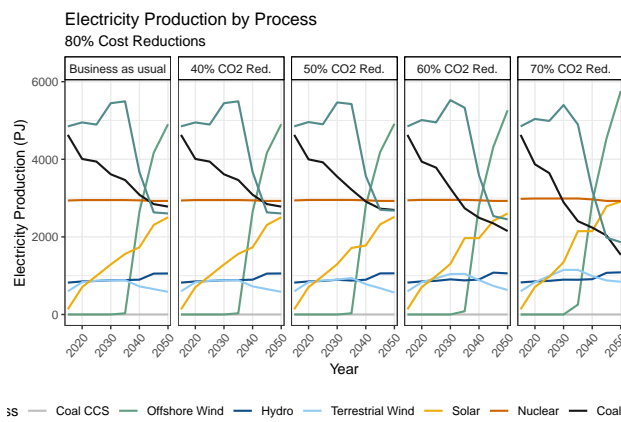
60% cost reduction



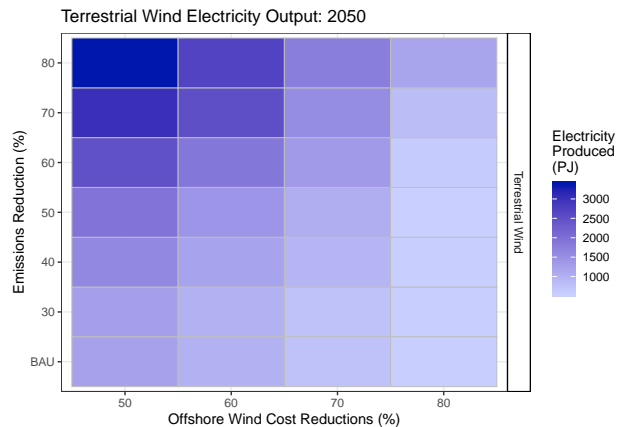
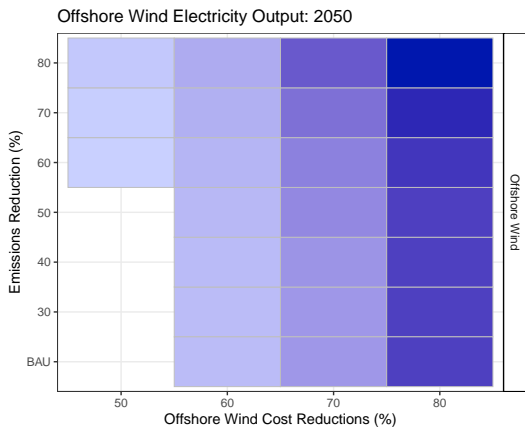
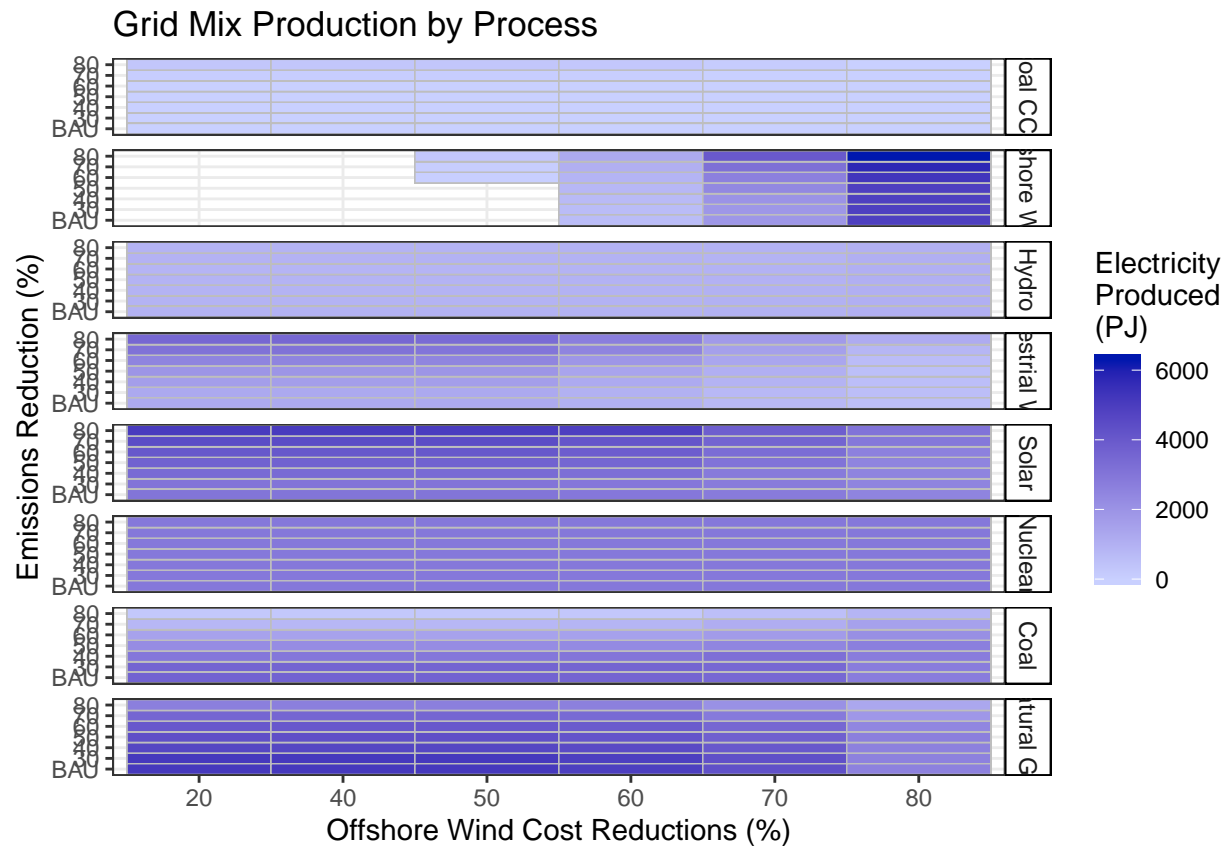
70% cost reduction

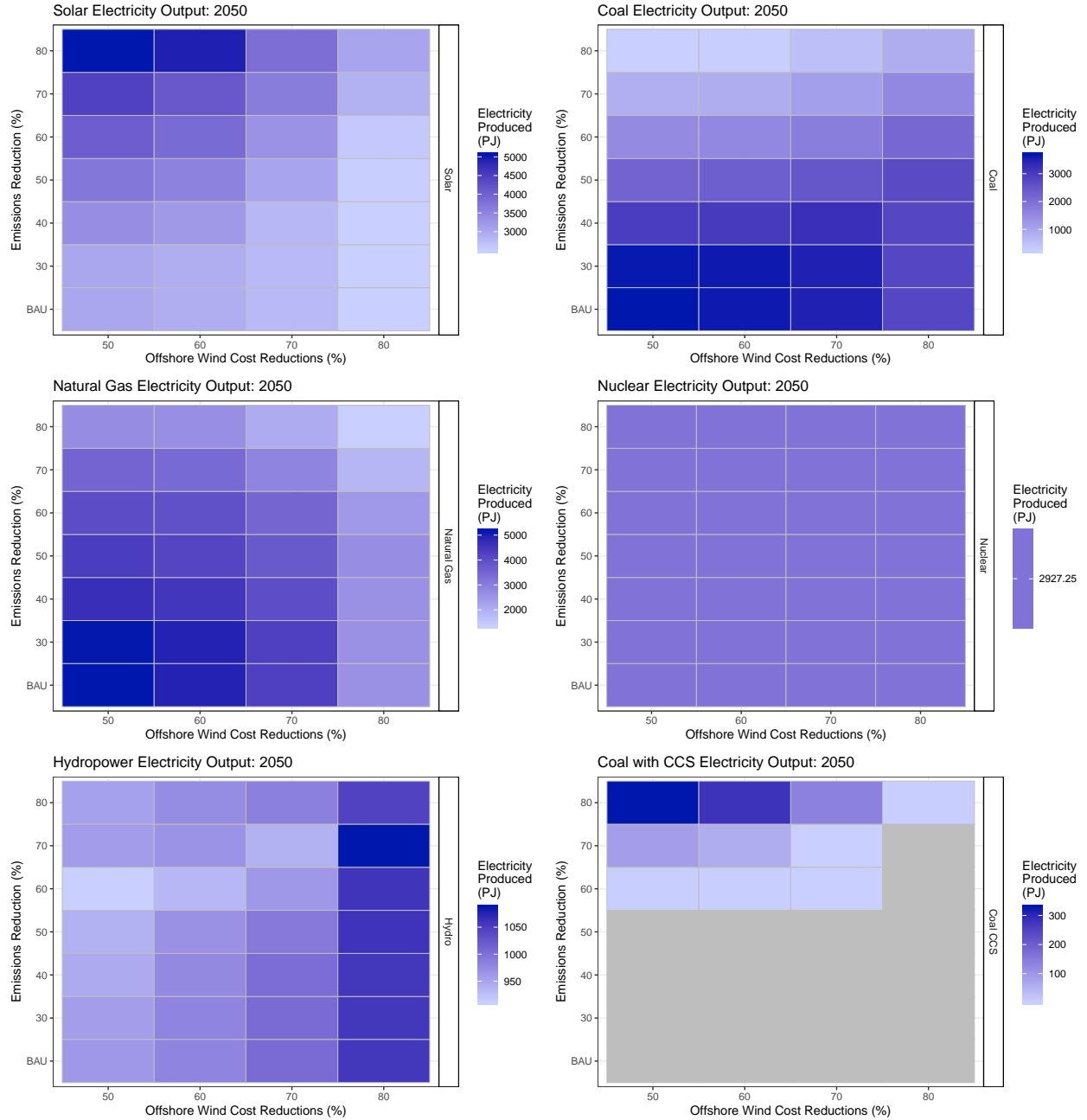


80% cost reduction



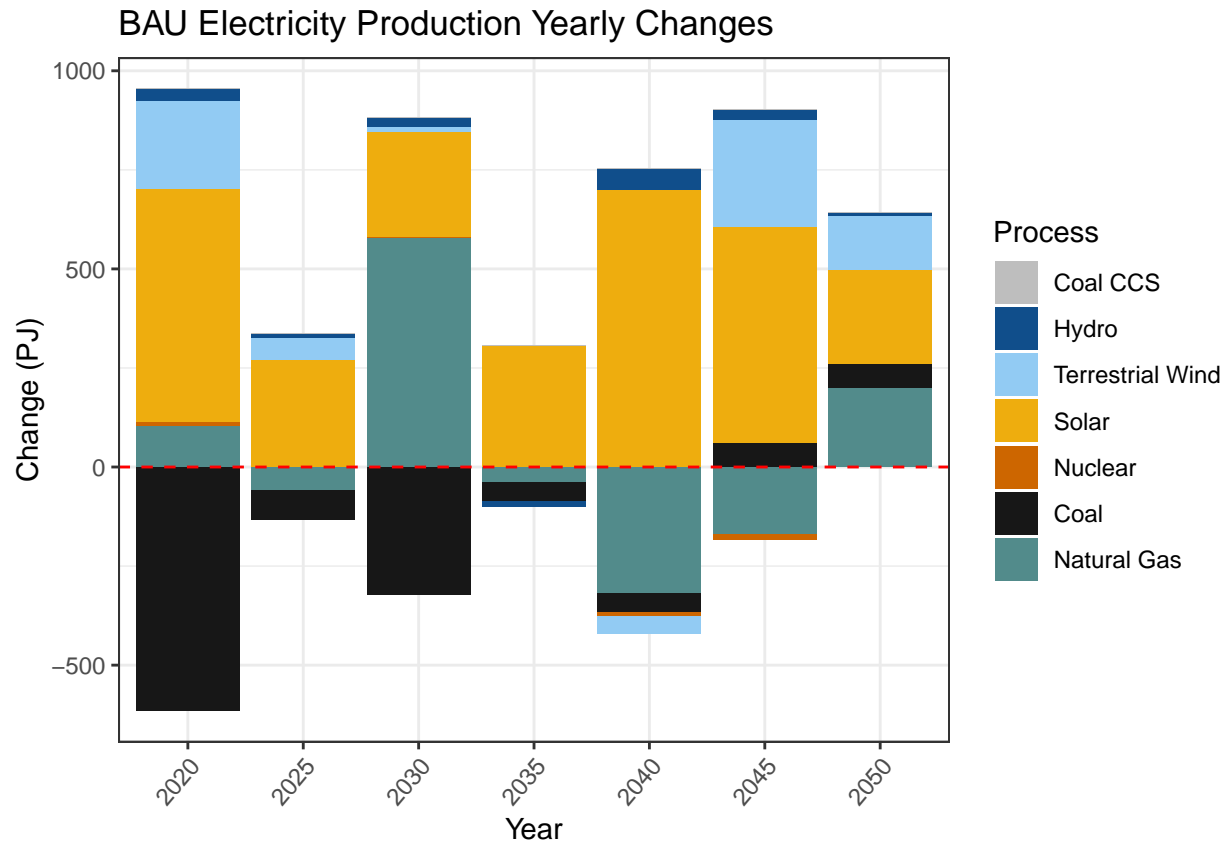
6.6 Heatmaps





## 6.7 Retirements and Additions

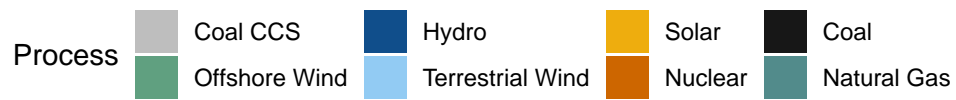
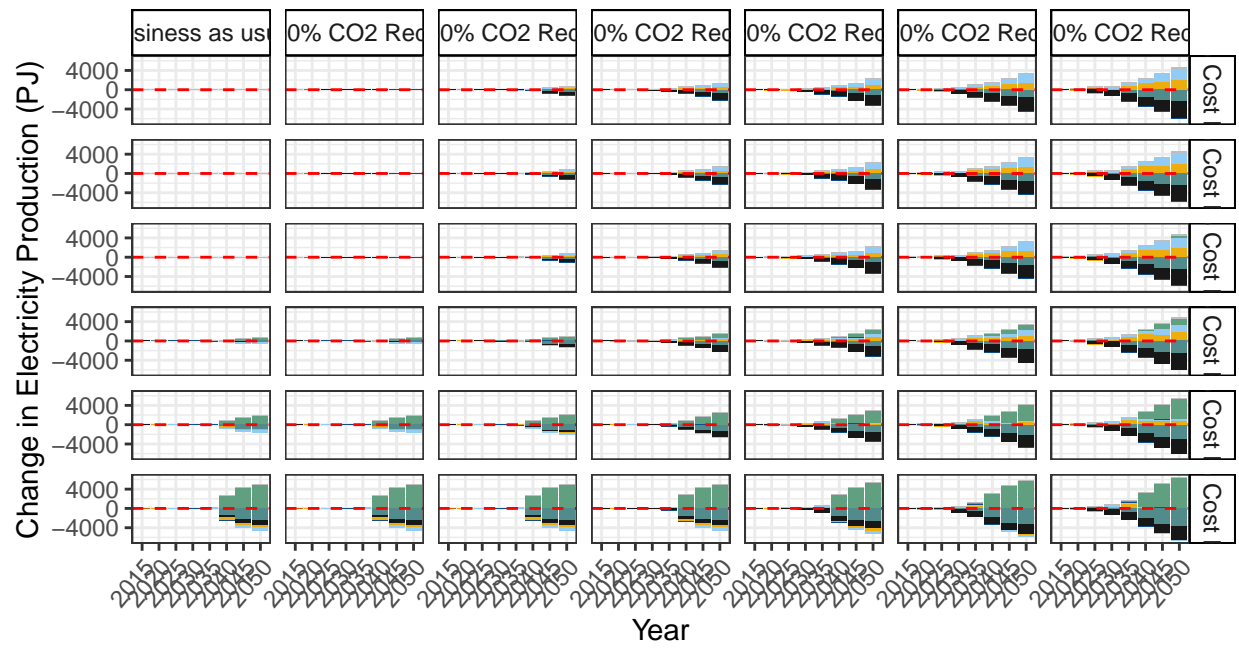
Basecase year-on-year changes in the grid mix. Shows the modeled fluctuations in generation. All following quantifications of grid mix changes are as compared to these changes in the basecase.



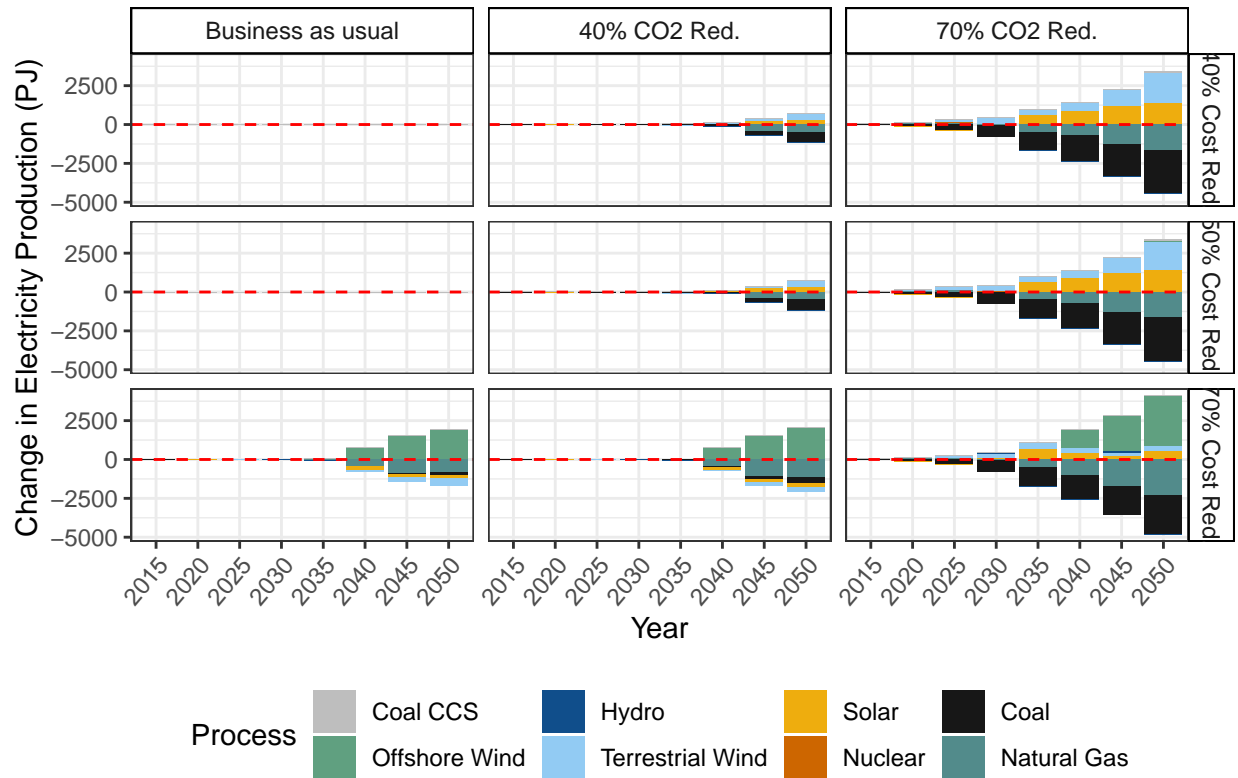
## 6.8 Changes Over Baseline

Summary Graph

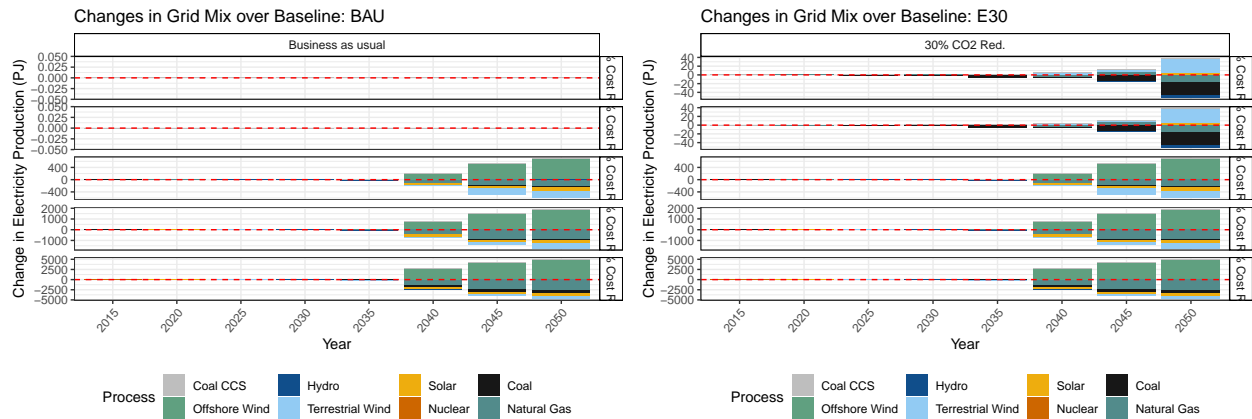
## Changes in Grid Mix over Baseline

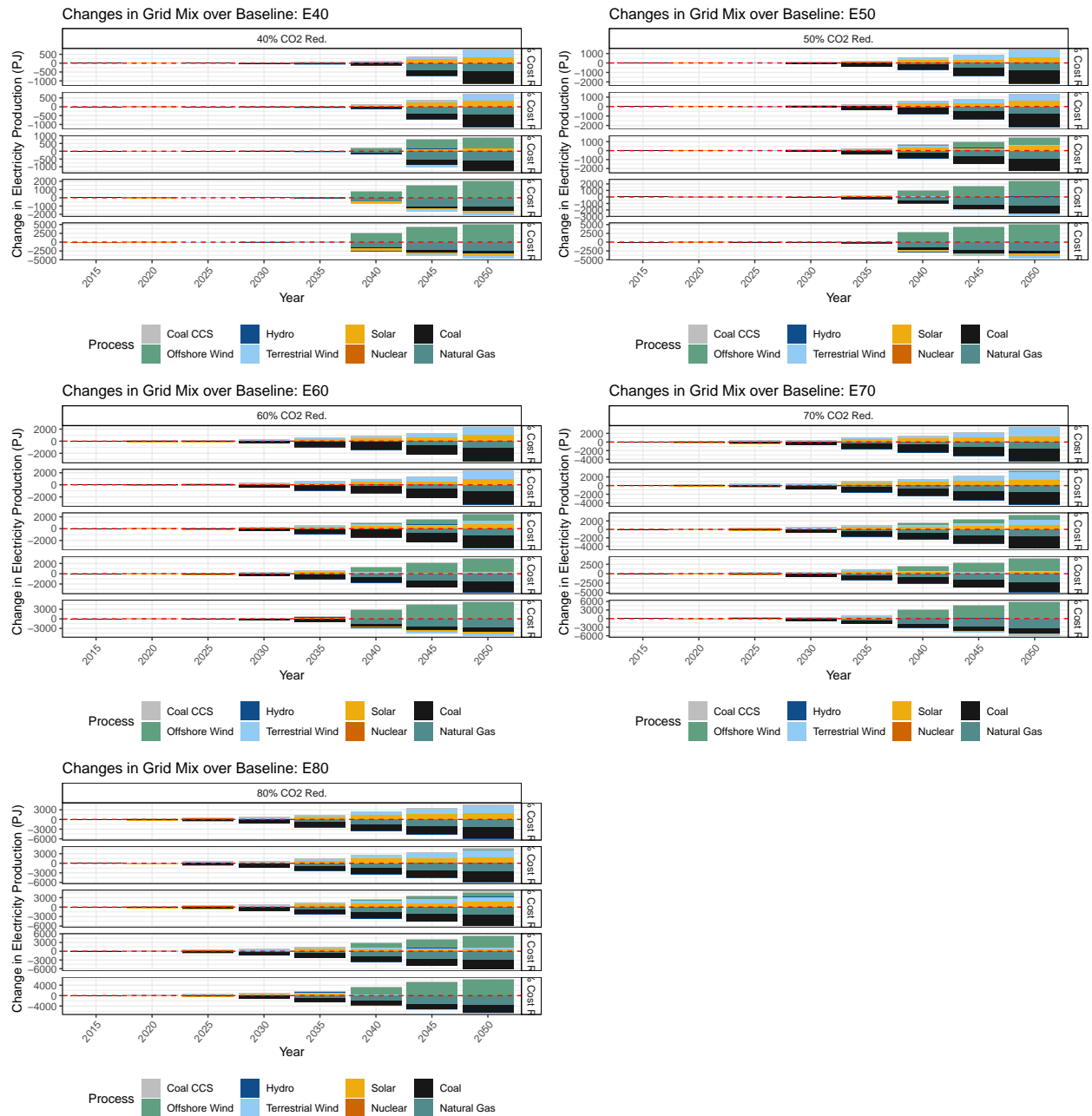


## Changes in Grid Mix over Baseline



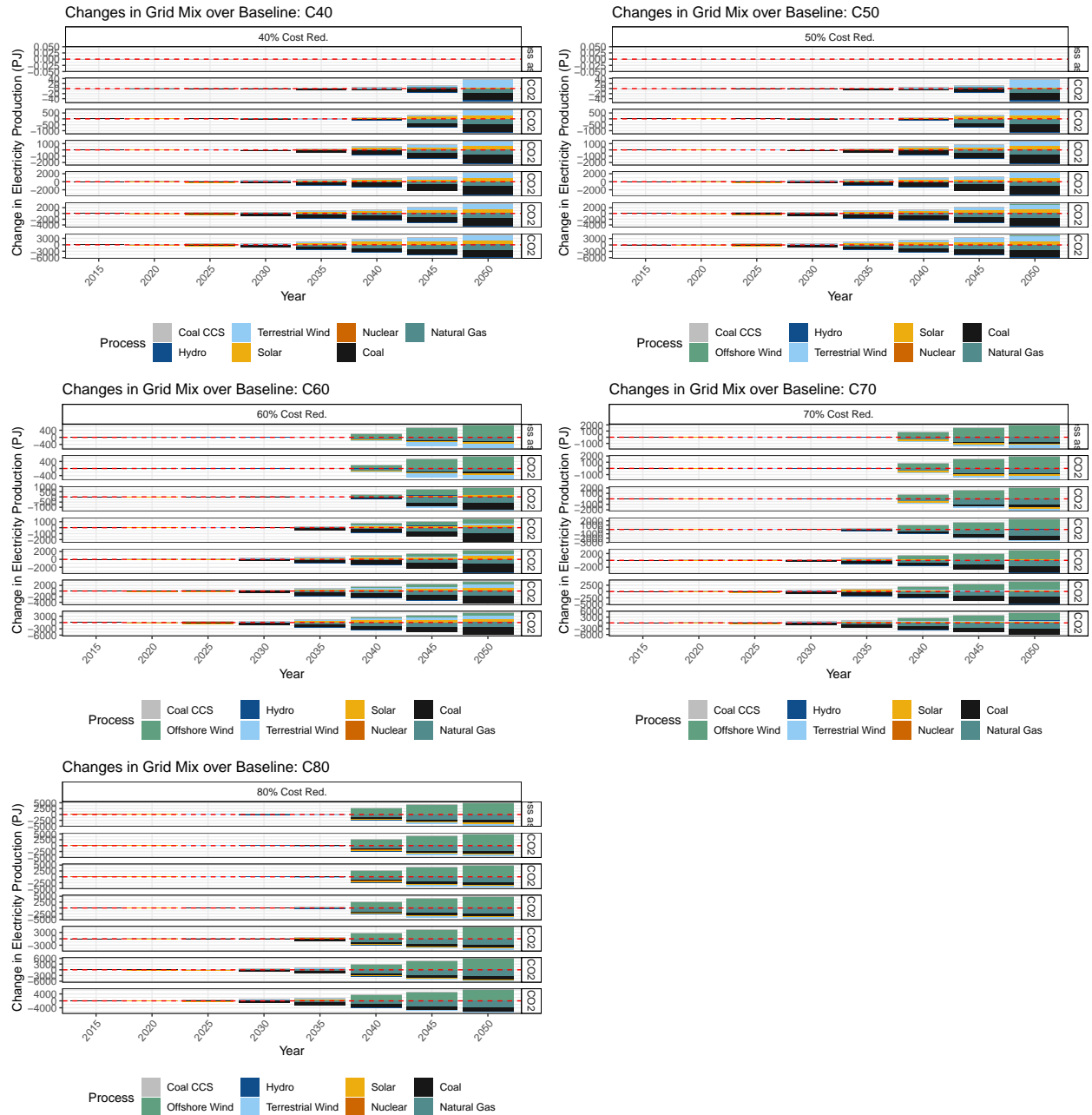
## By Emissions Reduction %





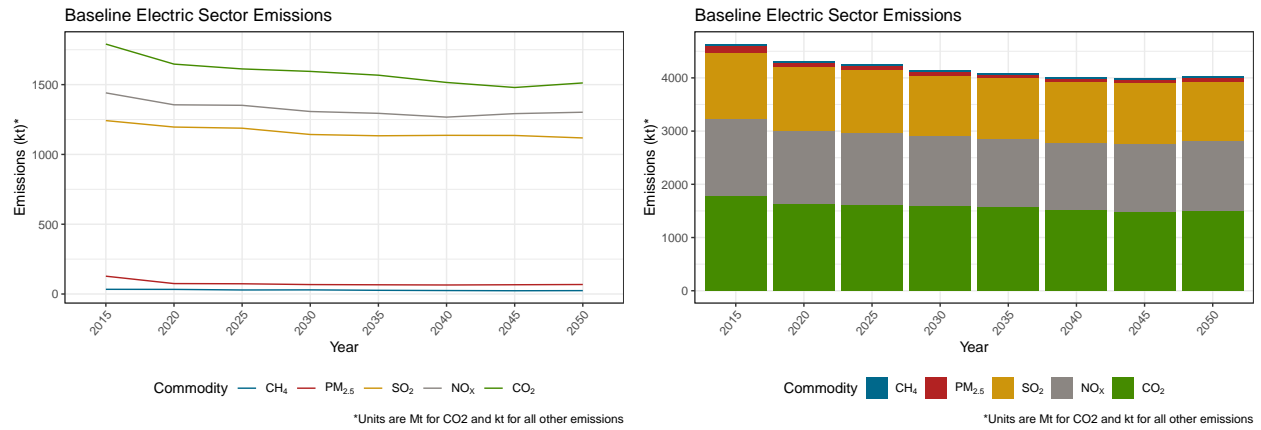
By Cost Reduction %



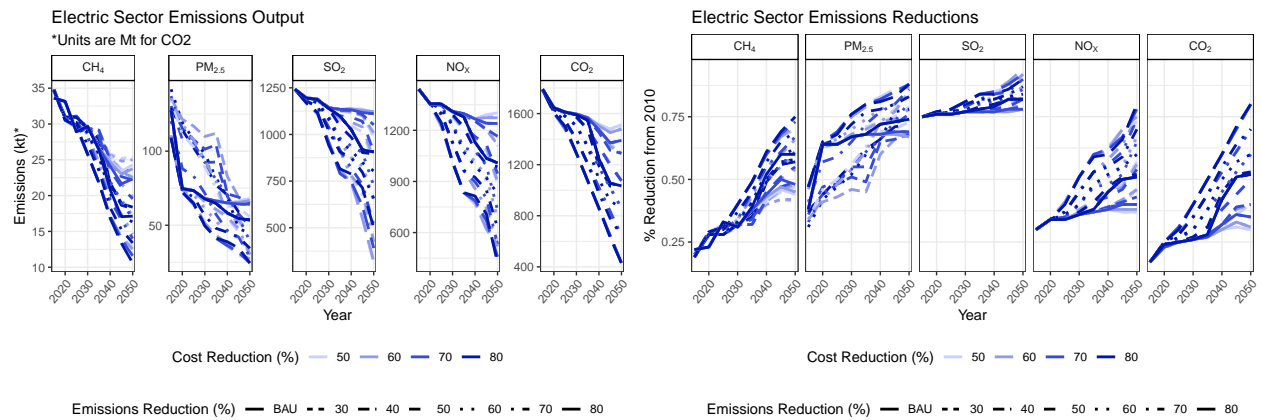


## 7 Emissions

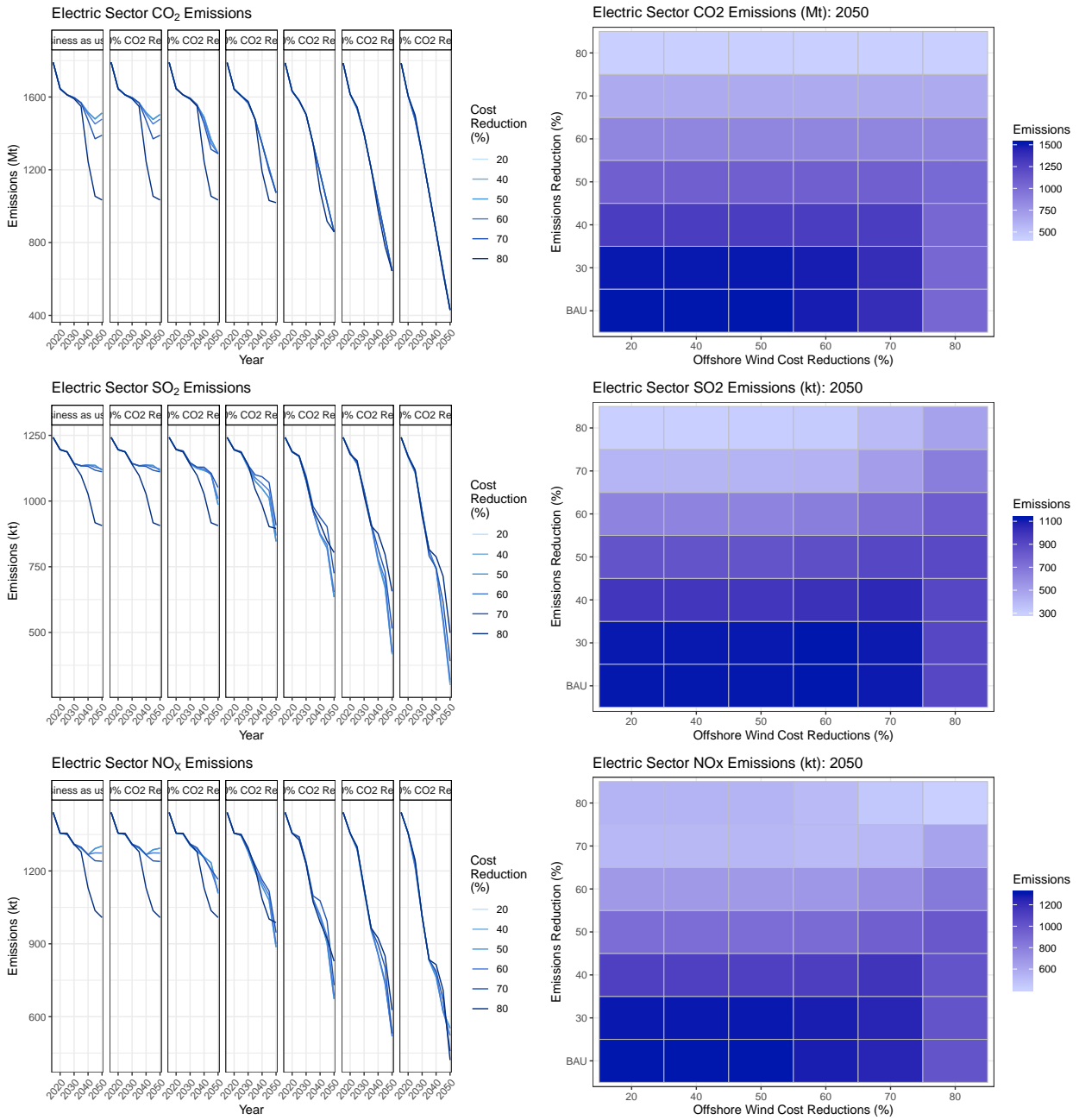
### 7.1 Baseline

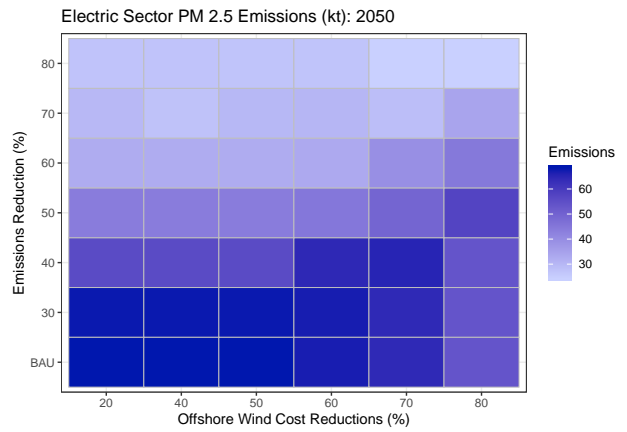
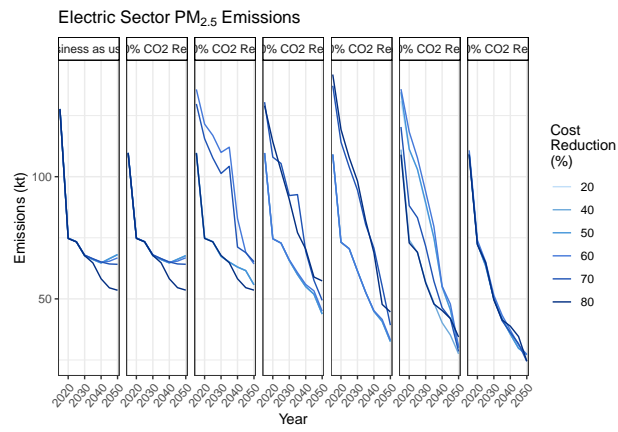
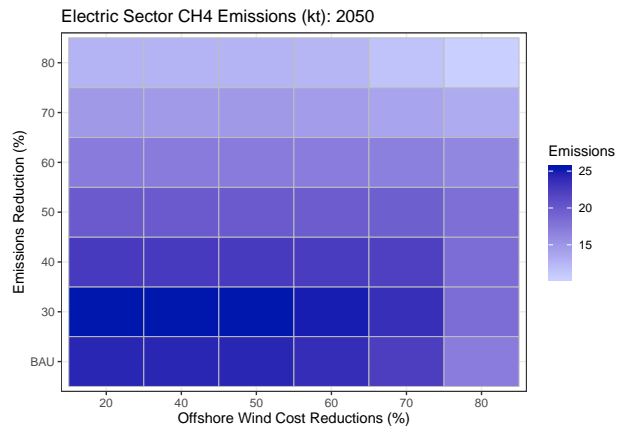
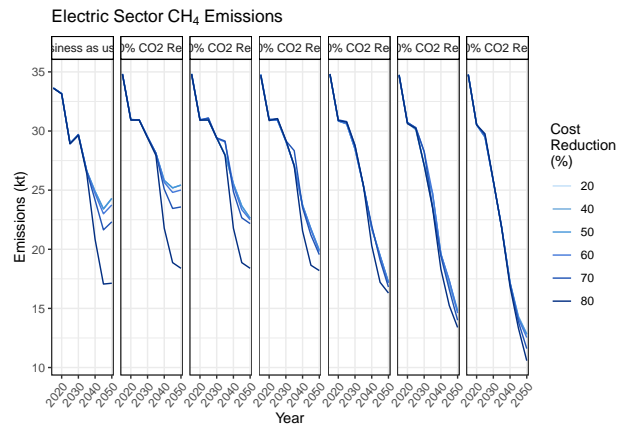


### 7.2 Emissions by Scenario and Commodity

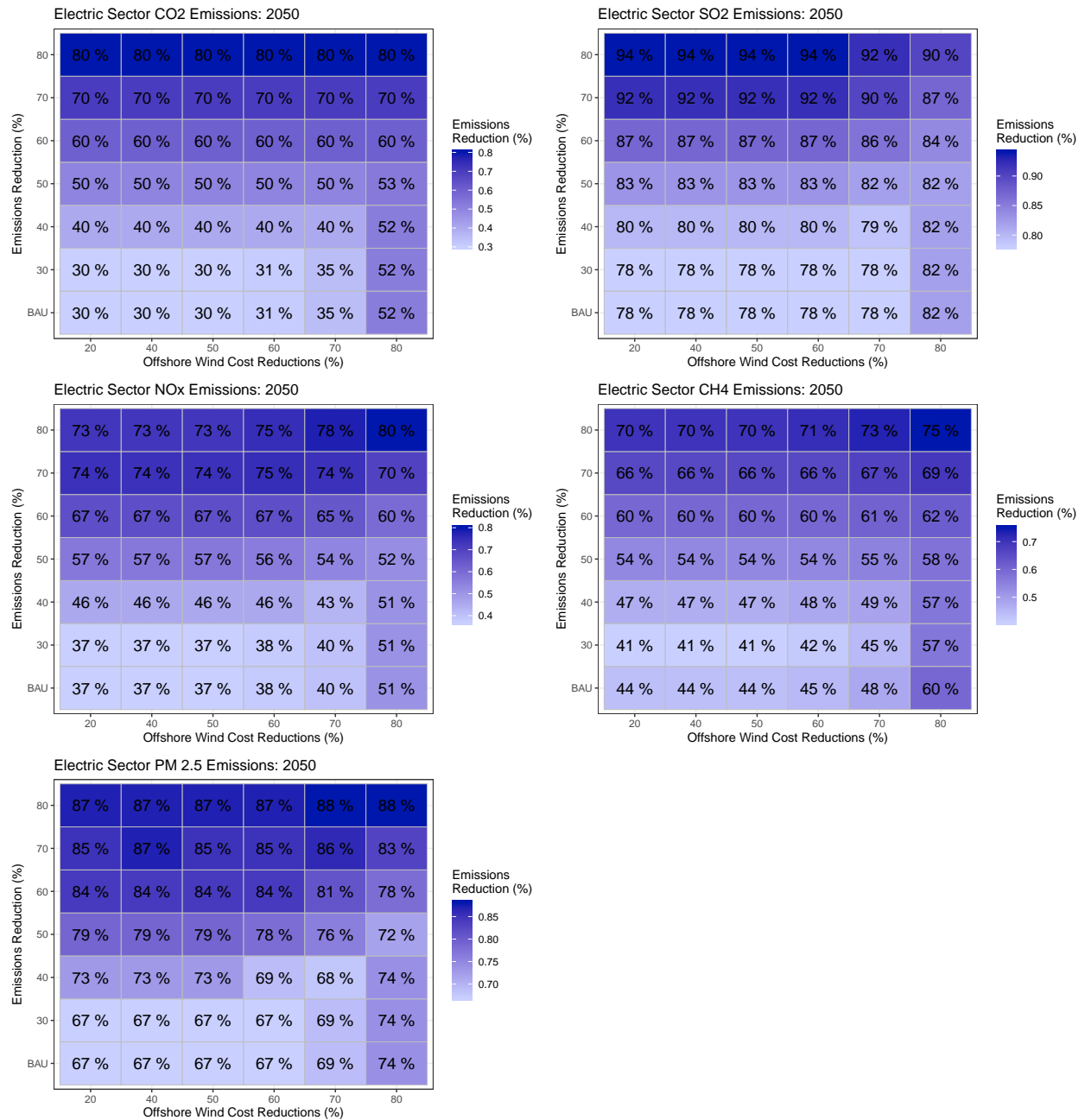


### 7.3 Emissions by Commodity - Values

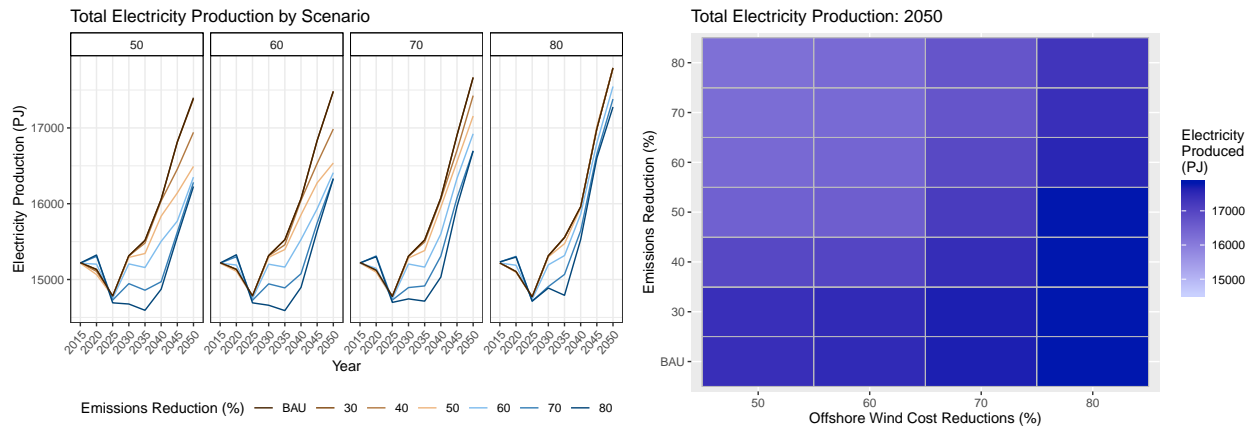




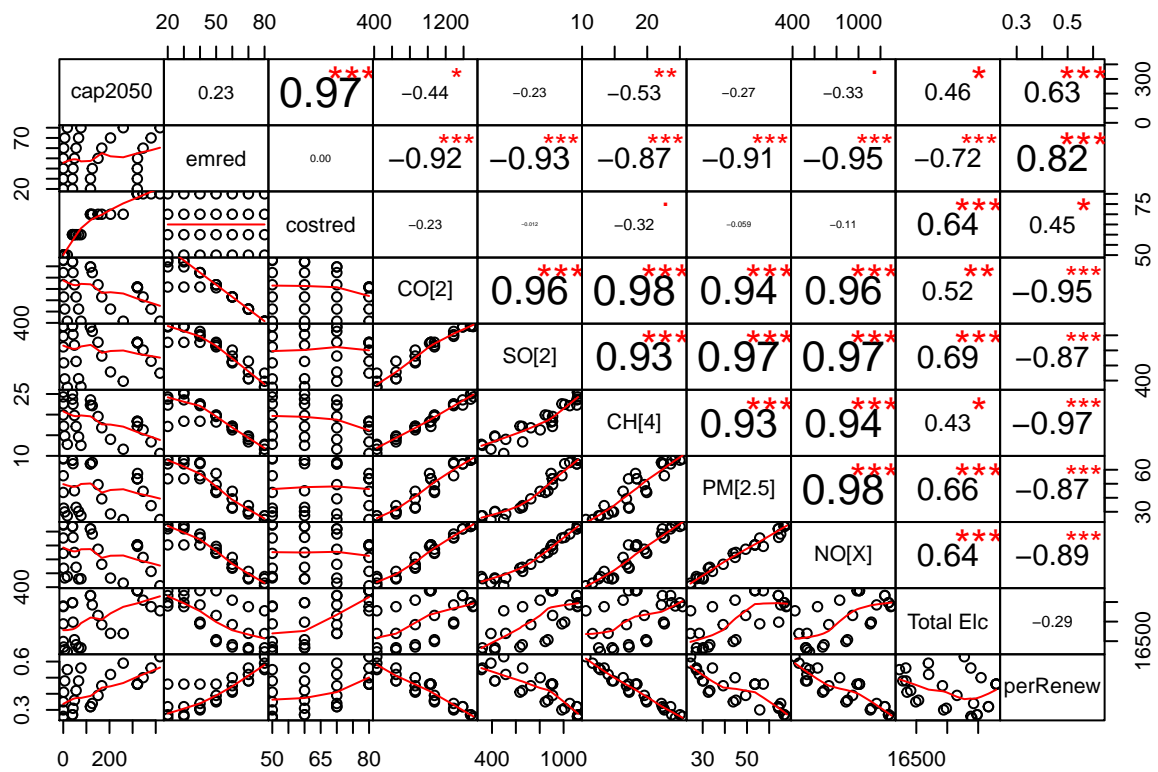
## 7.4 Emissions by Commodity - Percent Reduction



## 8 Total Electricity Production



## 9 Correlation



	OSW Capacity	% Renew	Total Elc
(Intercept)	141.60 *** (7.86)	0.42 *** (0.01)	17079.79 *** (38.62)
emred	24.04 ** (8.00)	0.09 *** (0.01)	-374.63 *** (39.33)
costred	129.73 *** (8.00)	0.05 *** (0.01)	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]
(Intercept)	989.23 *** (21.74)	797.97 *** (19.47)	887.10 *** (18.03)	18.39 *** (0.30)	46.97 *** (1.13)
emred	-318.36 *** (22.49)	-252.57 *** (20.14)	-273.35 *** (18.65)	-3.55 *** (0.31)	-14.38 *** (1.17)
cap2050	-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.