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

Morgan Browning

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Contents

1 Disclosure

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

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

2 Setup

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

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

3 Scenarios

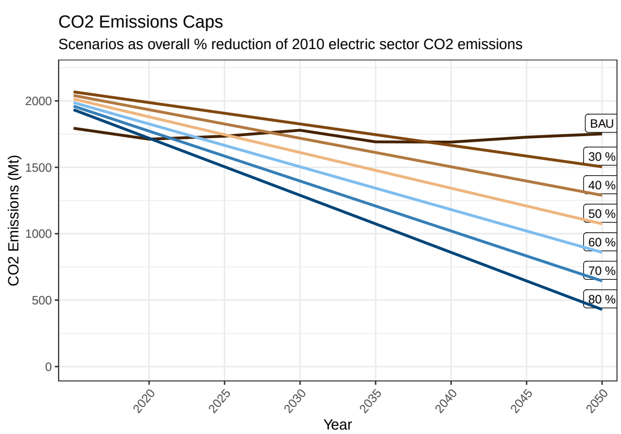
The nested parametric sensitivity analysis was built on combinations of two sets of scenarios:

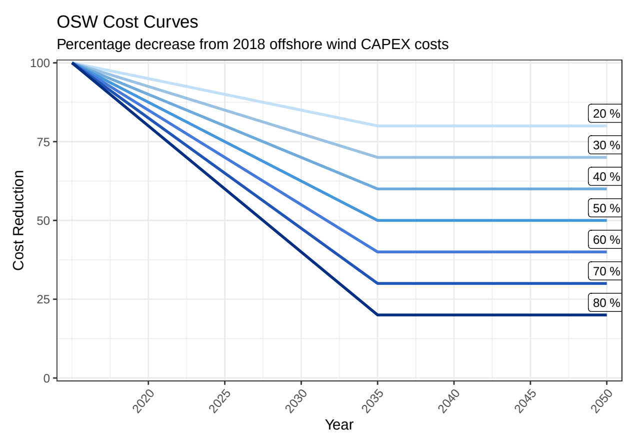
1. Electric sector CO_2 emissions caps, as a linear decrease to a given % decrease from 2010 emissions by 2050

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

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

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





4 LCOE

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

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

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

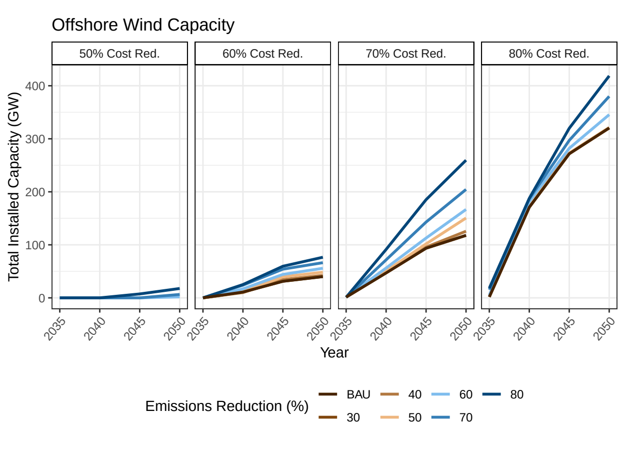
Note:
U.S. EIA Annual Energy Outlook 2019

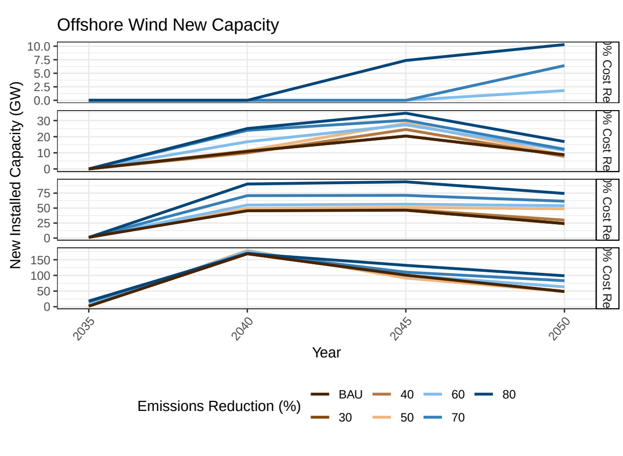
5 Offshore Wind

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

5.1 Capacity Buildout

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





5.2 Total Capacity

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

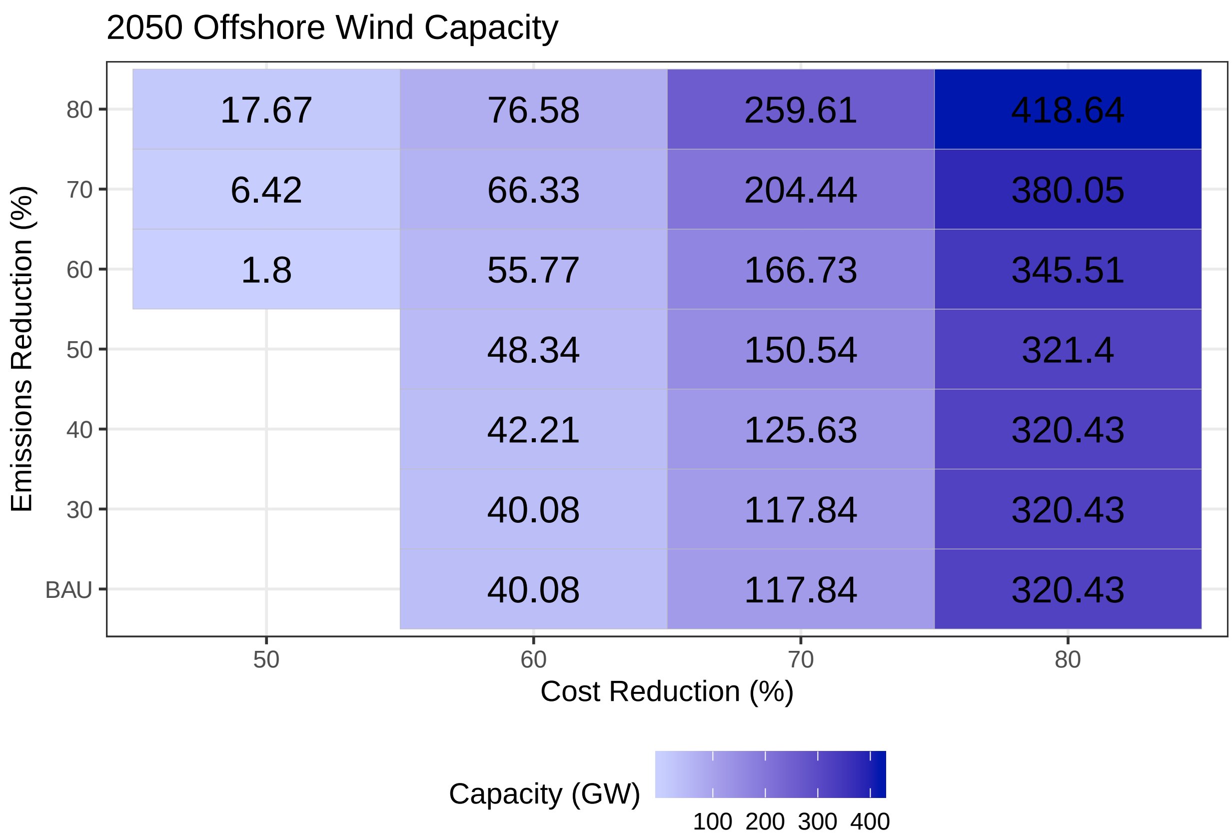


Table 2: Offshore Wind Total Installed Capacity (GW): 2050

CO2 Emissions Reduction (%)	Cost Reduction (%)			
	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.

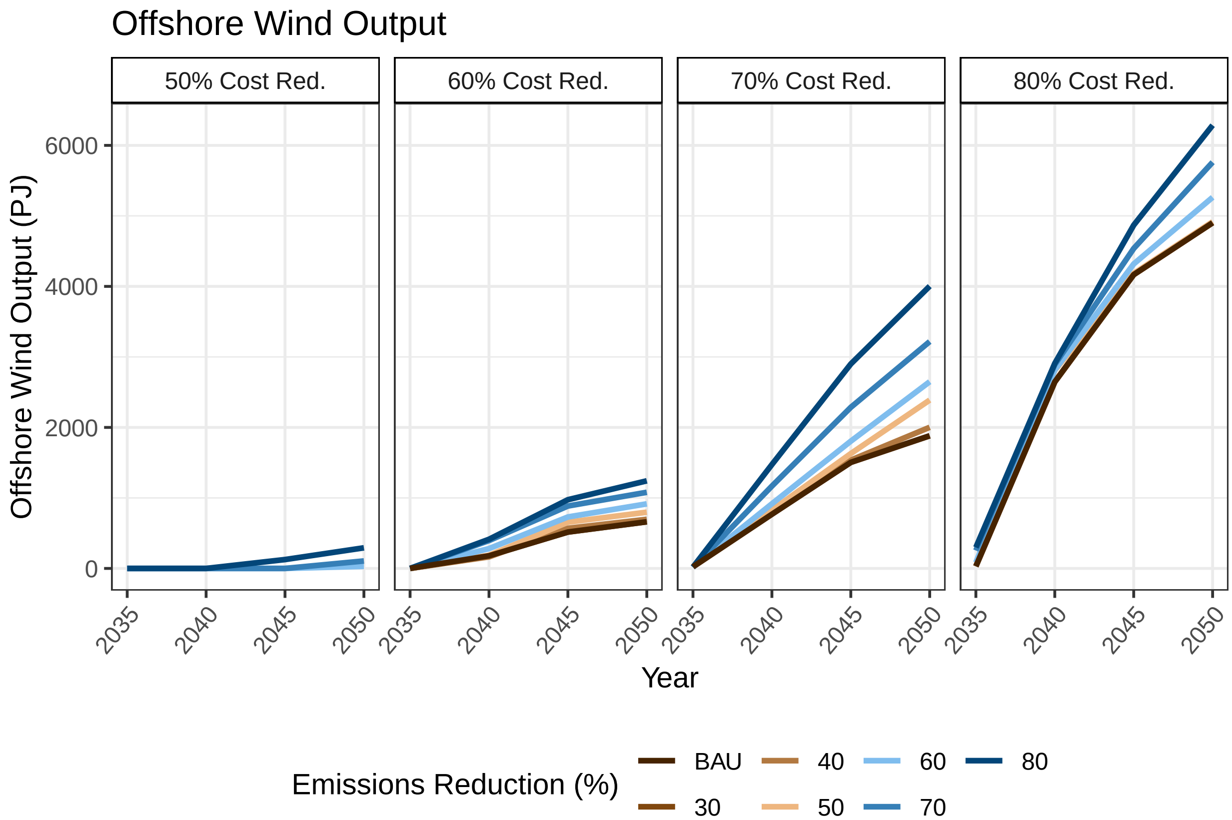
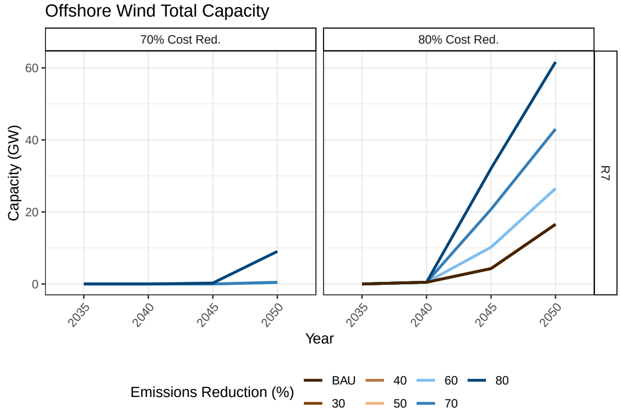


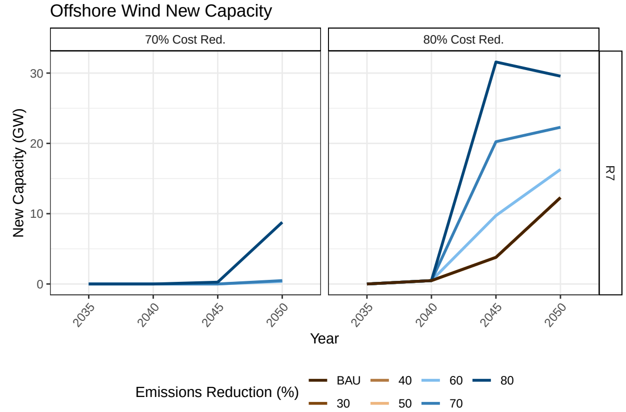
Table 3: Offshore Wind Total Output (PJ): 2050

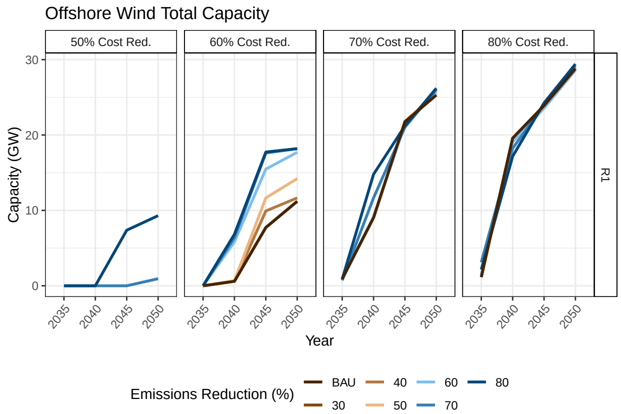
CO2 Emissions Reduction (%)	Cost Reduction (%)			
	50	60	70	80
BAU	NA	661.5	1881.1	4902.4
30	NA	661.5	1881.1	4902.4
40	NA	696.8	2001.7	4902.4
50	NA	797.6	2387.9	4917.0
60	29.4	915.7	2648.6	5263.3
70	105.9	1079.9	3217.6	5761.1
80	292.3	1242.4	4003.5	6285.8

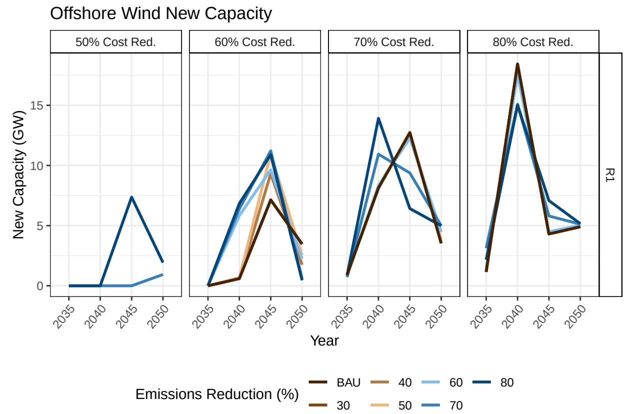
5.4 Regions

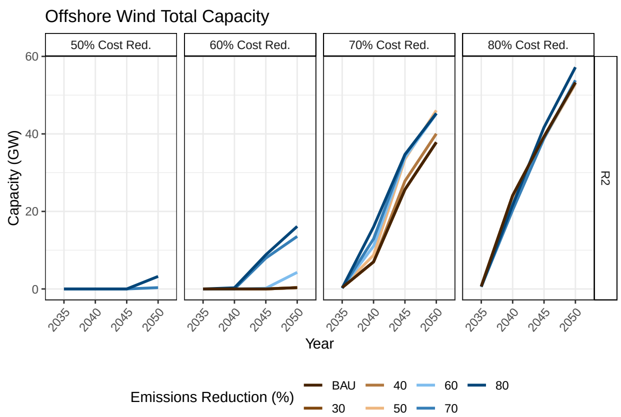
Cumulative and new addition offshore wind capacity by region. Regions are listed from least to highest electricity output.

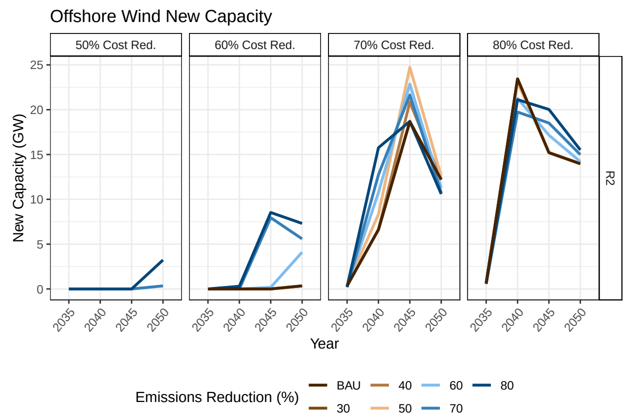

Offshore Wind Total Capacity
70% Cost Red.
80% Cost Red.
R7
Capacity (GW)
0
20
40
60
2035
2040
2045
2050
Year
Emissions Reduction (%)
BAU
30
40
50
60
70
80

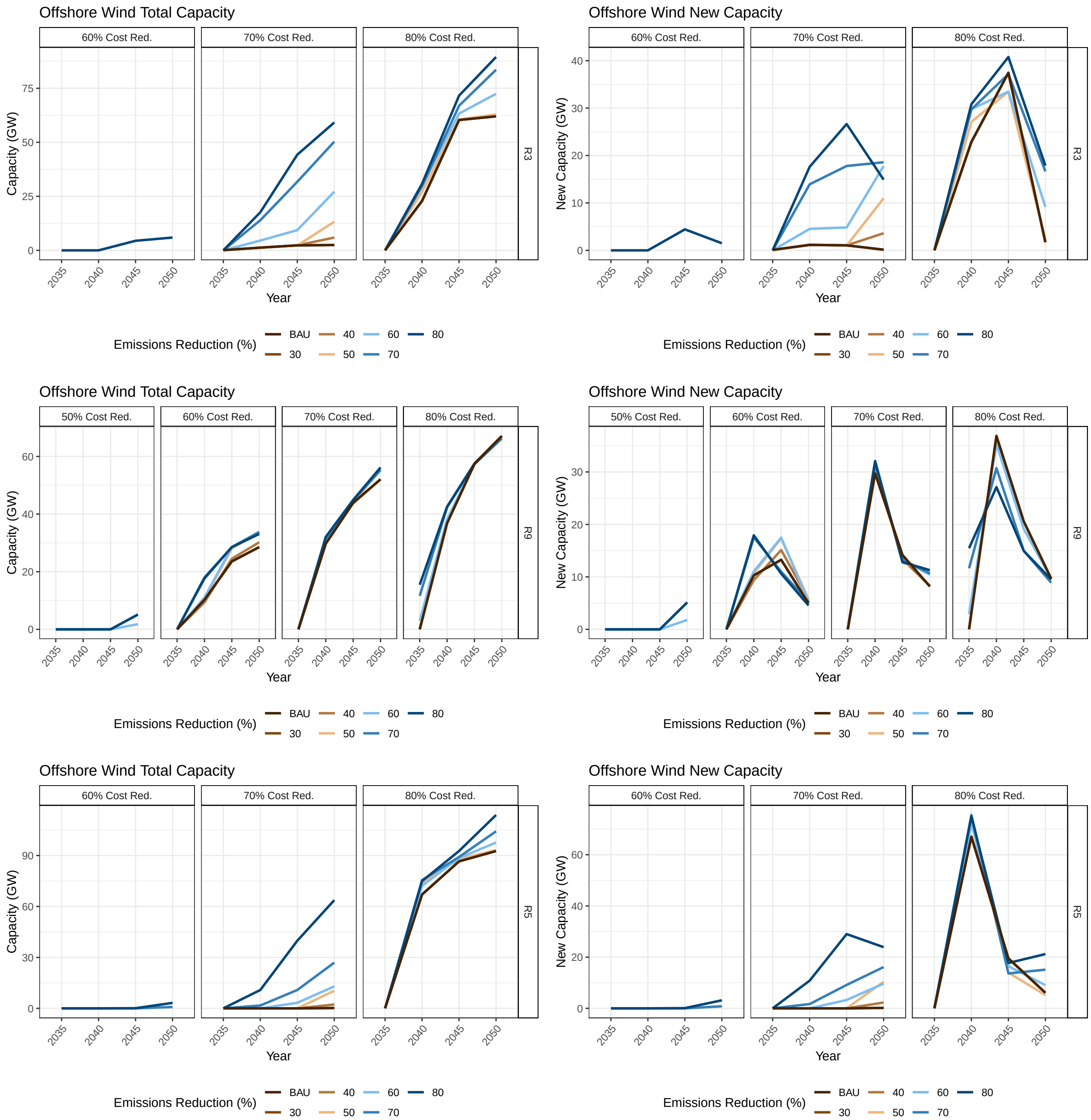

Offshore Wind New Capacity
70% Cost Red.
80% Cost Red.
R7
New Capacity (GW)
0
10
20
30
2035
2040
2045
2050
Year
Emissions Reduction (%)
BAU
30
40
50
60
70
80


Offshore Wind Total Capacity
50% Cost Red.
60% Cost Red.
70% Cost Red.
80% Cost Red.
R1
Capacity (GW)
0
10
20
30
2035
2040
2045
2050
Year
Emissions Reduction (%)
BAU
30
40
50
60
70
80

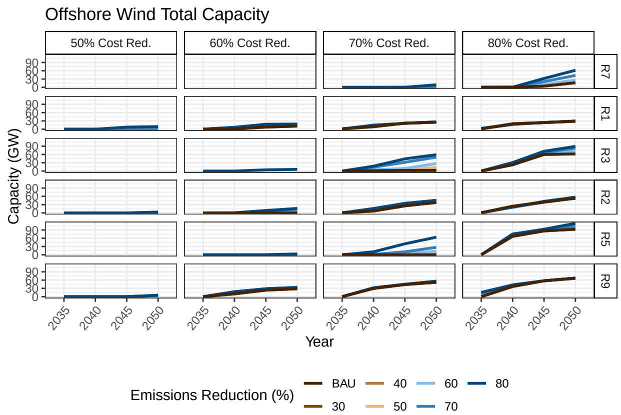

Offshore Wind New Capacity
50% Cost Red.
60% Cost Red.
70% Cost Red.
80% Cost Red.
R1
New Capacity (GW)
0
5
10
15
2035
2040
2045
2050
Year
Emissions Reduction (%)
BAU
30
40
50
60
70
80

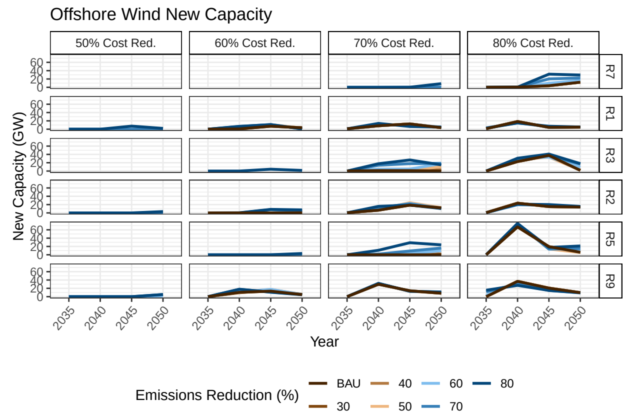

Offshore Wind Total Capacity
50% Cost Red.
60% Cost Red.
70% Cost Red.
80% Cost Red.
R2
Capacity (GW)
0
20
40
60
2035
2040
2045
2050
Year
Emissions Reduction (%)
BAU
30
40
50
60
70
80

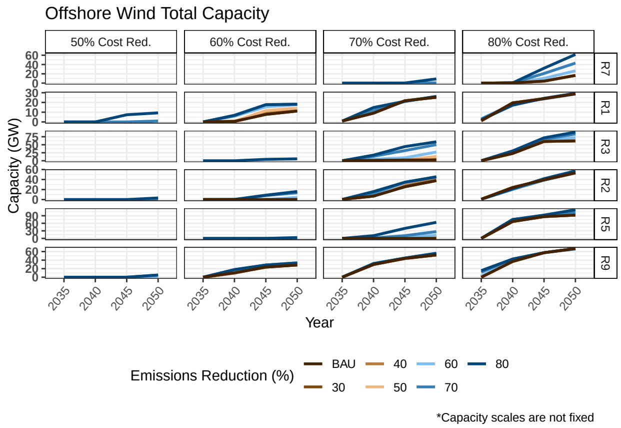

Offshore Wind New Capacity
50% Cost Red.
60% Cost Red.
70% Cost Red.
80% Cost Red.
R2
New Capacity (GW)
0
5
10
15
20
25
2035
2040
2045
2050
Year
Emissions Reduction (%)
BAU
30
40
50
60
70
80



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







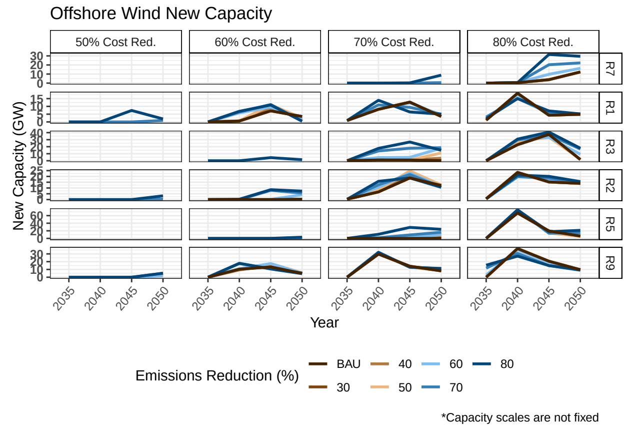


Table 4: Average Installed Capacity (GW)

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

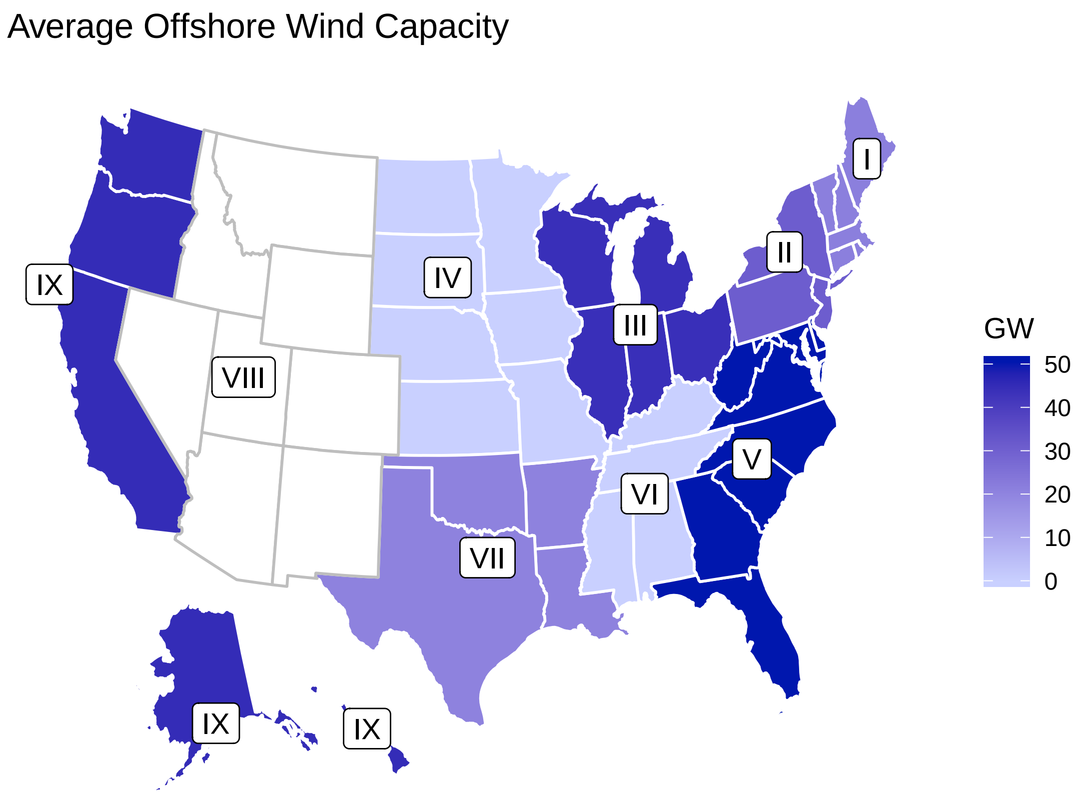
Note:
Average is across all scenarios

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

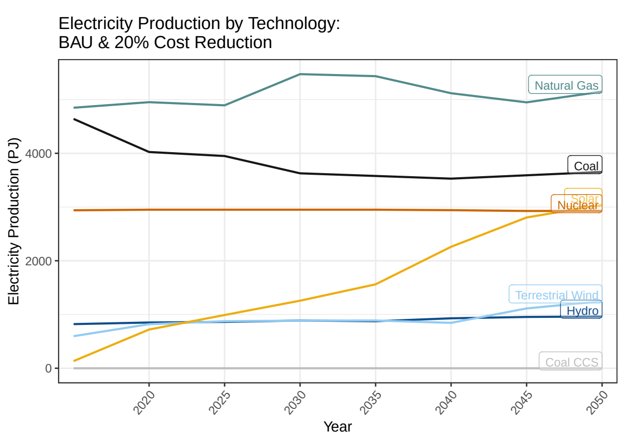
Map of average total capacity

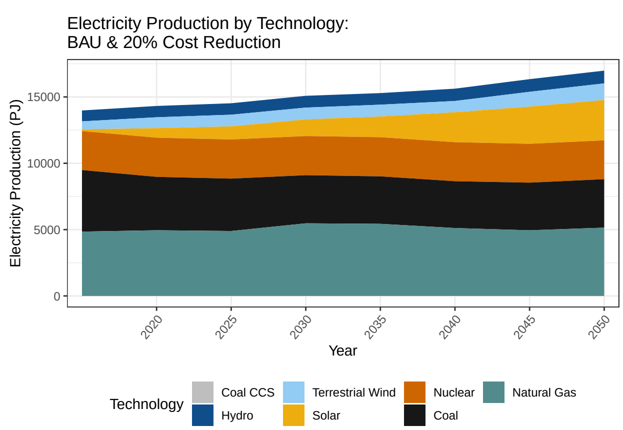


6 Grid Mix

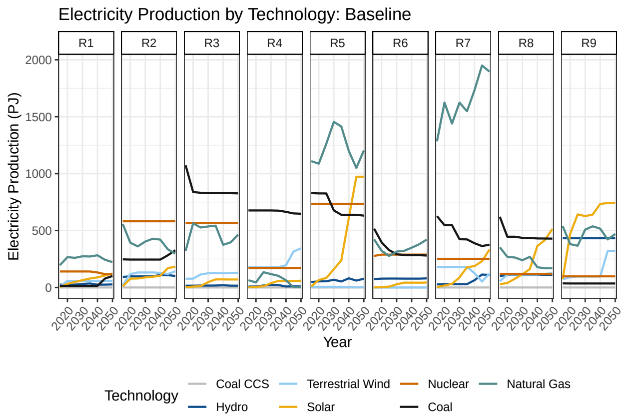
6.1 Baseline Production

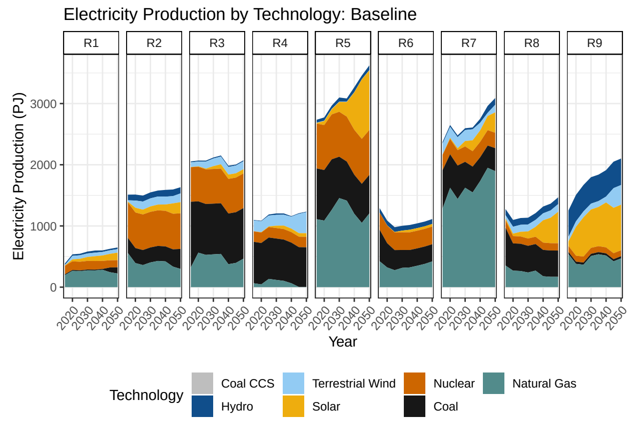
Grid mix without any offshore wind cost reduction or emissions cap.





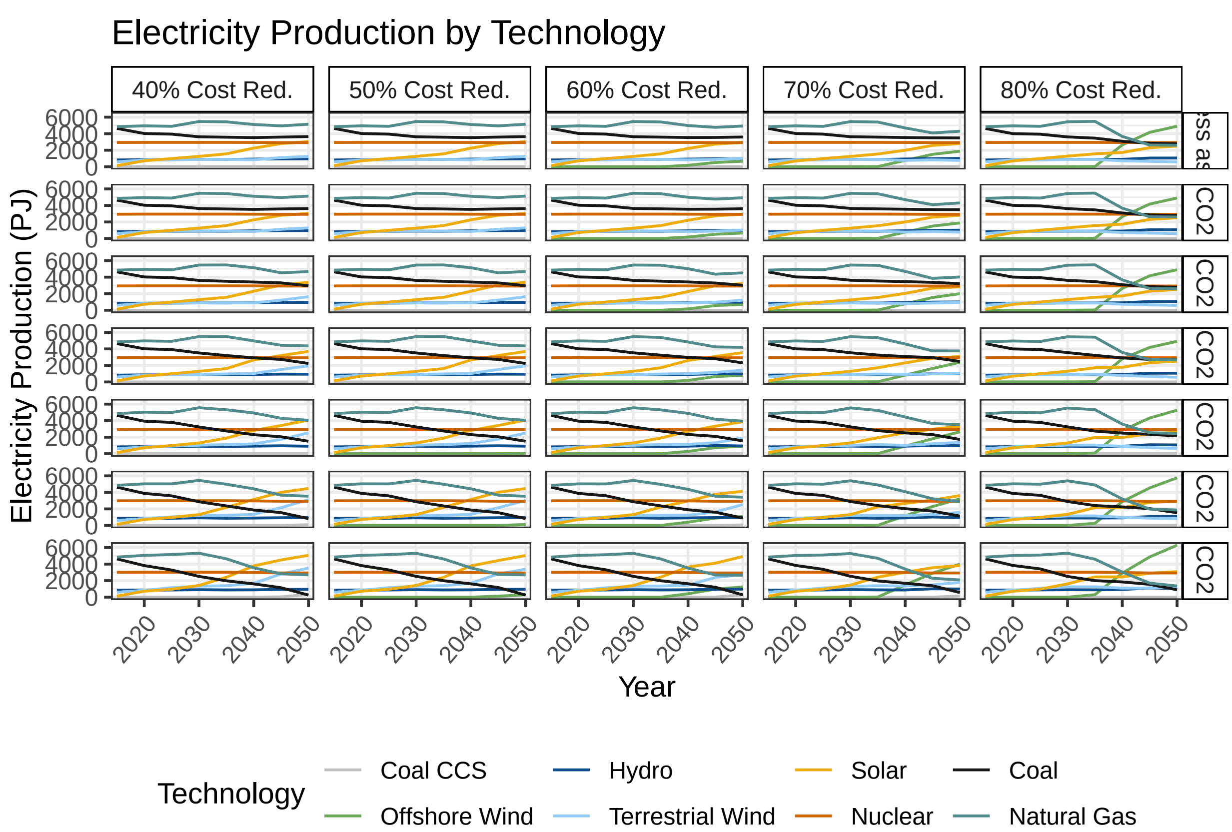
Regional baseline production



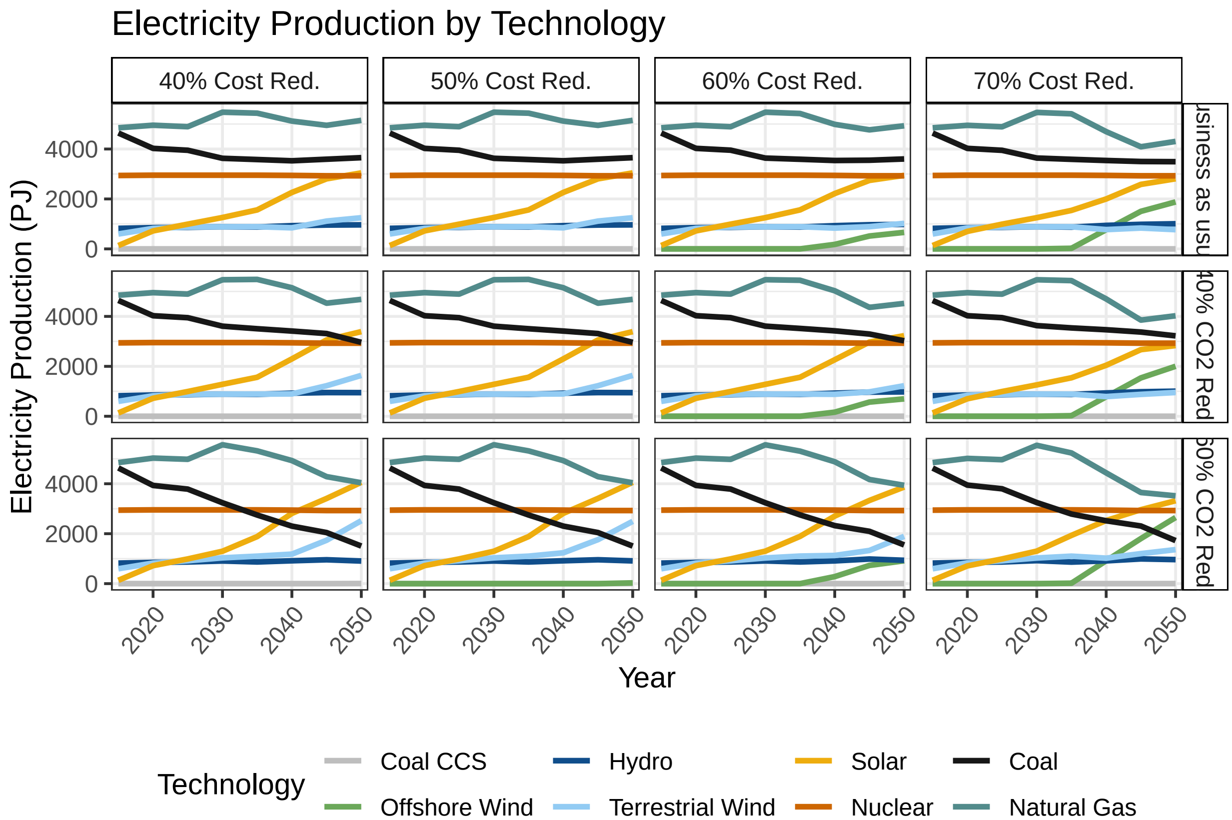


6.2 All Scenarios

Complete Set

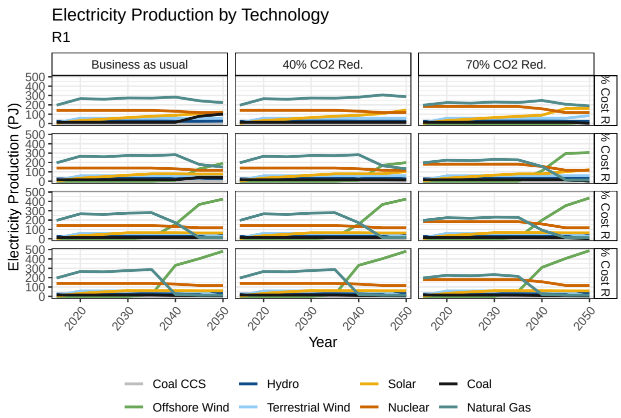


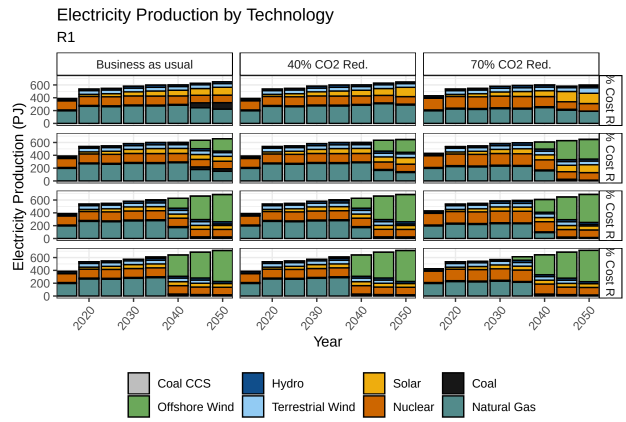
Parsed Set

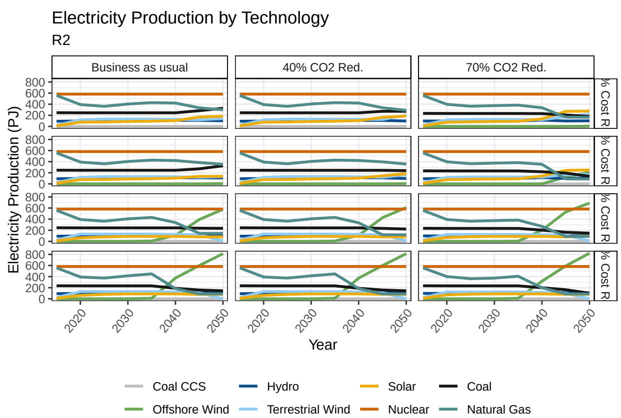


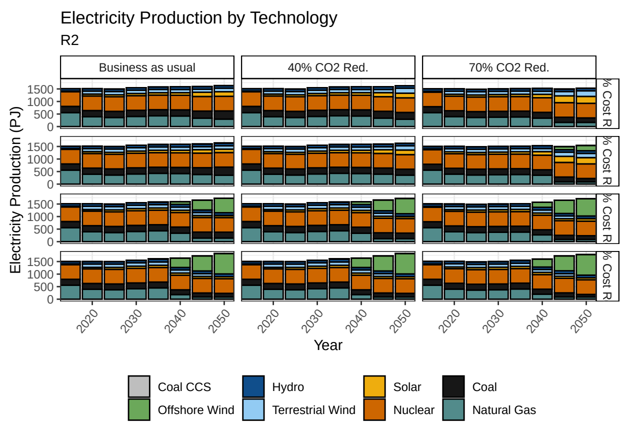
Electricity Production by Technology
40% Cost Red.
50% Cost Red.
60% Cost Red.
70% Cost Red.
usiness as usu
40% CO2 Red
60% CO2 Red
Electricity Production (PJ)
4000
2000
0
2020
2030
2040
2050
Year
Technology
Coal CCS
Offshore Wind
Hydro
Terrestrial Wind
Solar
Nuclear
Coal
Natural Gas

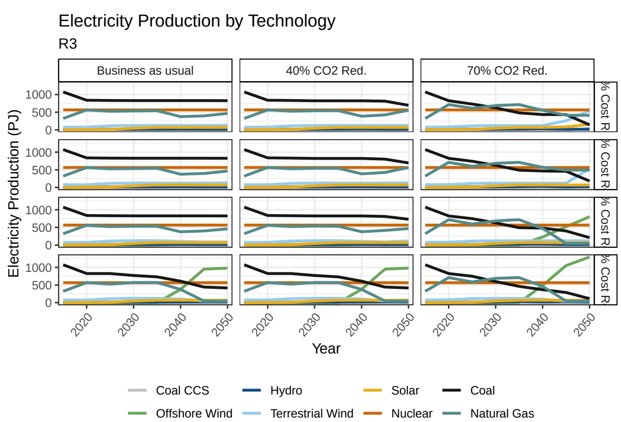
6.3 Regional Mix

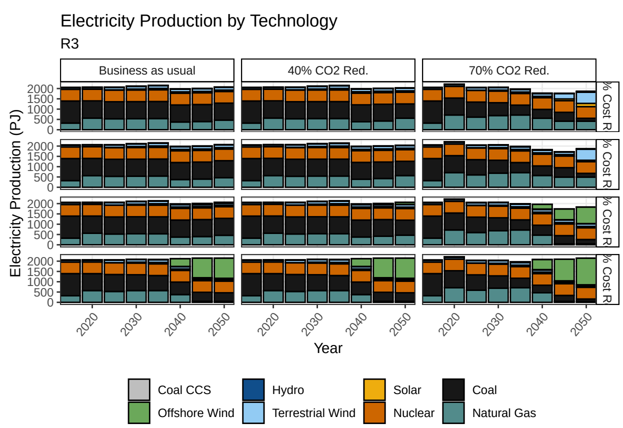


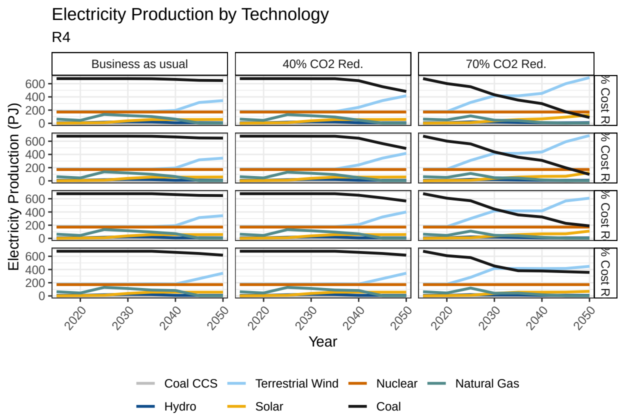


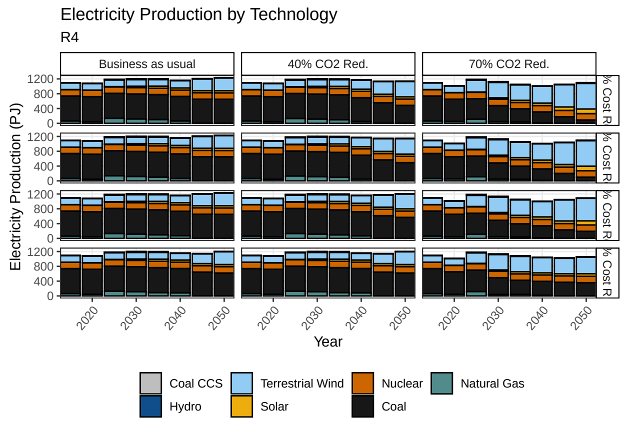


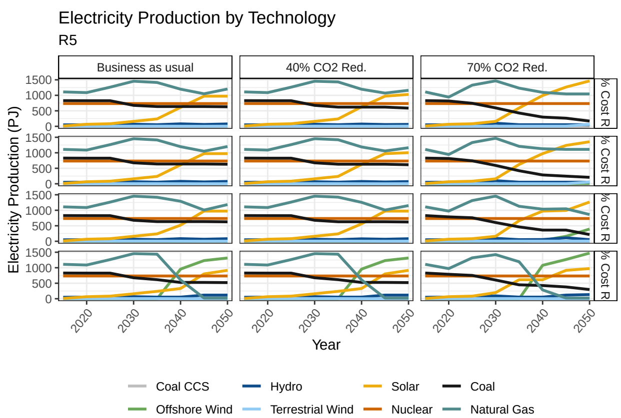


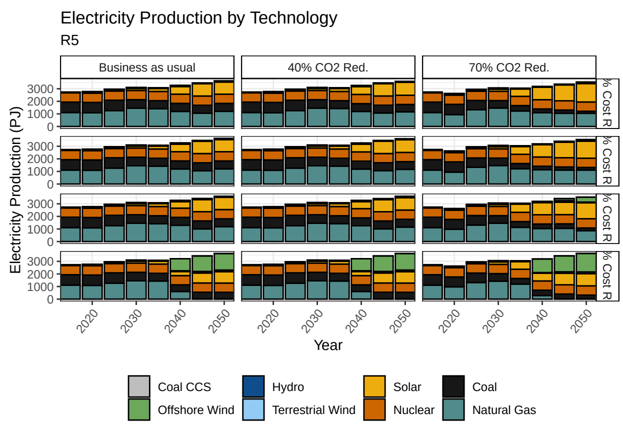


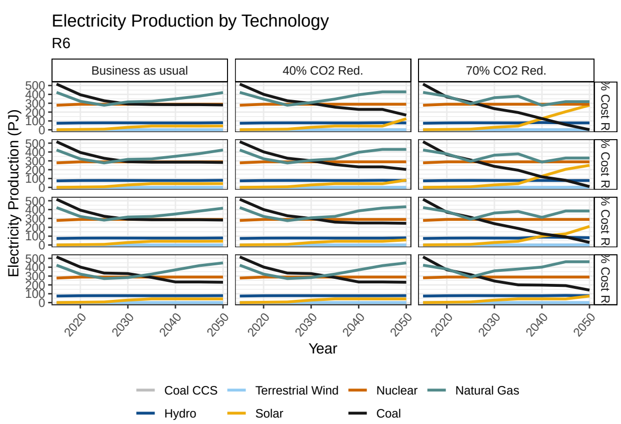


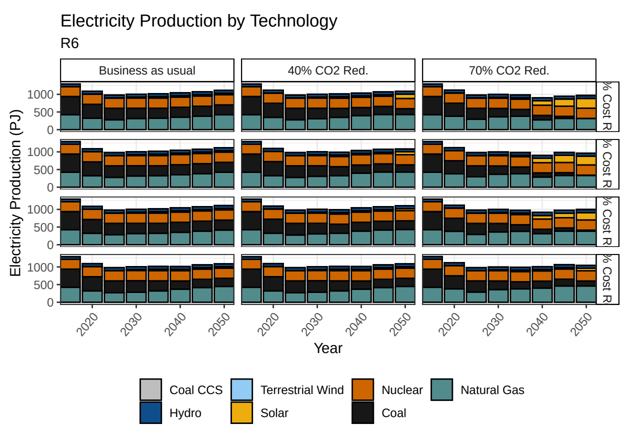

Electricity Production by Technology
R4
Business as usual
40% CO2 Red.
70% CO2 Red.
Electricity Production (PJ)
Year
Coal CCS
Terrestrial Wind
Nuclear
Natural Gas
Hydro
Solar
Coal

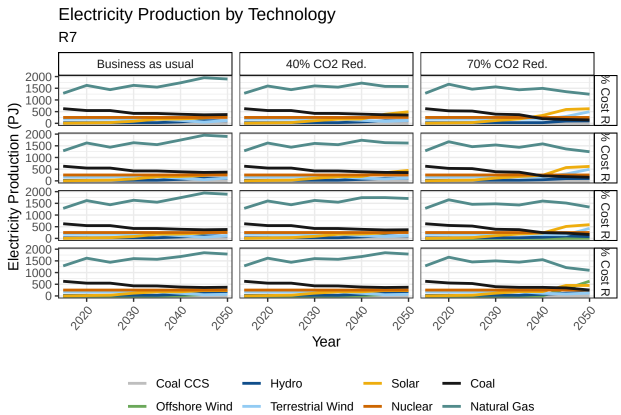

Electricity Production by Technology
R4
Business as usual
40% CO2 Red.
70% CO2 Red.
Electricity Production (PJ)
Year
Coal CCS
Terrestrial Wind
Nuclear
Natural Gas
Hydro
Solar
Coal

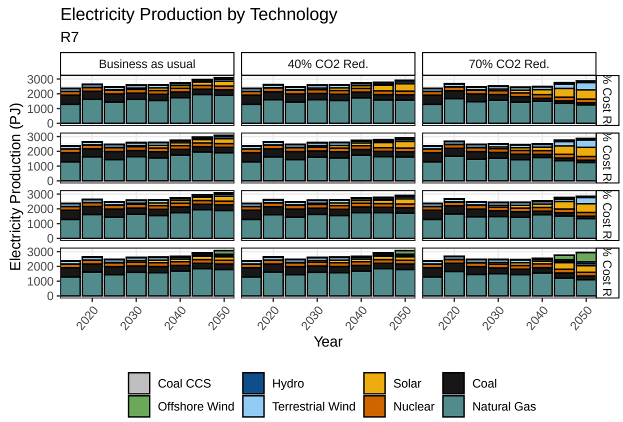

Electricity Production by Technology
R5
Business as usual
40% CO2 Red.
70% CO2 Red.
Electricity Production (PJ)
Year
Coal CCS
Hydro
Solar
Coal
Offshore Wind
Terrestrial Wind
Nuclear
Natural Gas

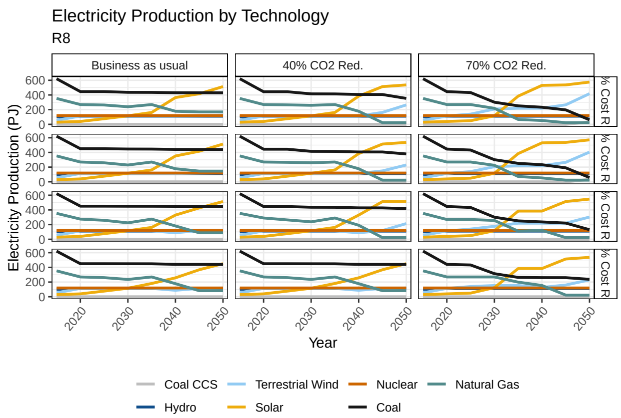

Electricity Production by Technology
R5
Business as usual
40% CO2 Red.
70% CO2 Red.
Electricity Production (PJ)
Year
Coal CCS
Hydro
Solar
Coal
Offshore Wind
Terrestrial Wind
Nuclear
Natural Gas

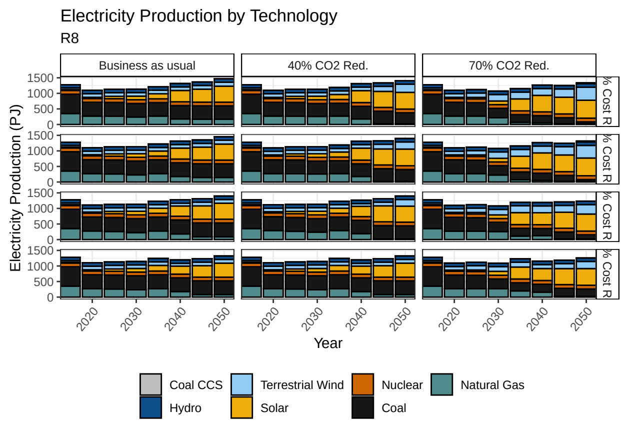

Electricity Production by Technology
R6
Business as usual
40% CO2 Red.
70% CO2 Red.
Electricity Production (PJ)
Year
Coal CCS
Terrestrial Wind
Nuclear
Natural Gas
Hydro
Solar
Coal

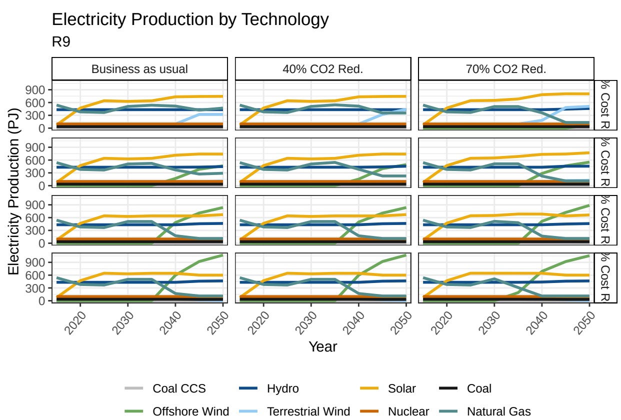

Electricity Production by Technology
R6
Business as usual
40% CO2 Red.
70% CO2 Red.
Electricity Production (PJ)
Year
Coal CCS
Terrestrial Wind
Nuclear
Natural Gas
Hydro
Solar
Coal

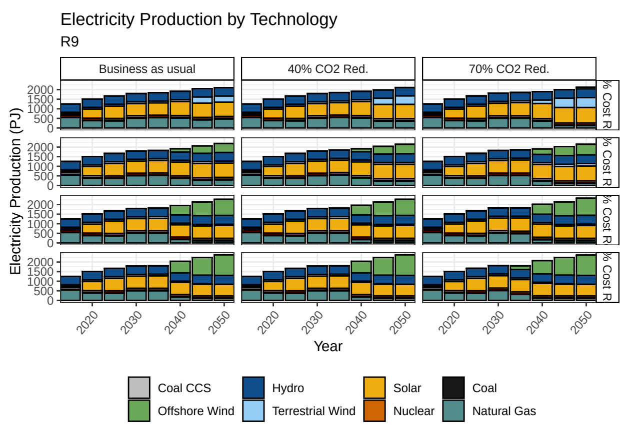






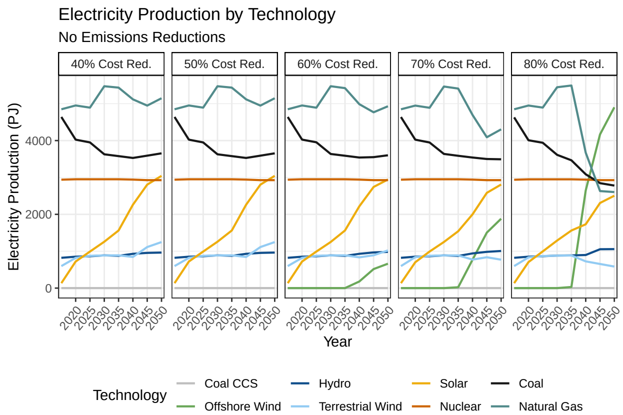


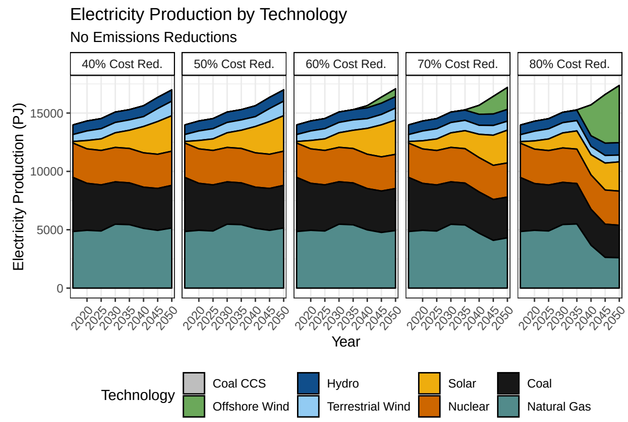




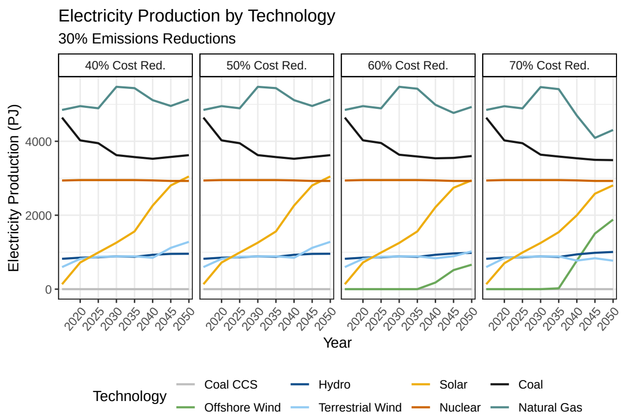
6.4 Emissions Cap

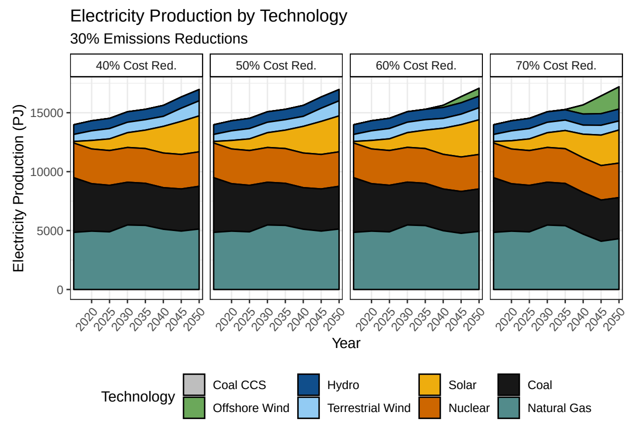
BAU emissions



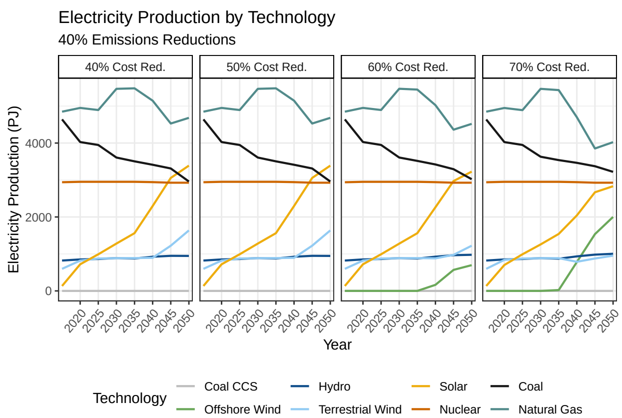


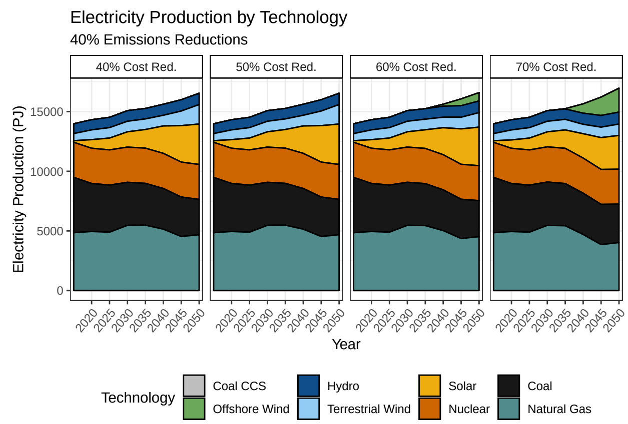
30% emissions reduction



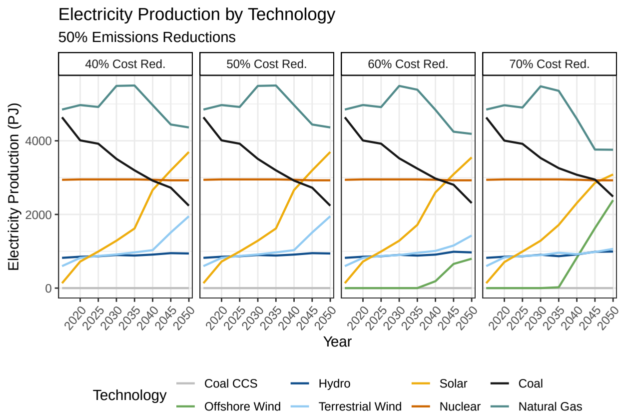


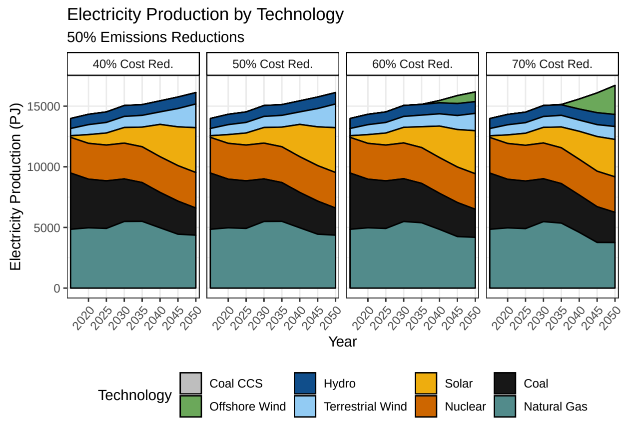
40% emissions reduction



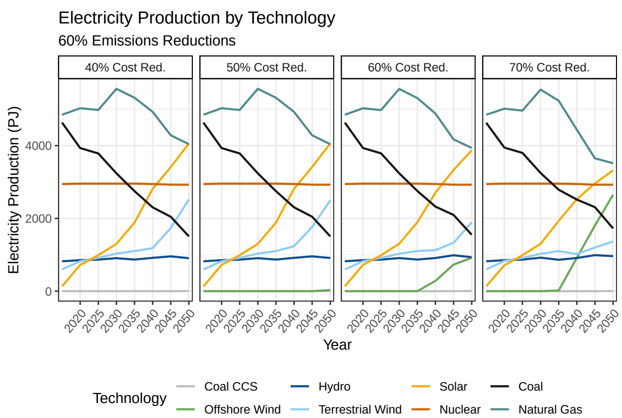


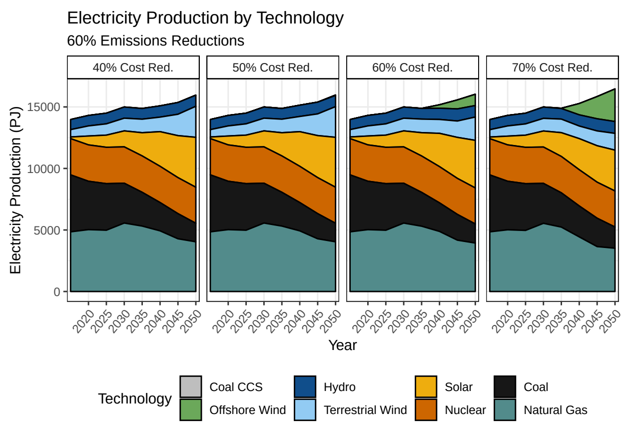
50% emissions reduction



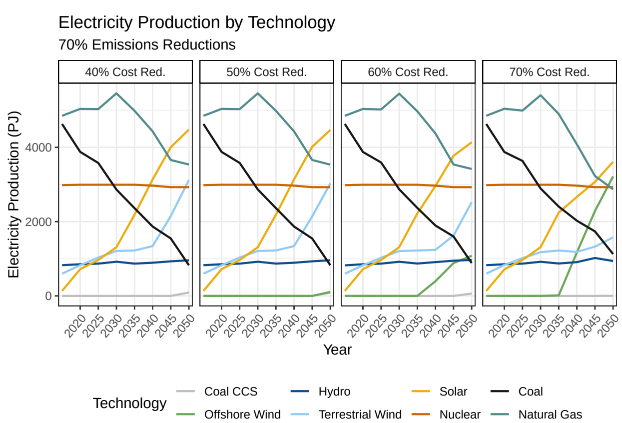


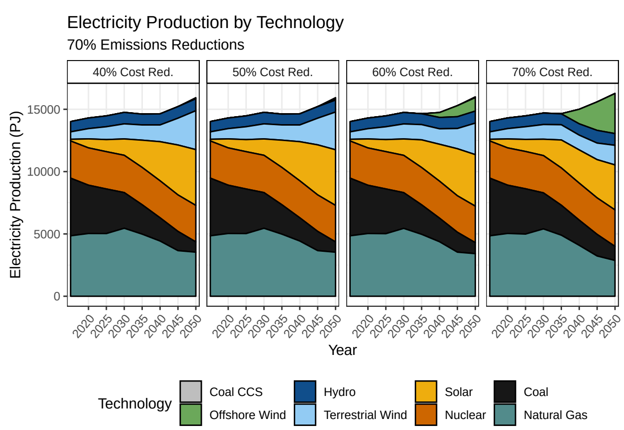
60% emissions reduction



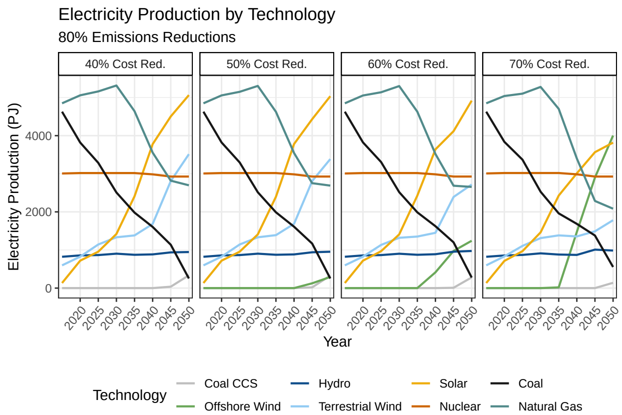


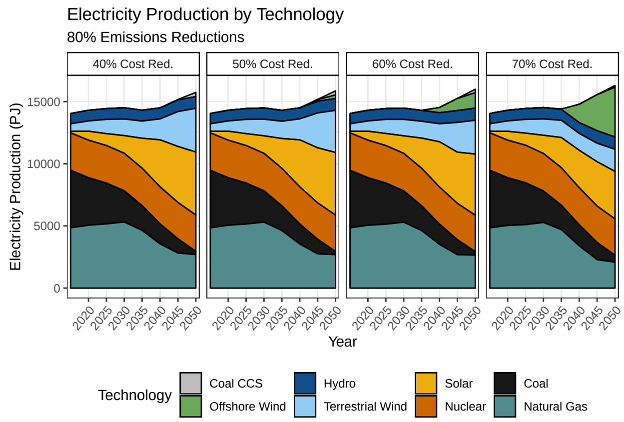
70% emissions reduction





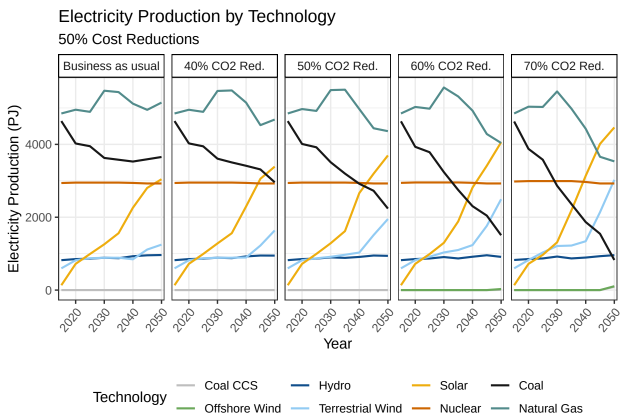
80% emissions reduction

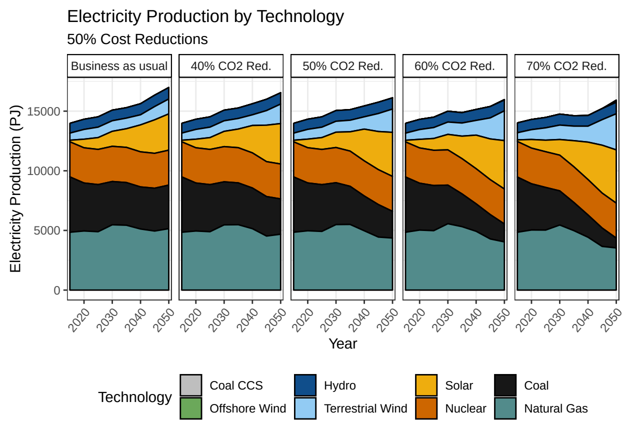




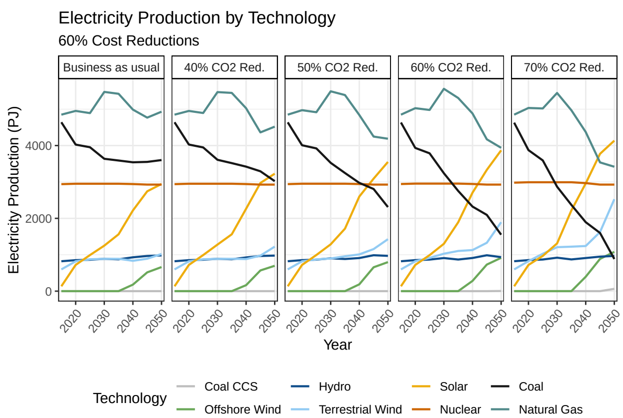
6.5 Cost Reductions

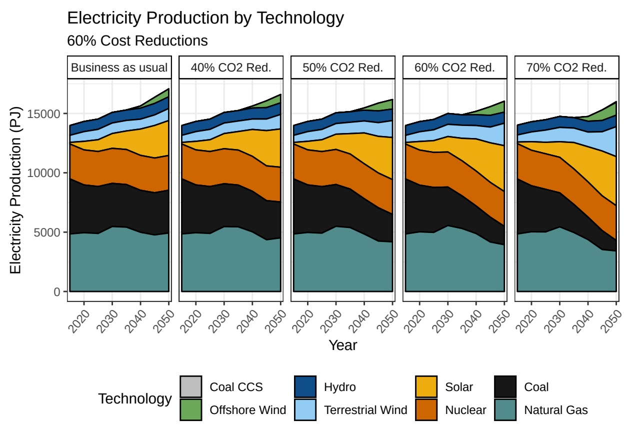
50% cost reduction



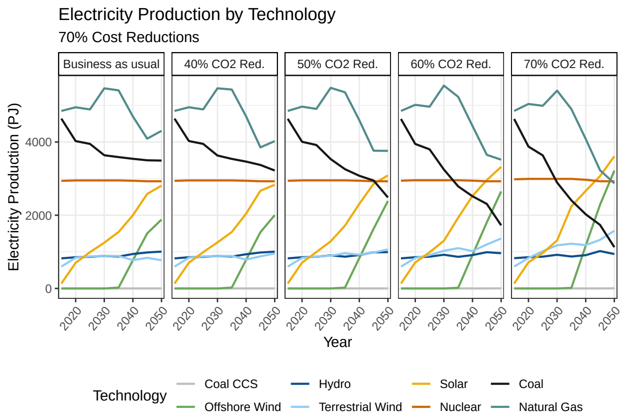


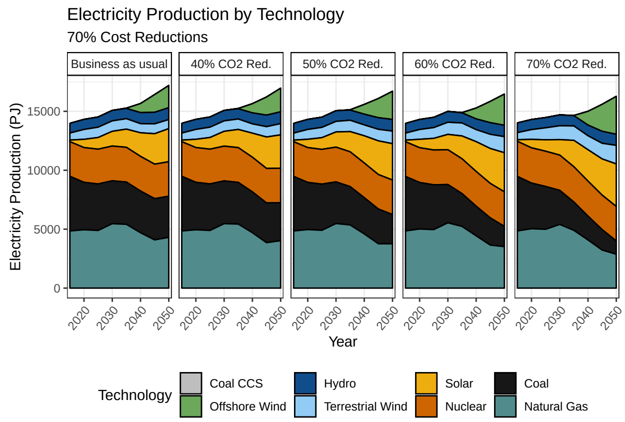
60% cost reduction



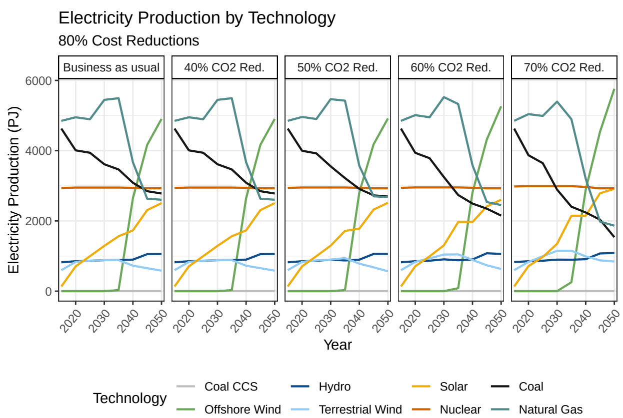


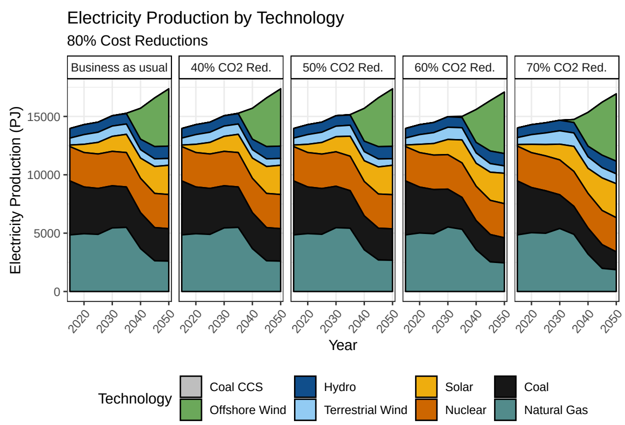
70% cost reduction



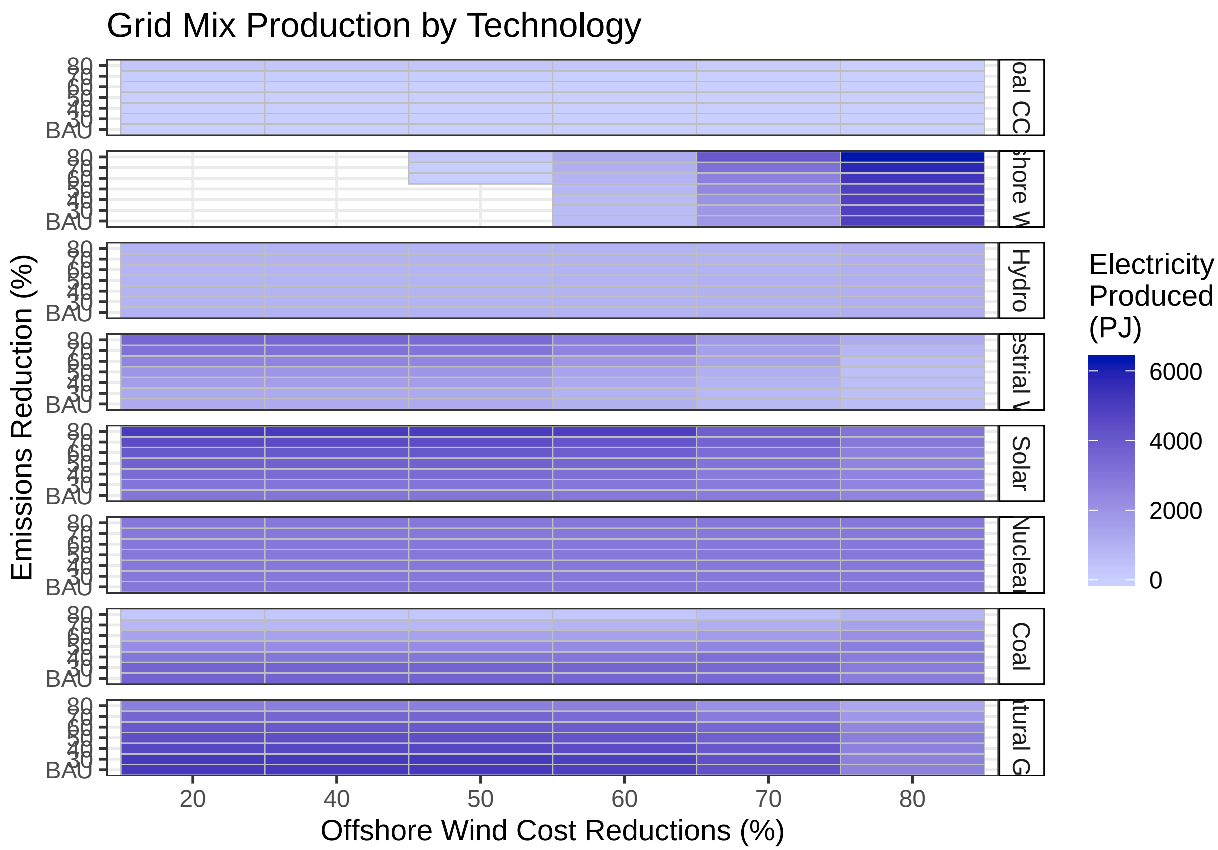


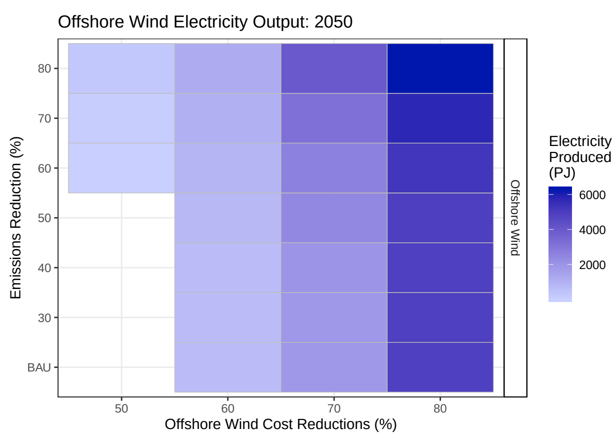
80% cost reduction

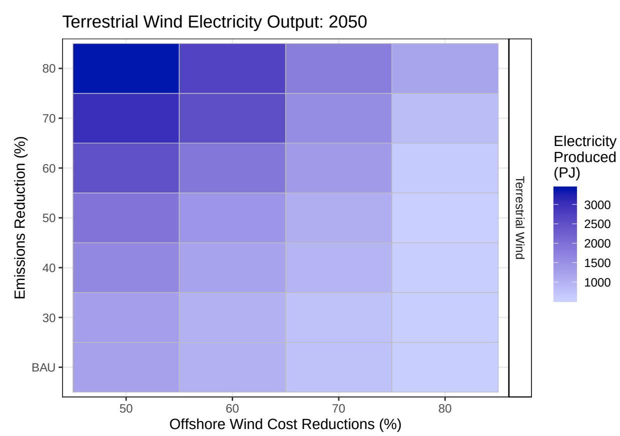


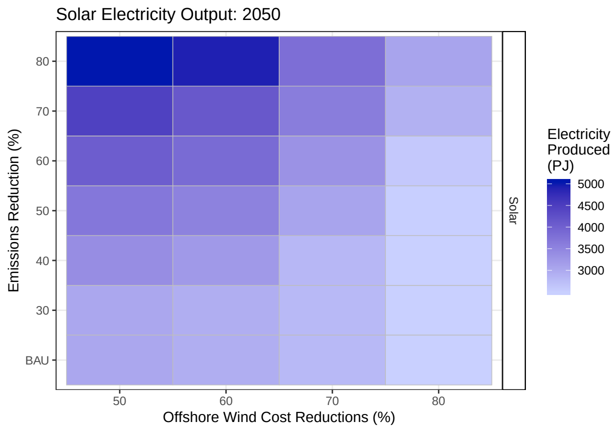


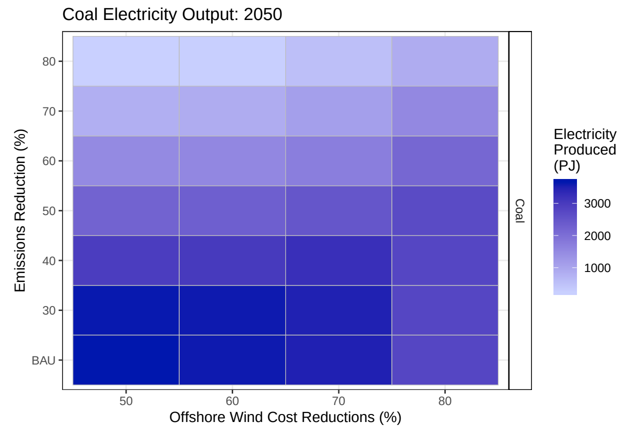
6.6 Heatmaps

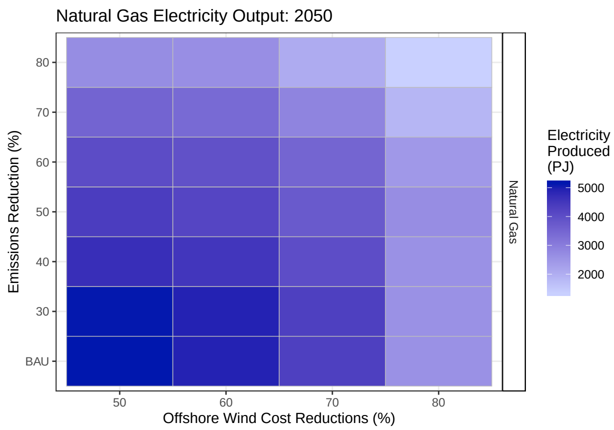

Grid Mix Production by Technology
Emissions Reduction (%)
Offshore Wind Cost Reductions (%)
Electricity Produced (PJ)
6000
4000
2000
0
Hydro
Solar
Coal
20
40
50
60
70
80
BAU

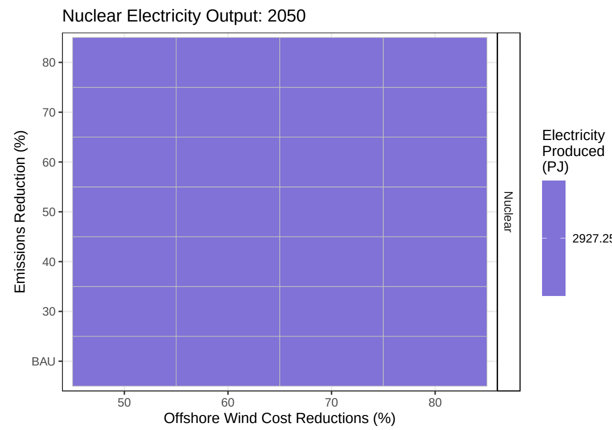

Offshore Wind Electricity Output: 2050
Emissions Reduction (%)
Offshore Wind Cost Reductions (%)
Offshore Wind
Electricity Produced (PJ)
6000
4000
2000
80
70
60
50
40
30
BAU

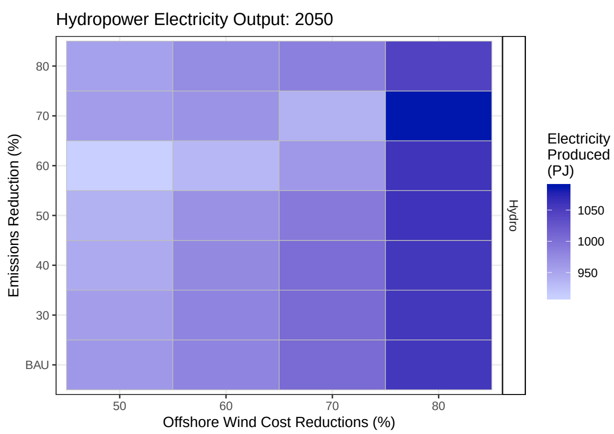

Terrestrial Wind Electricity Output: 2050
Emissions Reduction (%)
Offshore Wind Cost Reductions (%)
Terrestrial Wind
Electricity Produced (PJ)
3000
2500
2000
1500
1000
80
70
60
50
40
30
BAU

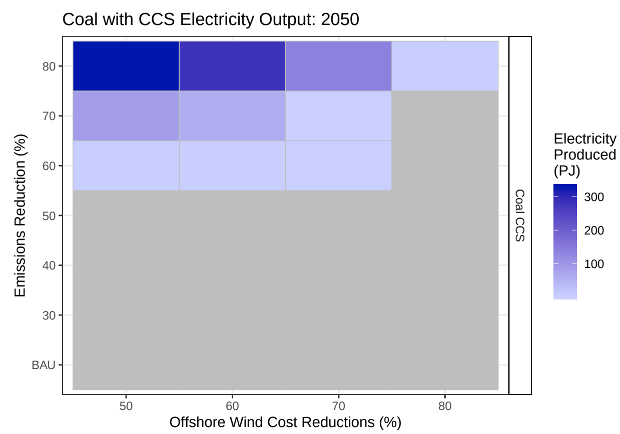












6.7 Market Share

```
## $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
```

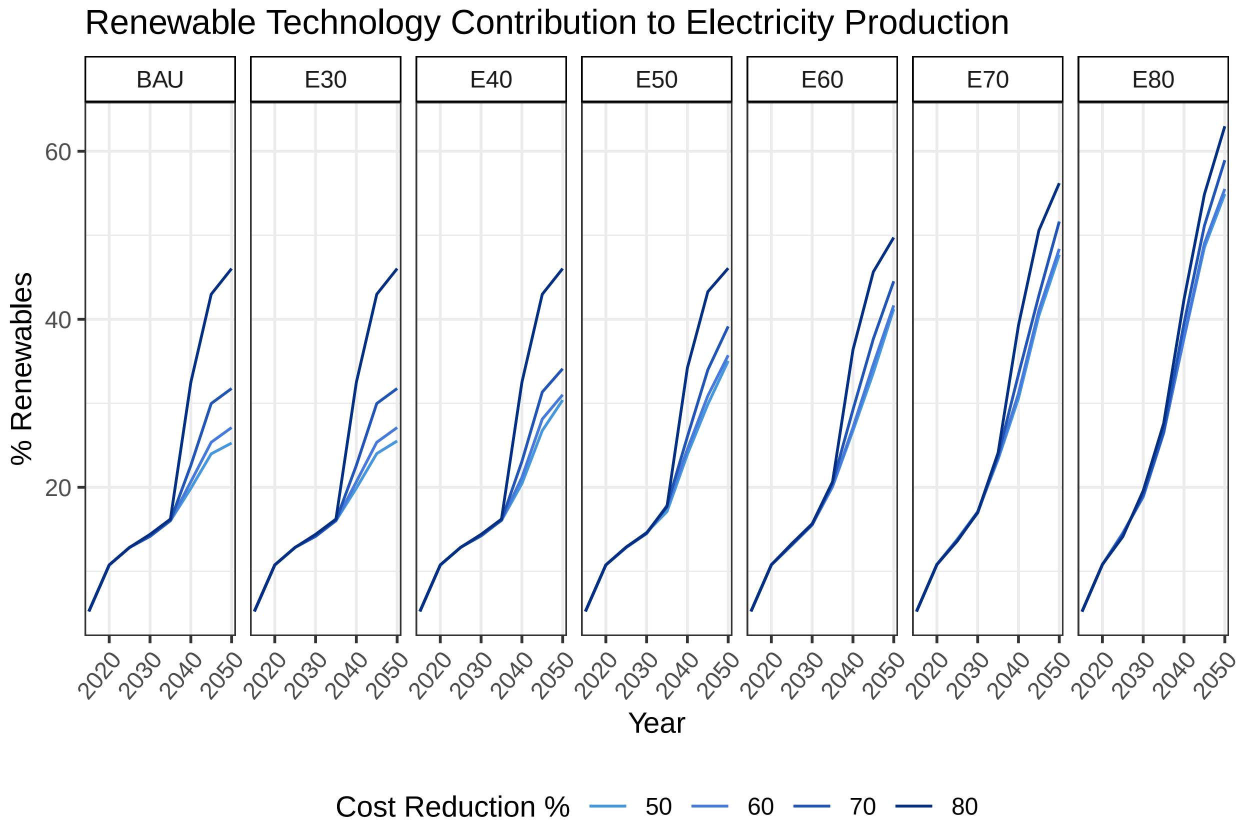
```
##  Min.   : 133.3   Min.   :13967   Min.   : 0.950
##  1st Qu.: 897.3   1st Qu.:14323   1st Qu.: 6.232
##  Median :1541.6   Median :14993   Median :10.095
##  Mean   :1767.7   Mean   :15060   Mean   :11.446
##  3rd Qu.:2677.9   3rd Qu.:15621   3rd Qu.:16.920
##  Max.   :5064.4   Max.   :17360   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

		Cost Reduction (%)					
Technology	CO2 Cap	20	40	50	60	70	80
	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
Coal	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
	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
Coal CCS	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
	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
Hydro	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

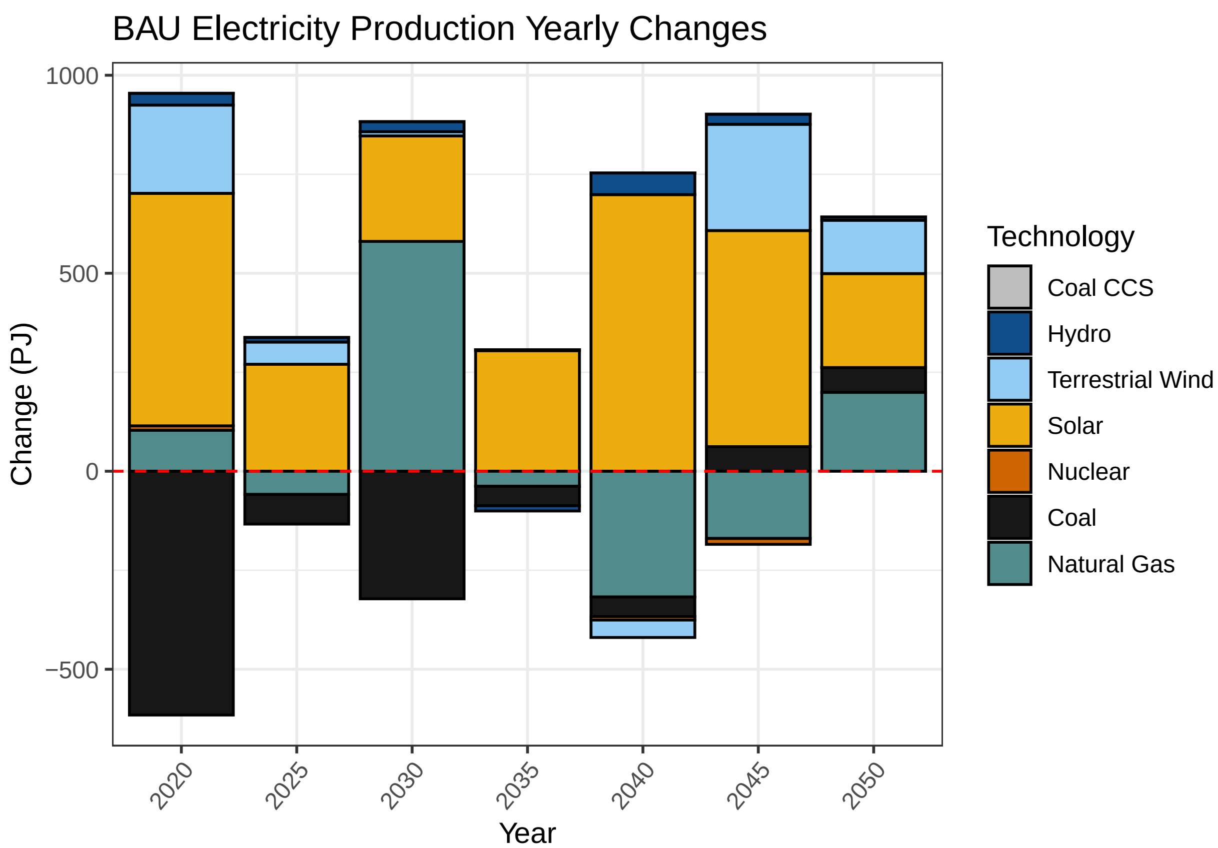
Natural Gas	30	30.2	30.2	30.2	28.9	25.1	15.0
	40	28.3	28.3	28.3	27.2	23.7	15.0
	50	27.1	27.1	27.1	25.9	22.5	15.4
	60	25.3	25.3	25.3	24.6	21.4	14.3
	70	22.2	22.2	22.2	21.4	17.6	11.0
	80	17.1	17.1	16.9	16.6	12.8	8.0
Nuclear	BAU	17.2	17.2	17.2	17.1	17.0	16.9
	30	17.2	17.2	17.2	17.1	17.0	16.9
	40	17.7	17.7	17.7	17.6	17.3	16.9
	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
Offshore Wind	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
	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
Solar	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
	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
Terrestrial Wind	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
	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



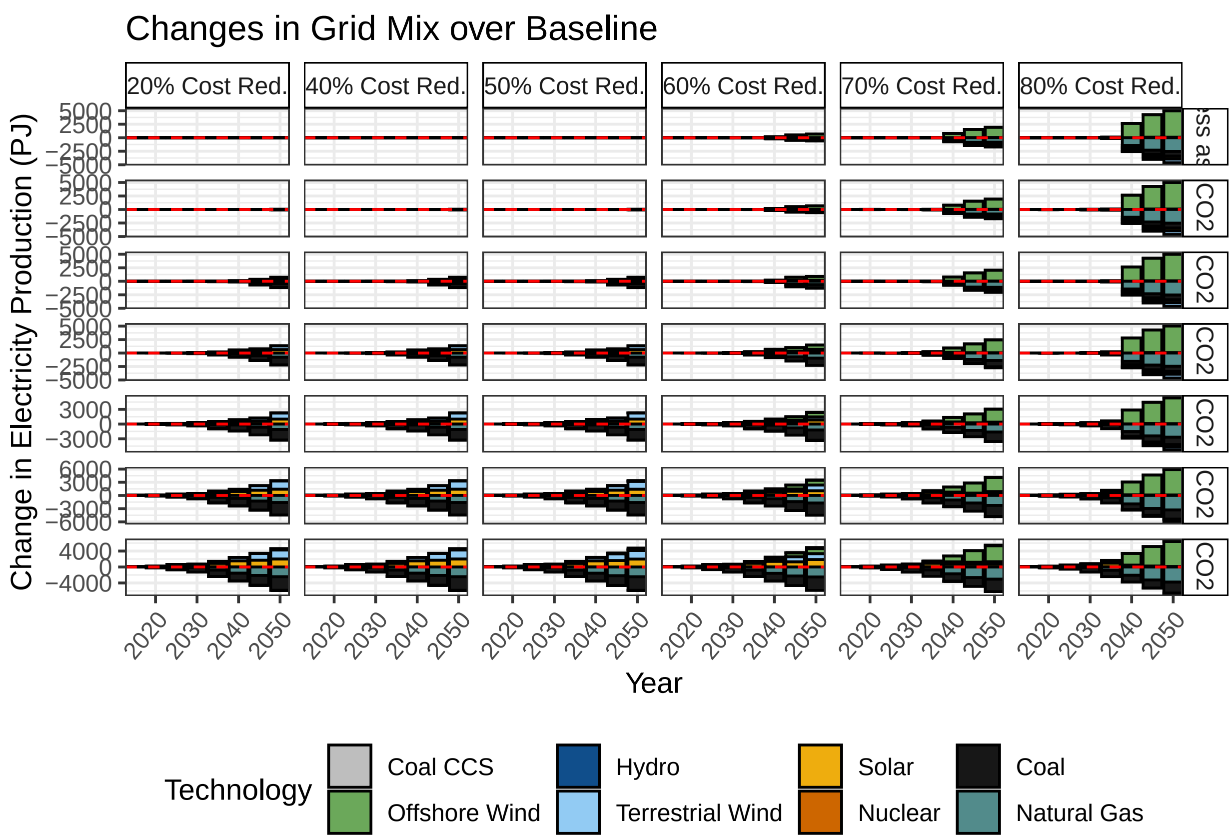
6.9 Retirements and Additions

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

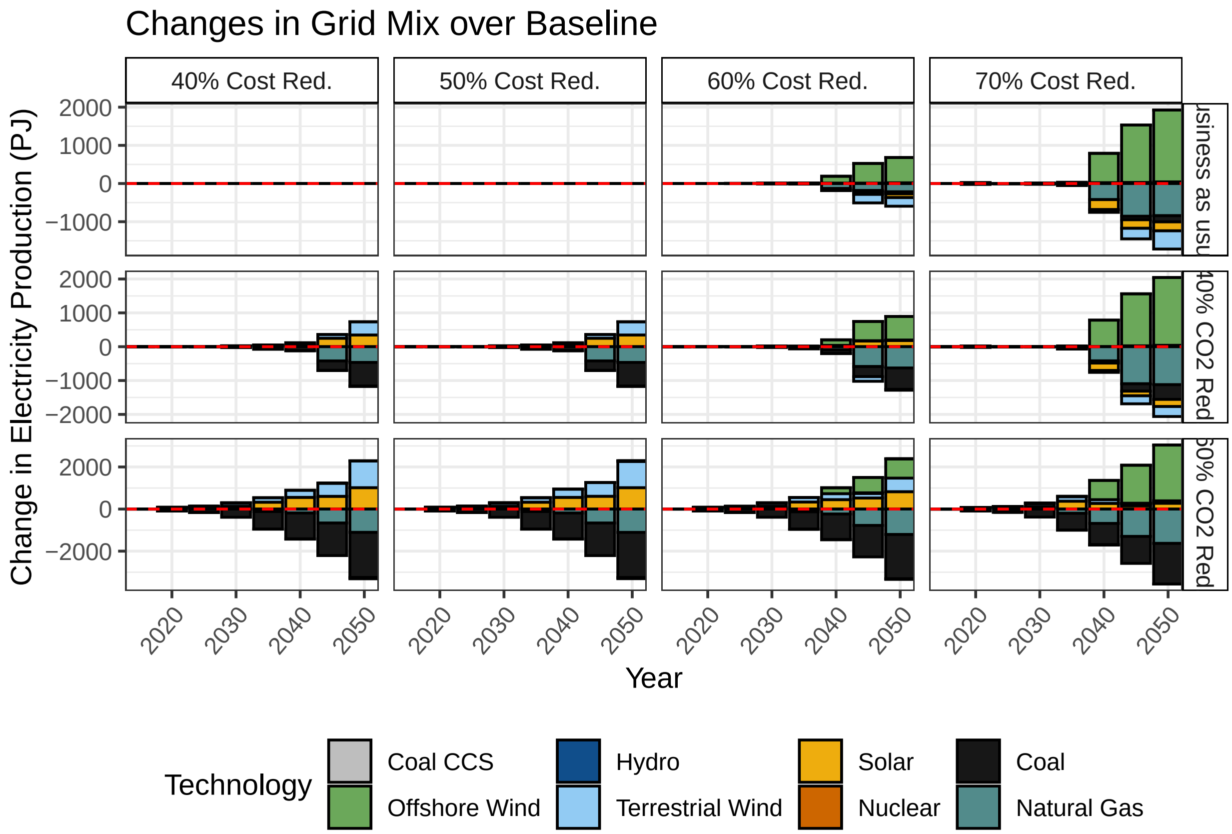


6.10 Changes Over Baseline

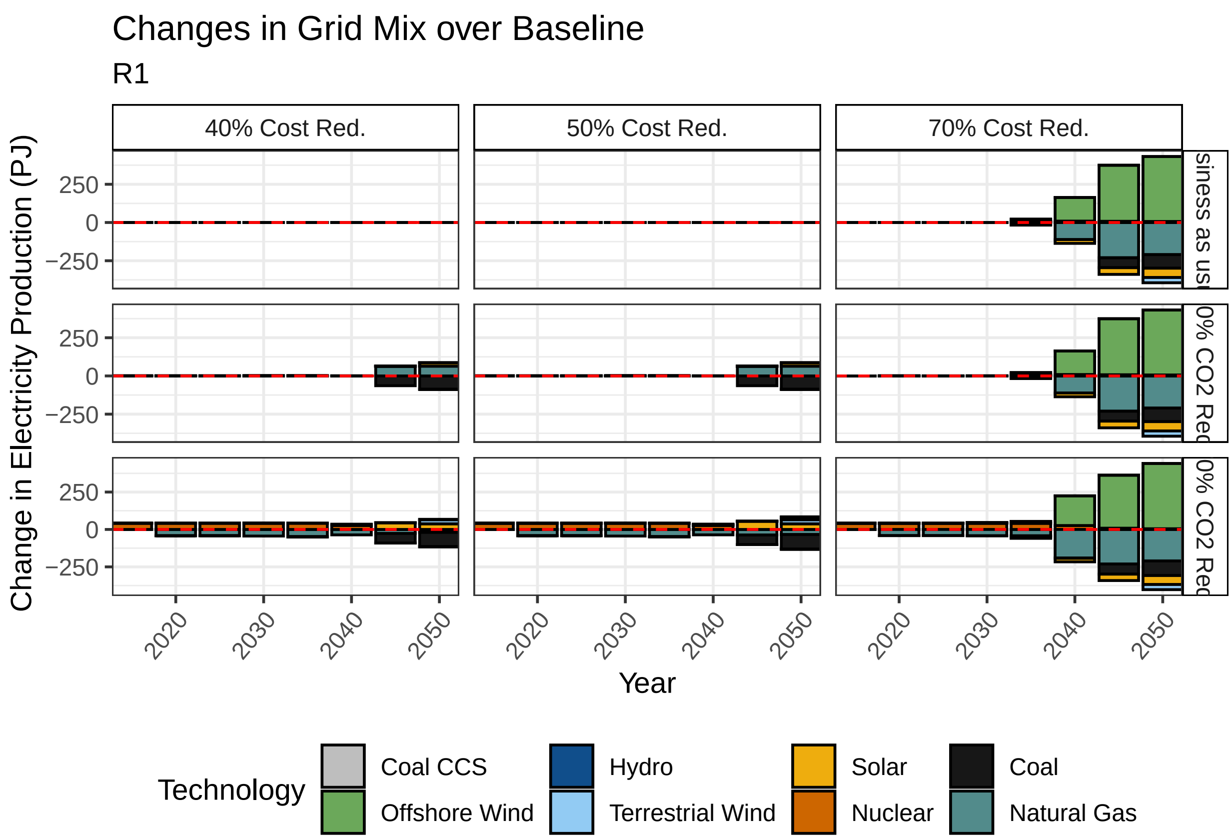
Summary Graph

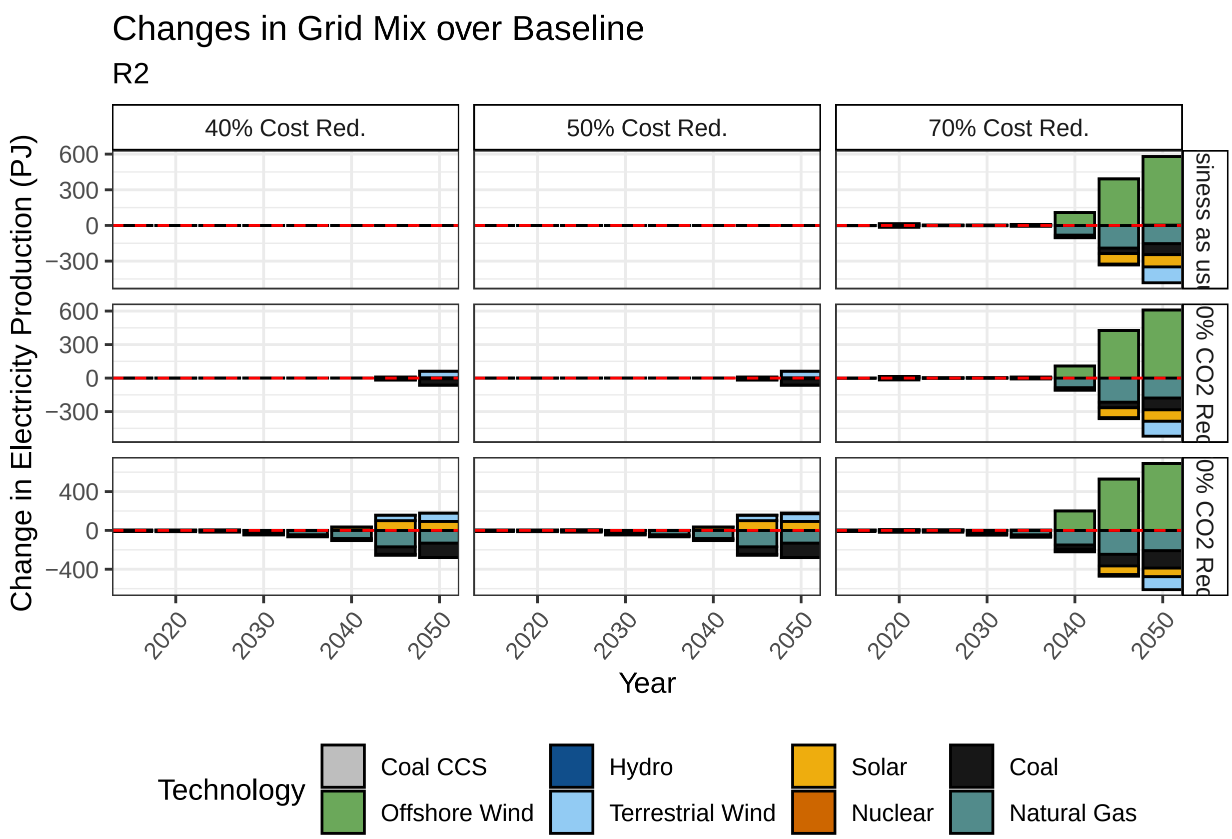


Changes in Grid Mix over Baseline
20% Cost Red.
40% Cost Red.
50% Cost Red.
60% Cost Red.
70% Cost Red.
80% Cost Red.
Change in Electricity Production (PJ)
Year
2020
2030
2040
2050
Technology
Coal CCS
Offshore Wind
Hydro
Terrestrial Wind
Solar
Nuclear
Coal
Natural Gas

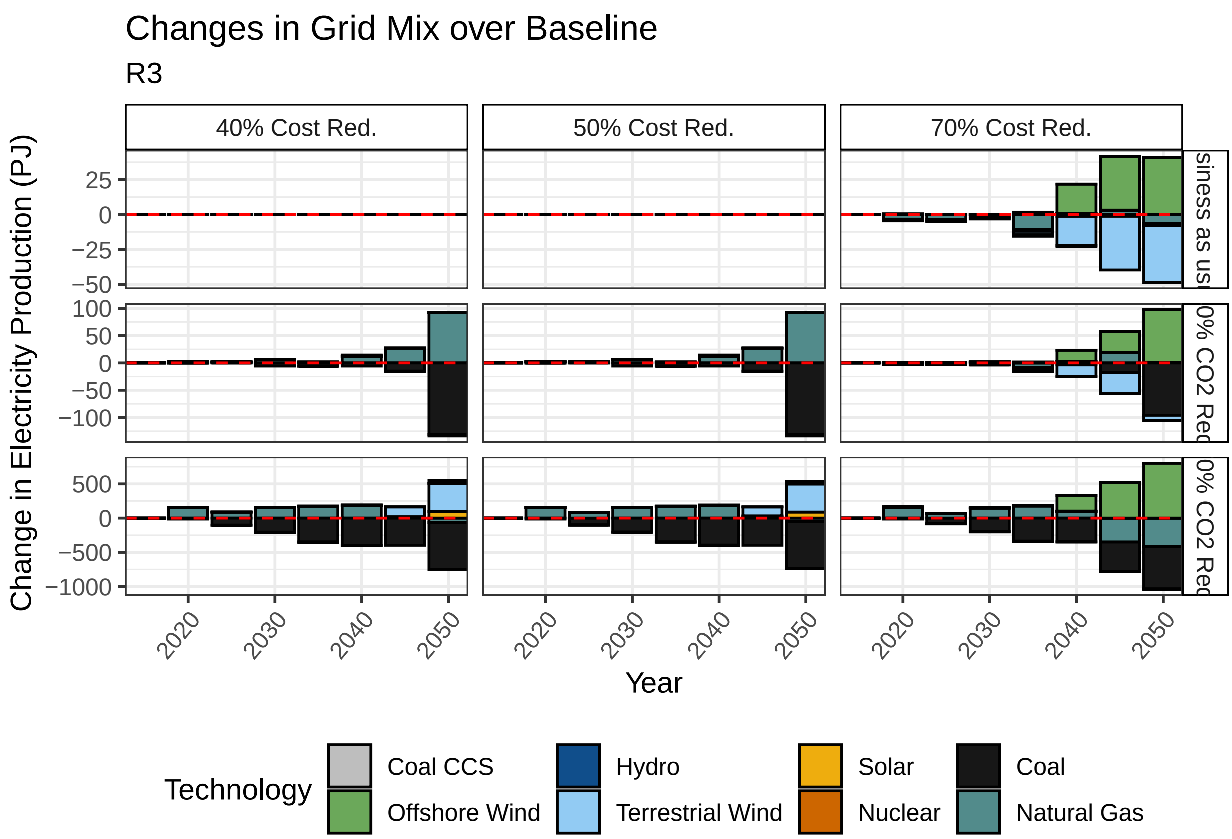


Regional Summary Graphs

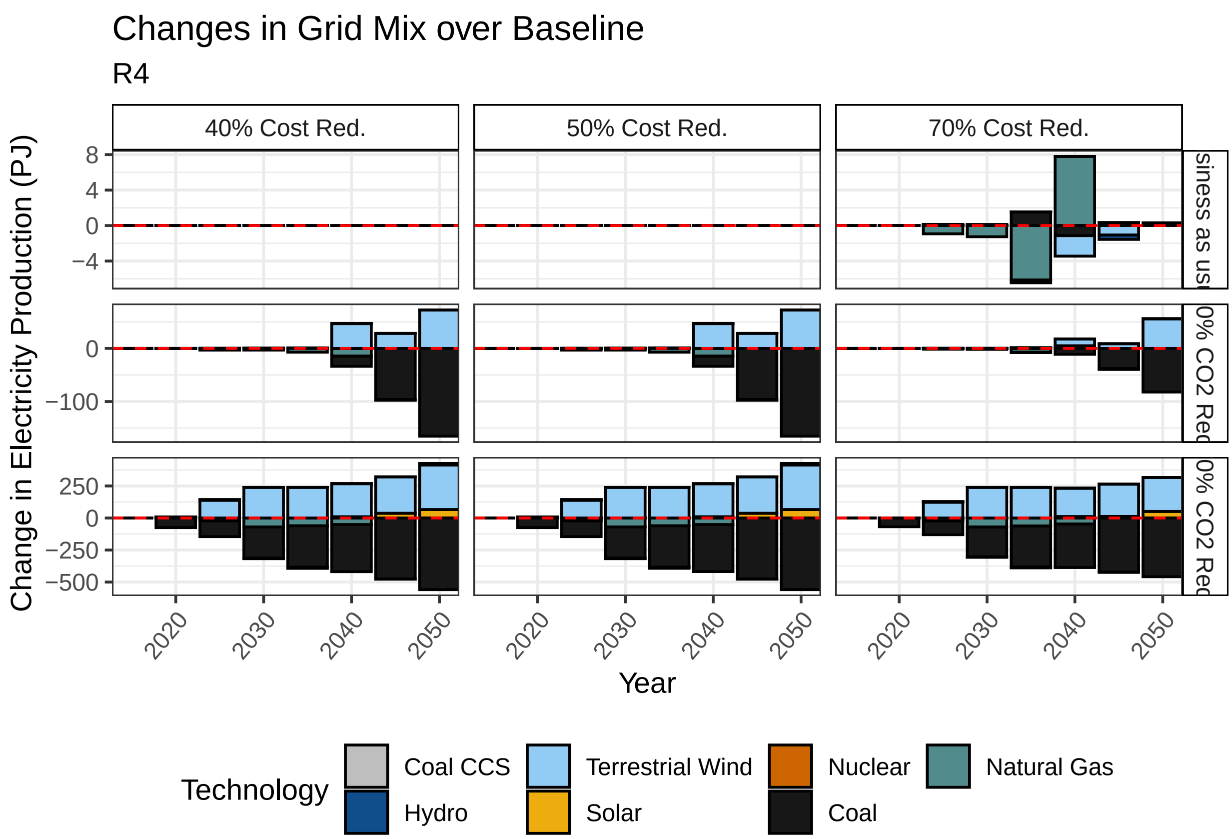

Changes in Grid Mix over Baseline
R1
40% Cost Red.
50% Cost Red.
70% Cost Red.
siness as us
0% CO2 Red
0% CO2 Red
250
0
−250
Change in Electricity Production (PJ)
2020
2030
2040
2050
Year
Technology
Coal CCS
Offshore Wind
Hydro
Terrestrial Wind
Solar
Nuclear
Coal
Natural Gas



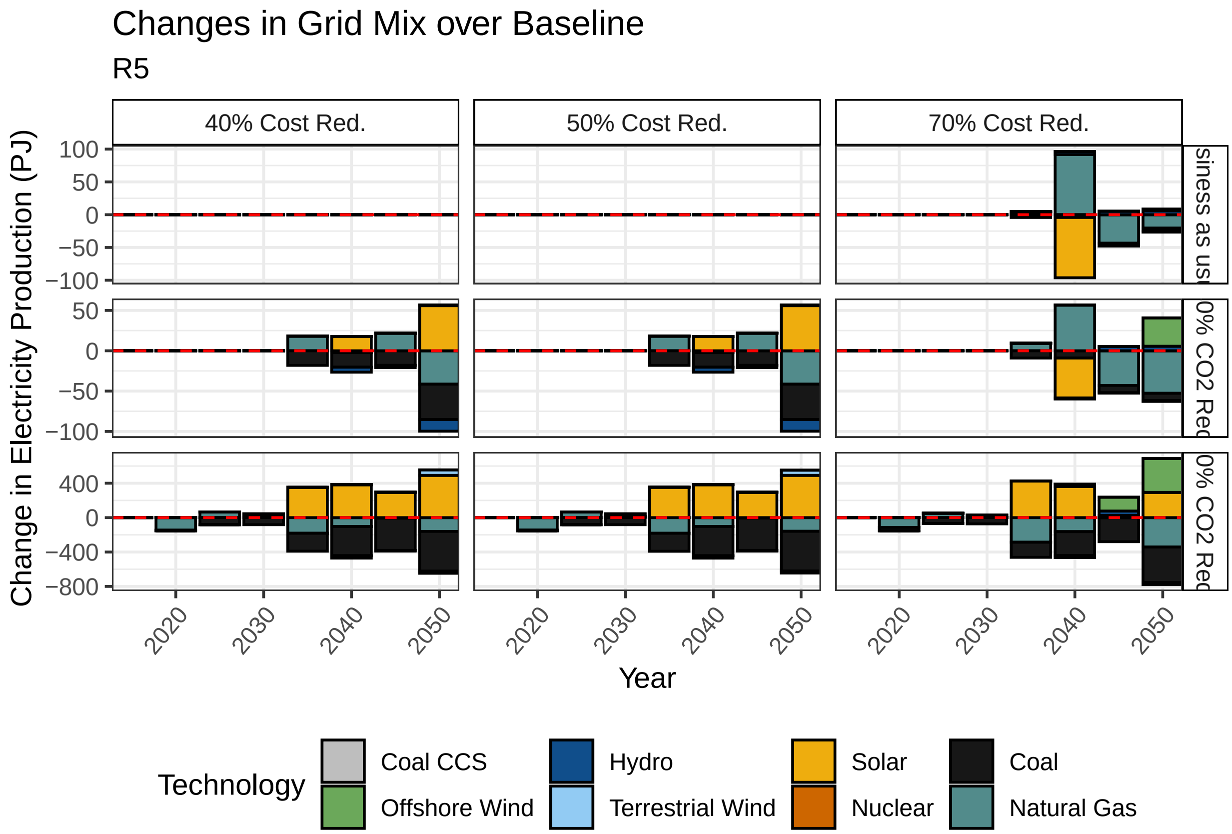
Changes in Grid Mix over Baseline
R2
40% Cost Red.
50% Cost Red.
70% Cost Red.
siness as usu
0% CO2 Red
0% CO2 Red
Change in Electricity Production (PJ)
600
300
0
−300
400
−400
2020
2030
2040
2050
Year
Technology
Coal CCS
Offshore Wind
Hydro
Terrestrial Wind
Solar
Nuclear
Coal
Natural Gas



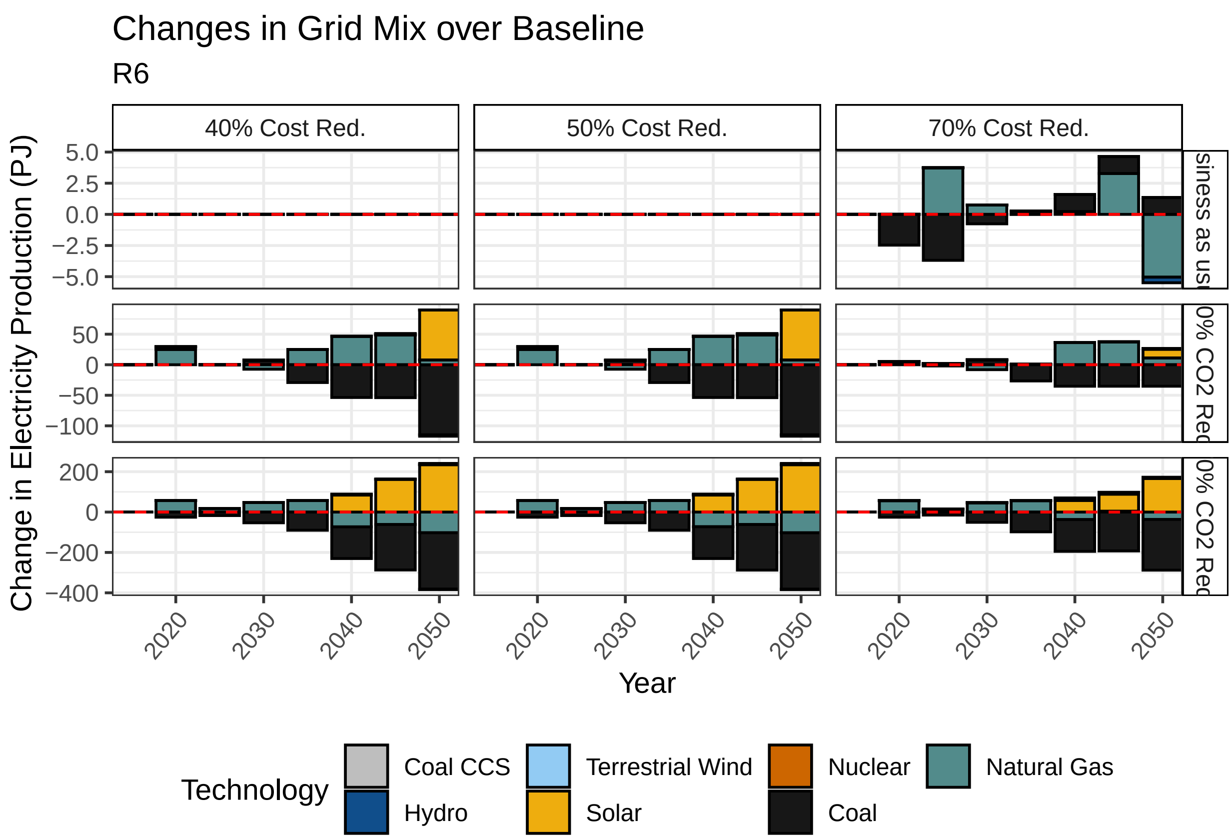
Changes in Grid Mix over Baseline
R3
40% Cost Red.
50% Cost Red.
70% Cost Red.
Change in Electricity Production (PJ)
Year
Technology
Coal CCS
Hydro
Solar
Coal
Offshore Wind
Terrestrial Wind
Nuclear
Natural Gas

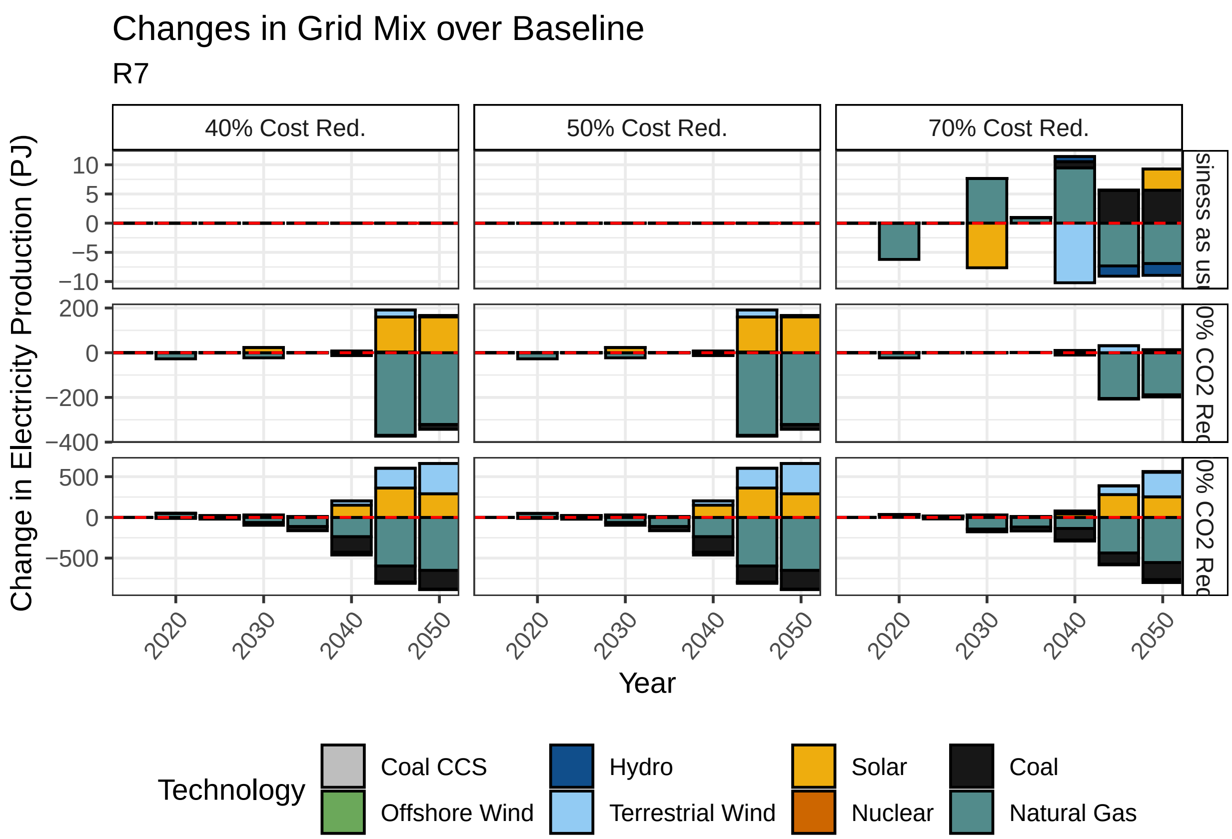


Changes in Grid Mix over Baseline
R4
40% Cost Red.
50% Cost Red.
70% Cost Red.
siness as us
0% CO2 Red
0% CO2 Red
8
4
0
−4
0
−100
250
0
−250
−500
Change in Electricity Production (PJ)
2020
2030
2040
2050
Year
Technology
Coal CCS
Hydro
Terrestrial Wind
Solar
Nuclear
Coal
Natural Gas

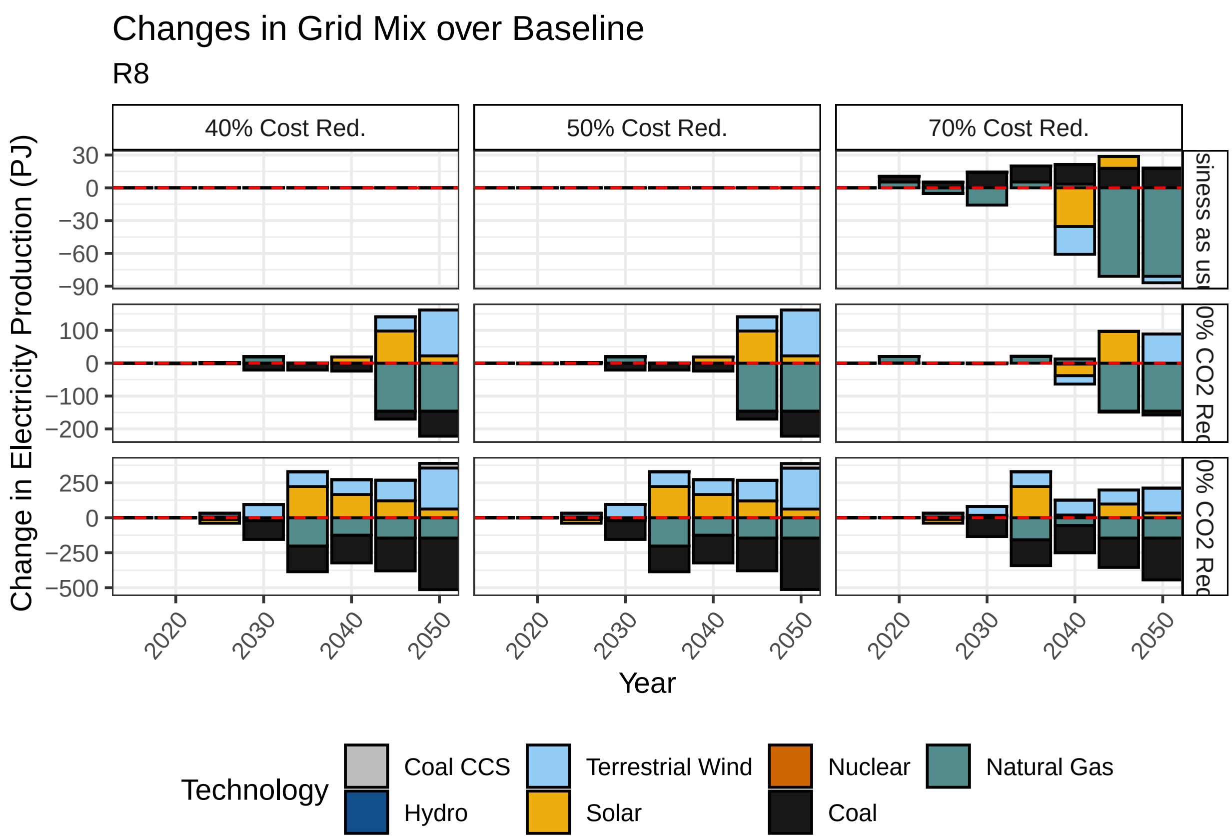


Changes in Grid Mix over Baseline
R5
40% Cost Red.
50% Cost Red.
70% Cost Red.
siness as usı
0% CO2 Rec
0% CO2 Rec
Change in Electricity Production (PJ)
100
50
0
−50
−100
400
0
−400
−800
2020
2030
2040
2050
Year
Technology
Coal CCS
Offshore Wind
Hydro
Terrestrial Wind
Solar
Nuclear
Coal
Natural Gas

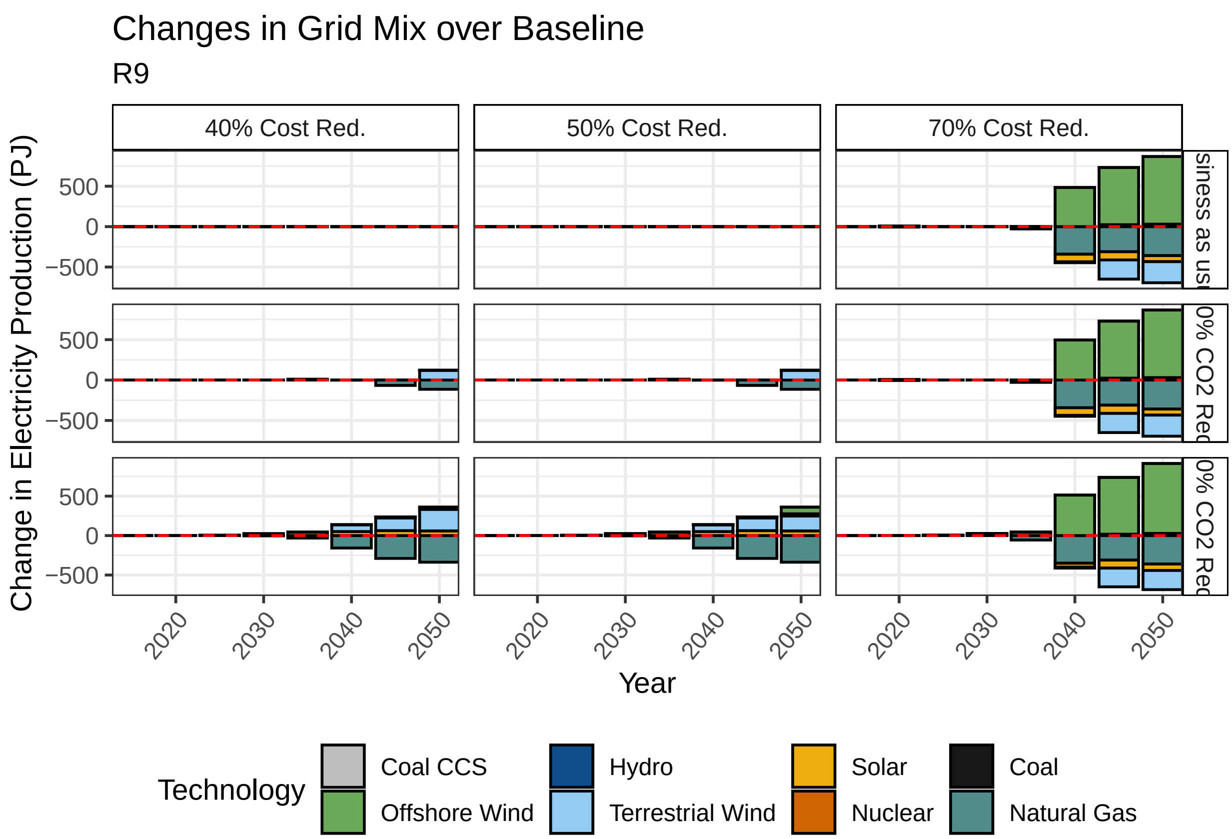

Changes in Grid Mix over Baseline
R6
40% Cost Red.
50% Cost Red.
70% Cost Red.
Change in Electricity Production (PJ)
Year
2020
2030
2040
2050
Technology
Coal CCS
Hydro
Terrestrial Wind
Solar
Nuclear
Coal
Natural Gas



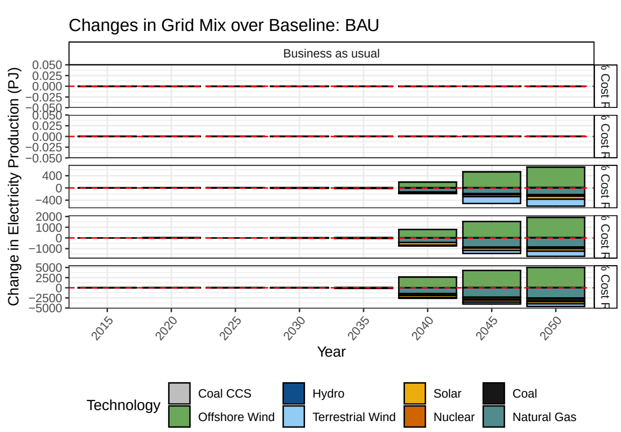
Changes in Grid Mix over Baseline
R7
40% Cost Red.
50% Cost Red.
70% Cost Red.
Change in Electricity Production (PJ)
Year
Technology
Coal CCS
Offshore Wind
Hydro
Terrestrial Wind
Solar
Nuclear
Coal
Natural Gas

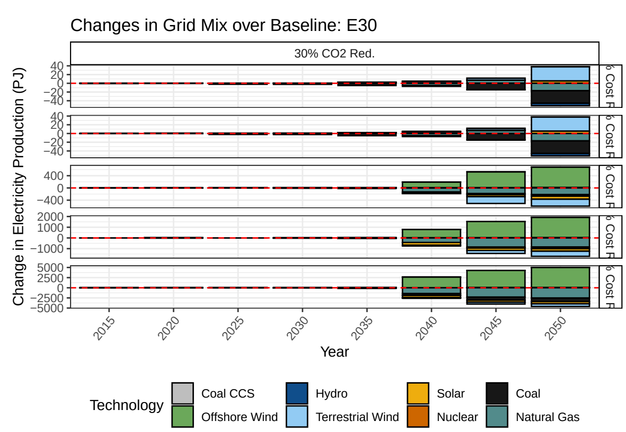


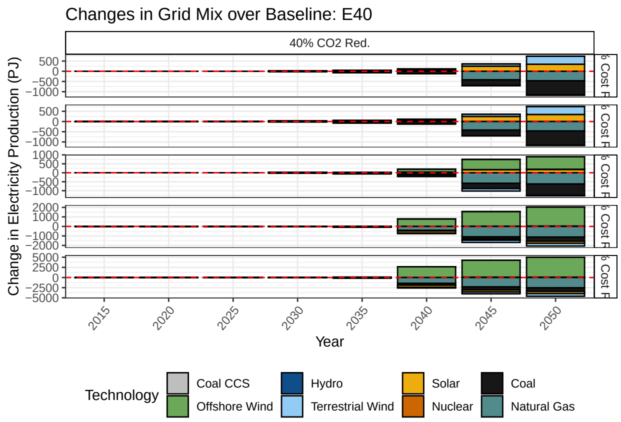
Changes in Grid Mix over Baseline
R8
40% Cost Red.
50% Cost Red.
70% Cost Red.
siness as us
0% CO2 Rec
0% CO2 Rec
30
0
−30
−60
−90
100
0
−100
−200
250
0
−250
−500
Change in Electricity Production (PJ)
2020
2030
2040
2050
Year
Technology
Coal CCS
Hydro
Terrestrial Wind
Solar
Nuclear
Coal
Natural Gas

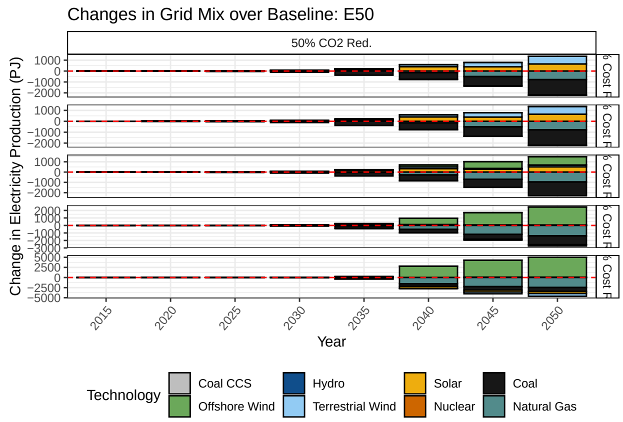


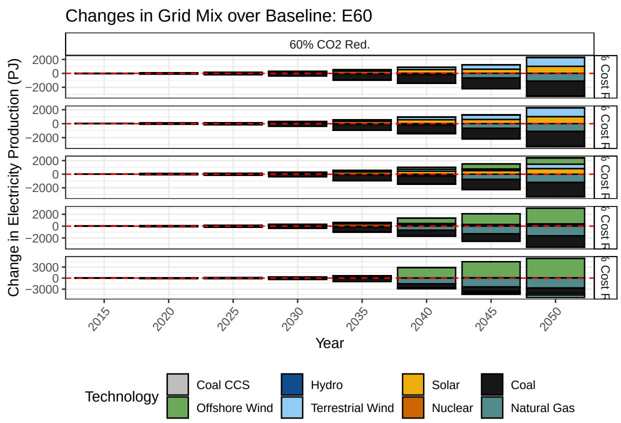
By Emissions Reduction %

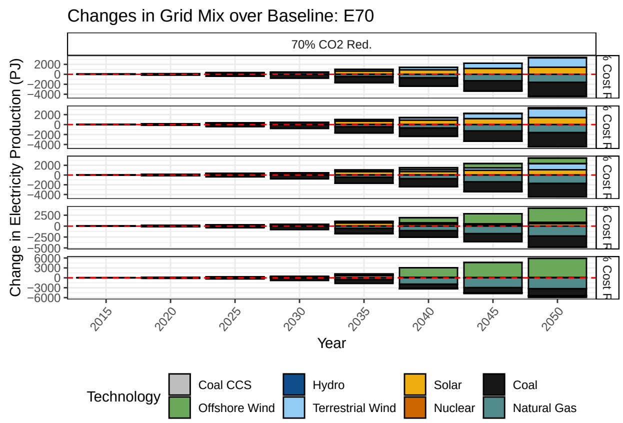


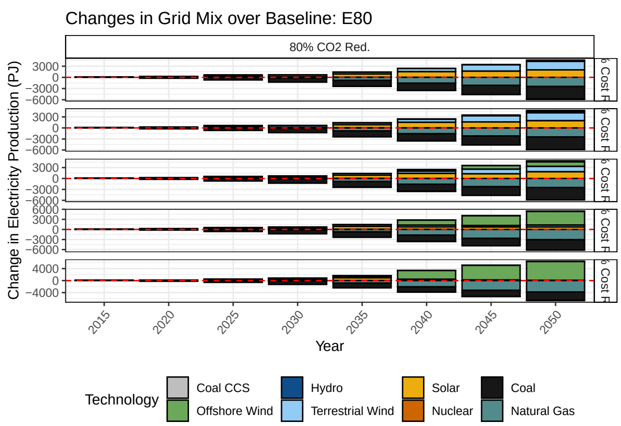




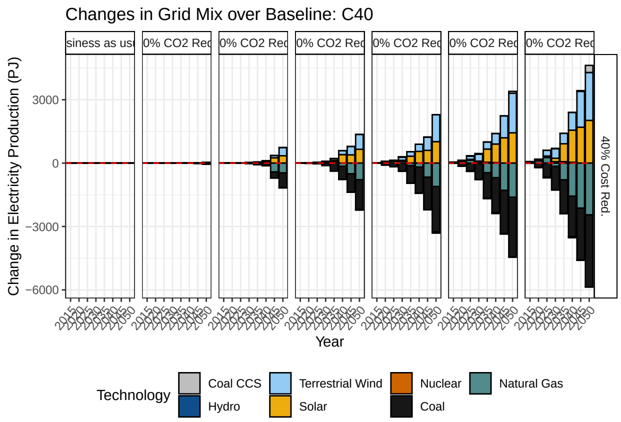


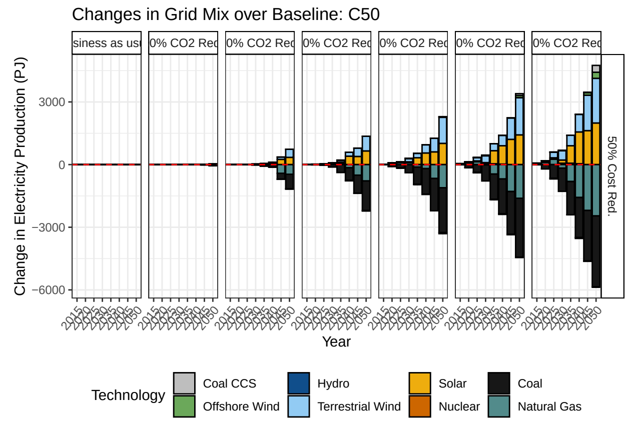


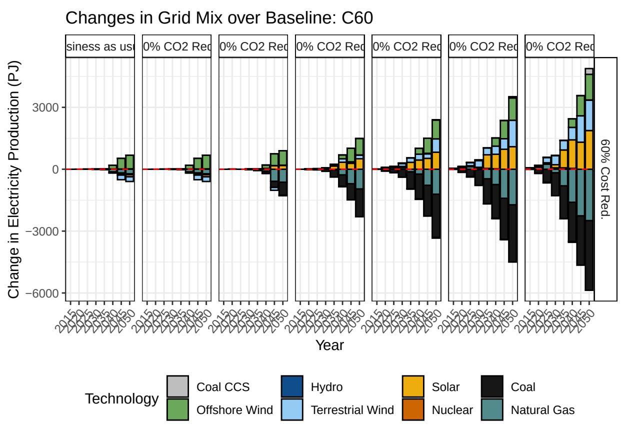


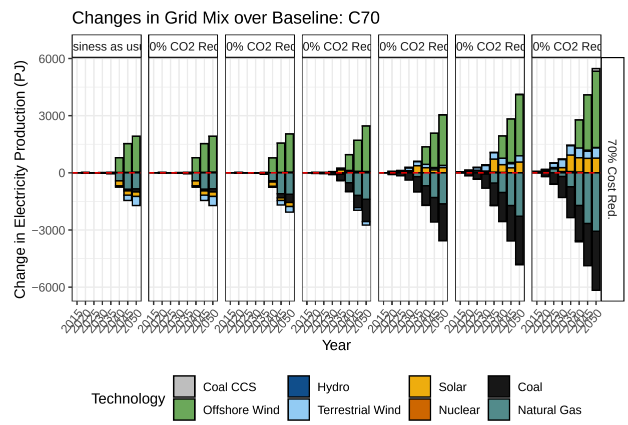


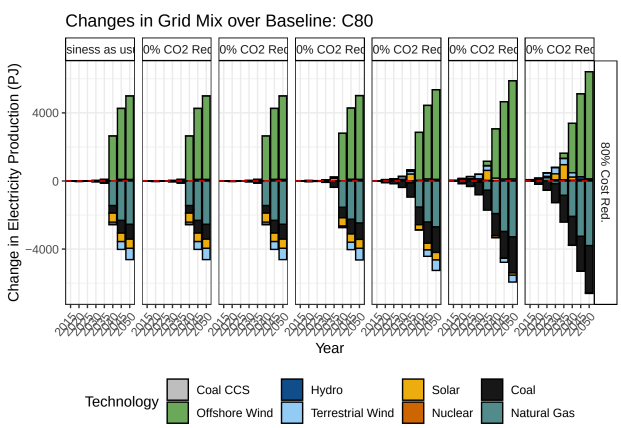
By Cost Reduction %


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


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

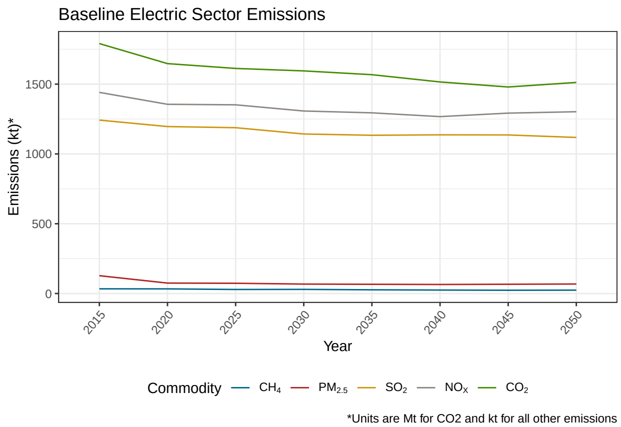

Changes in Grid Mix over Baseline: C60
Change in Electricity Production (PJ)
60% Cost Red.
Year
Technology
Coal CCS
Hydro
Solar
Coal
Offshore Wind
Terrestrial Wind
Nuclear
Natural Gas

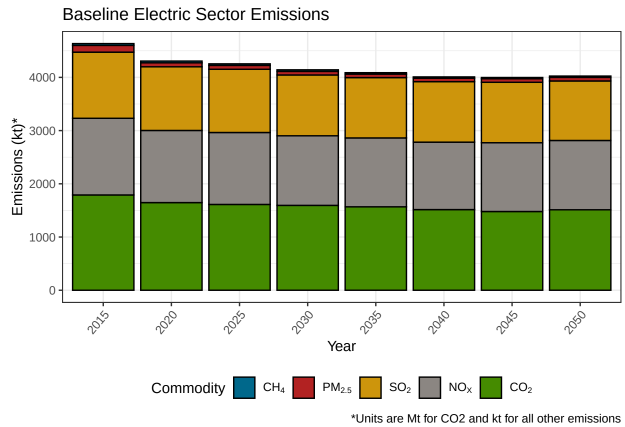

Changes in Grid Mix over Baseline: C70
Change in Electricity Production (PJ)
70% Cost Red.
Year
Technology
Coal CCS
Hydro
Solar
Coal
Offshore Wind
Terrestrial Wind
Nuclear
Natural Gas


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

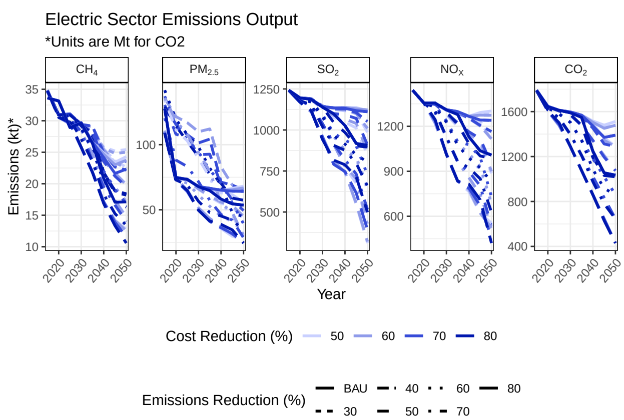
7 Emissions

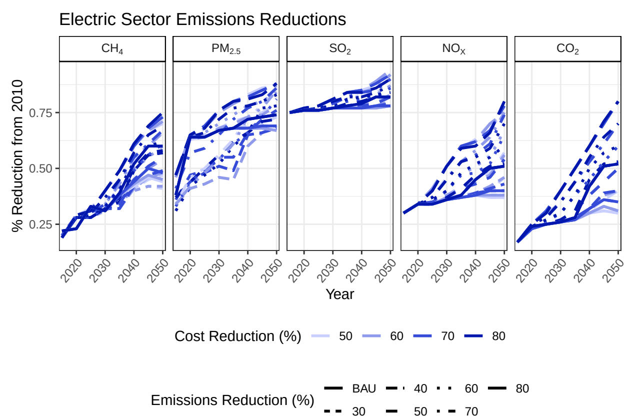
7.1 Baseline



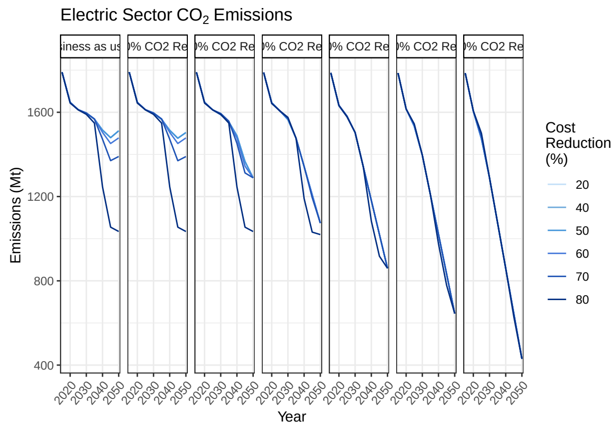


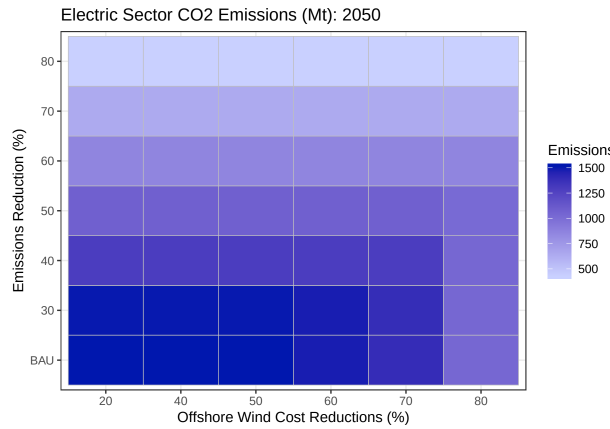
7.2 Emissions by Scenario and Commodity

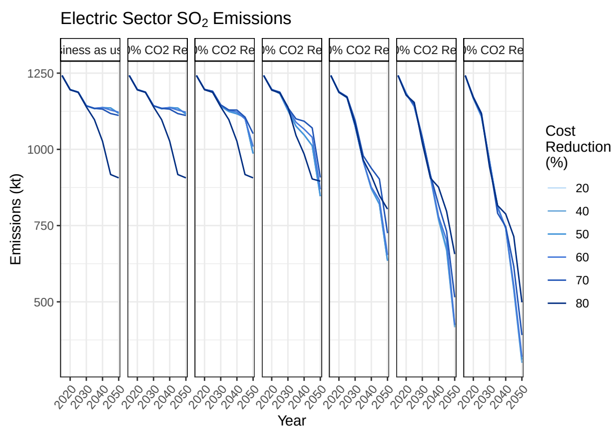


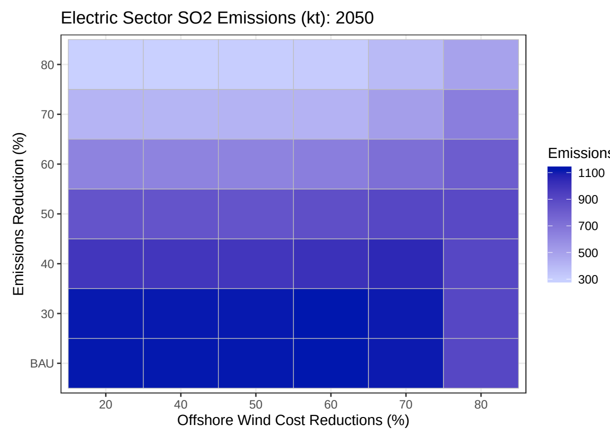


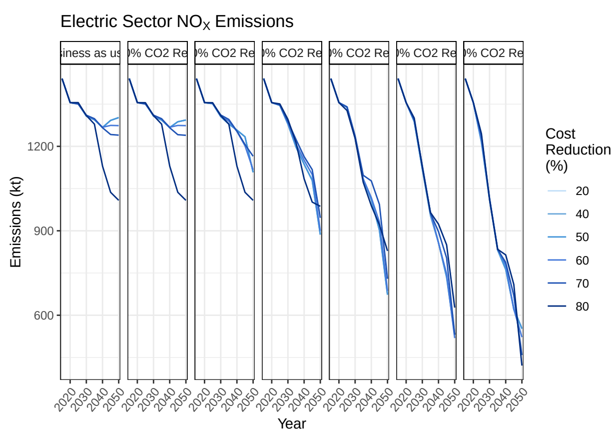
7.3 Emissions by Commodity - Values

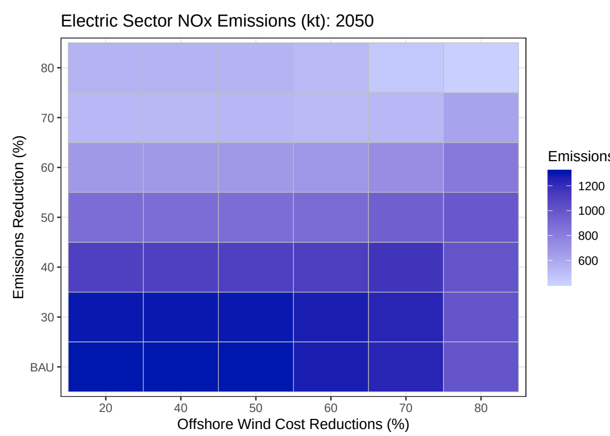


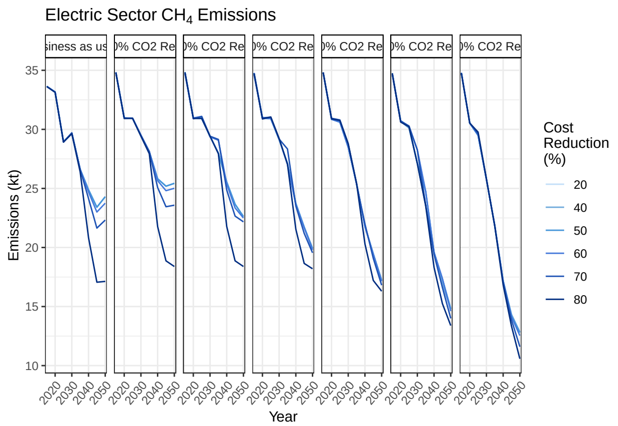


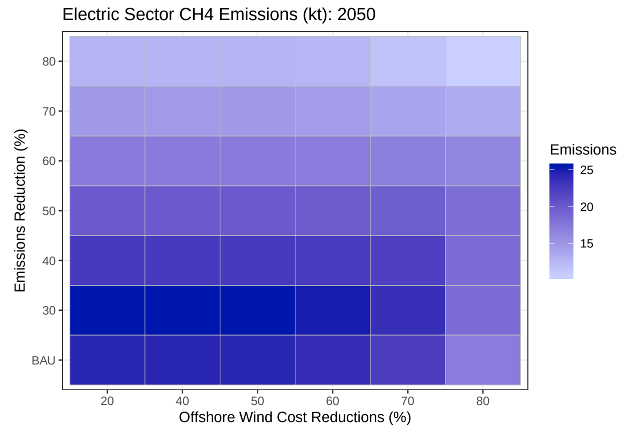


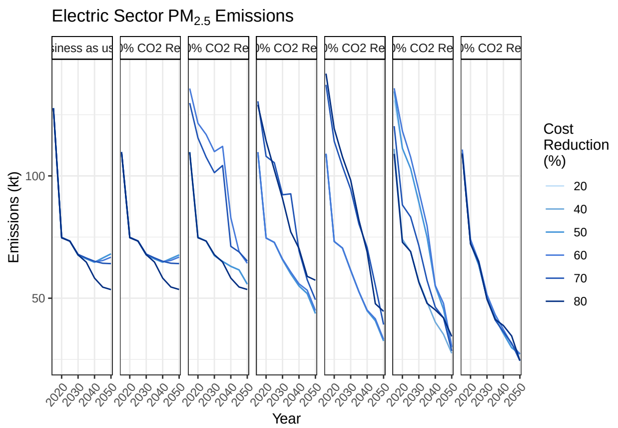


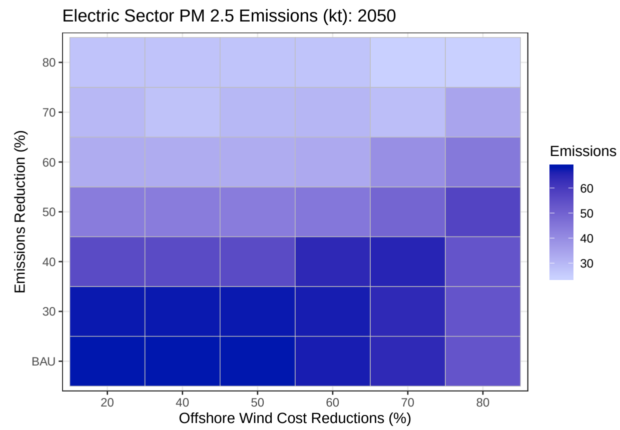




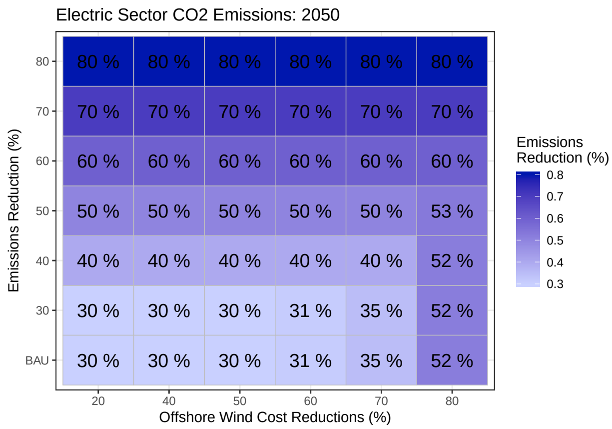

Electric Sector CH_4 Emissions
Emissions (kt)
Year
Cost Reduction (%)
20
40
50
60
70
80

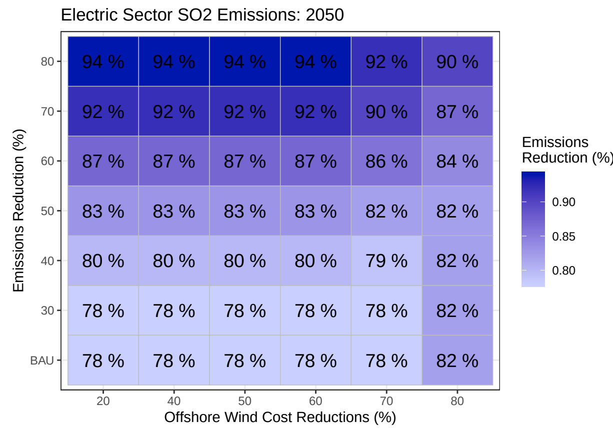

Electric Sector CH4 Emissions (kt): 2050
Emissions Reduction (%)
Offshore Wind Cost Reductions (%)
Emissions

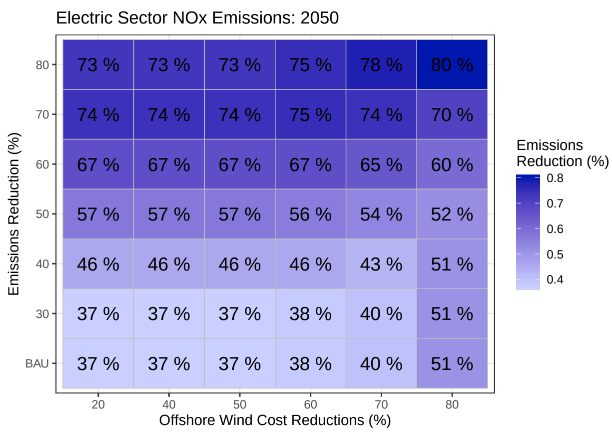

Electric Sector $PM_{2.5}$ Emissions
Emissions (kt)
Year
Cost Reduction (%)
20
40
50
60
70
80

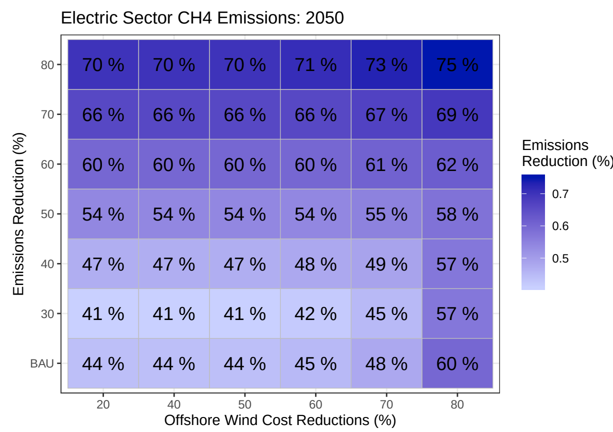

Electric Sector PM 2.5 Emissions (kt): 2050
Emissions Reduction (%)
Offshore Wind Cost Reductions (%)
Emissions

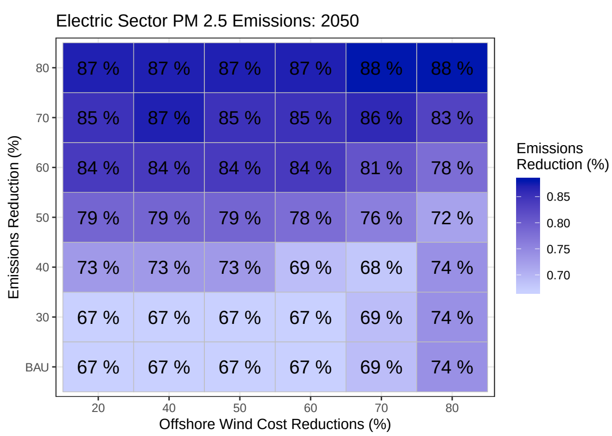
7.4 Emissions by Commodity - Percent Reduction



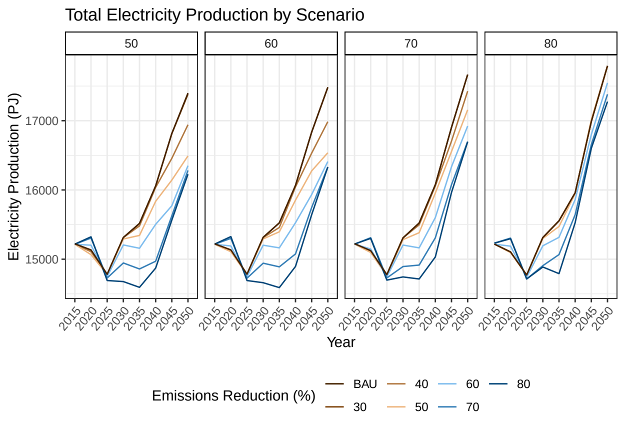


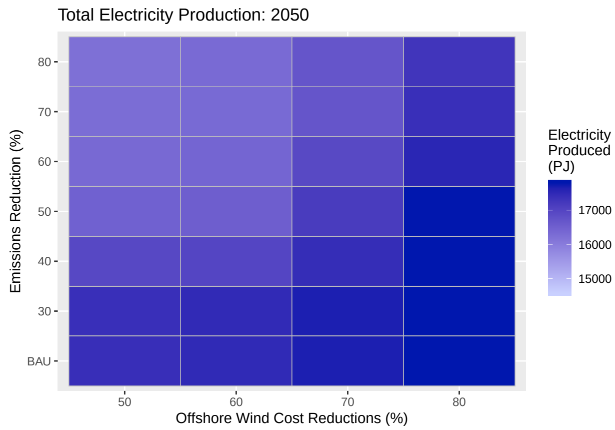




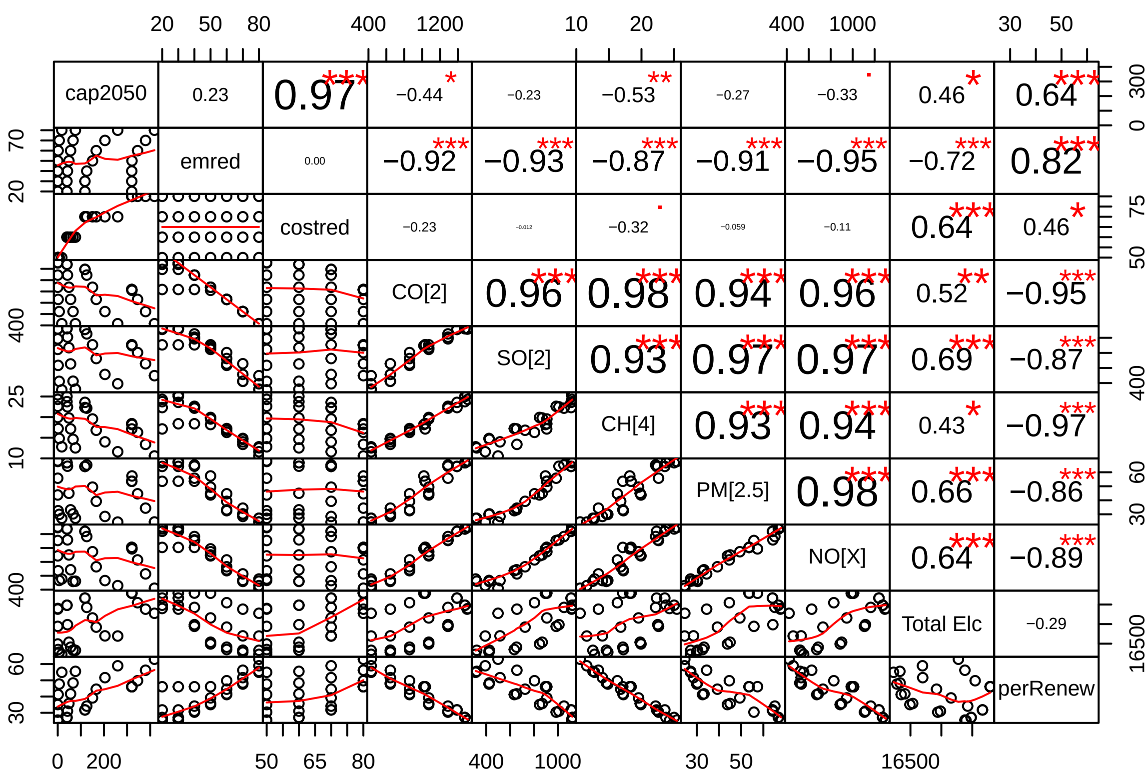


8 Total Electricity Production





9 Correlations



10 Regressions

	OSW Capacity	% Renewables	Total Elc
CO2 Cap	24.04 **	8.89 ***	-374.63 ***
	(8.00)	(0.77)	(39.33)
Cost Reduction	129.73 ***	4.95 ***	350.49 ***
	(8.00)	(0.77)	(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 ***	-252.57 ***	-273.35 ***	-3.55 ***	-14.38 ***
	(22.49)	(20.14)	(18.65)	(0.31)	(1.17)
OSW Capacity	-73.17 **	7.26	-27.54	-1.45 ***	-0.49
	(22.49)	(20.14)	(18.65)	(0.31)	(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.