# Offshore Wind Results and Analysis

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*25 September, 2019*

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## 1 Disclosure

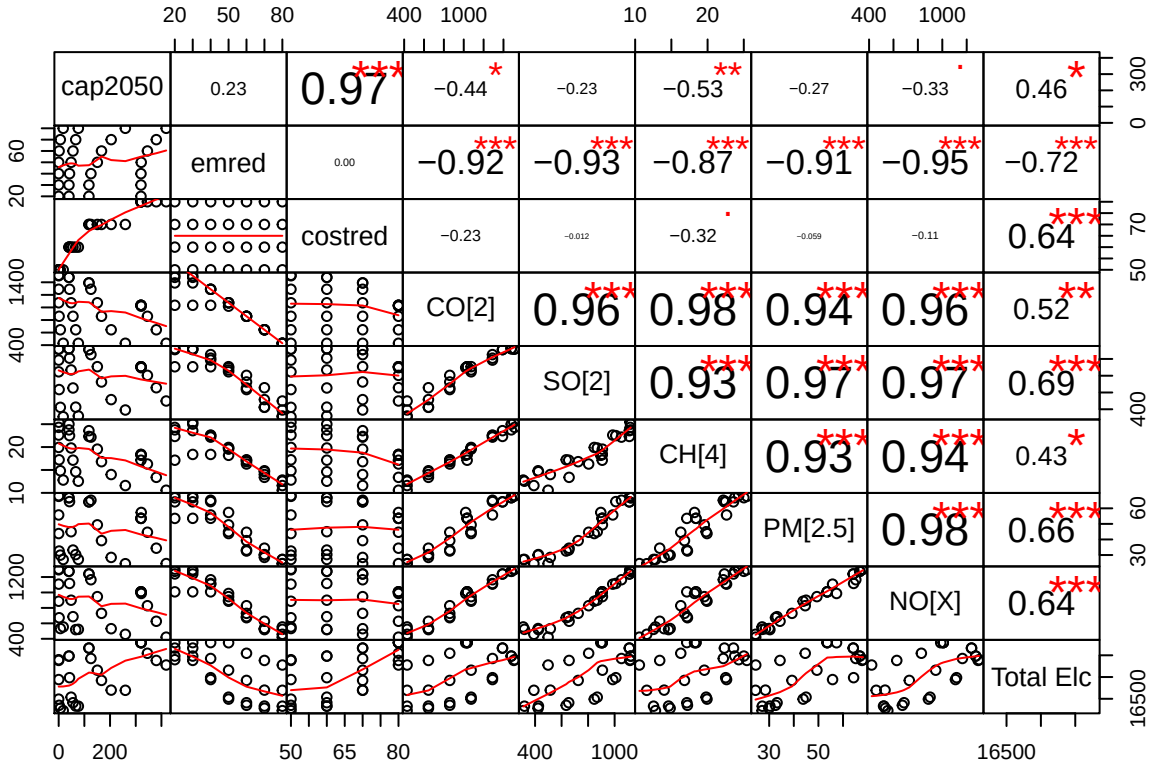
This document functions as an all-inclusive working directory for synthesis and graphical analysis of the results from the offshore wind research of Morgan Browning, an ORISE Fellow at the U.S. Environmental Protection Agency's Office of Research and Development. This document and its contents are not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

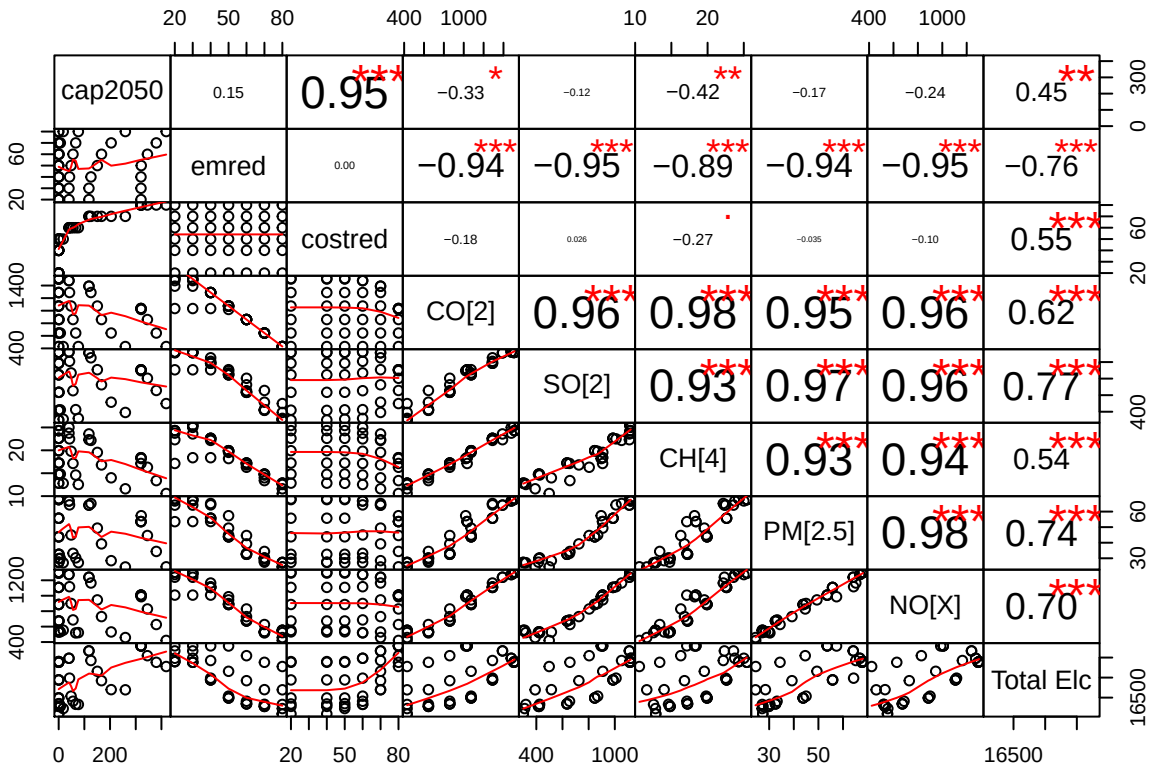
It is annotated primarily for ease of reproducability and a general understanding of the results.

## 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

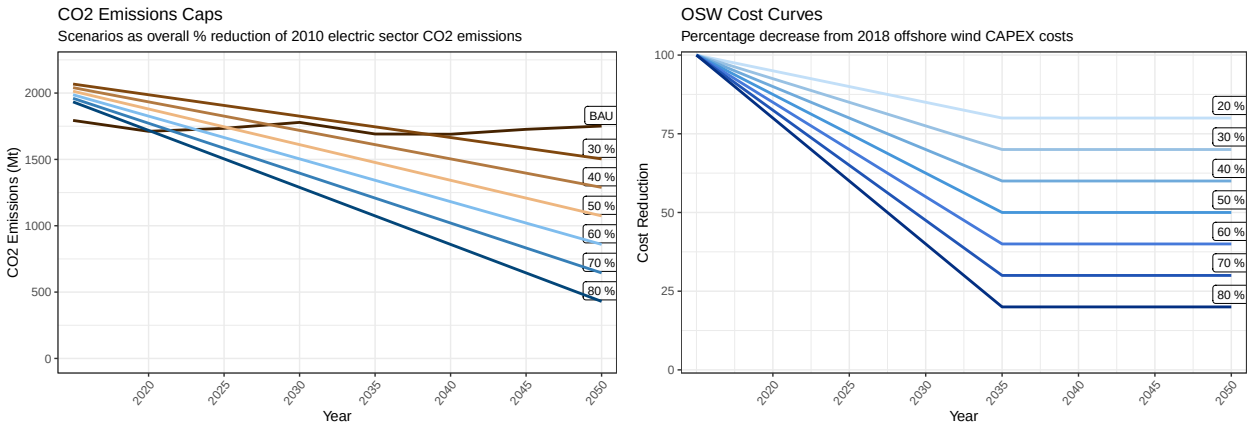
The nested parametric sensitivity analysis was built on combinations of two sets of scenarios:

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 |

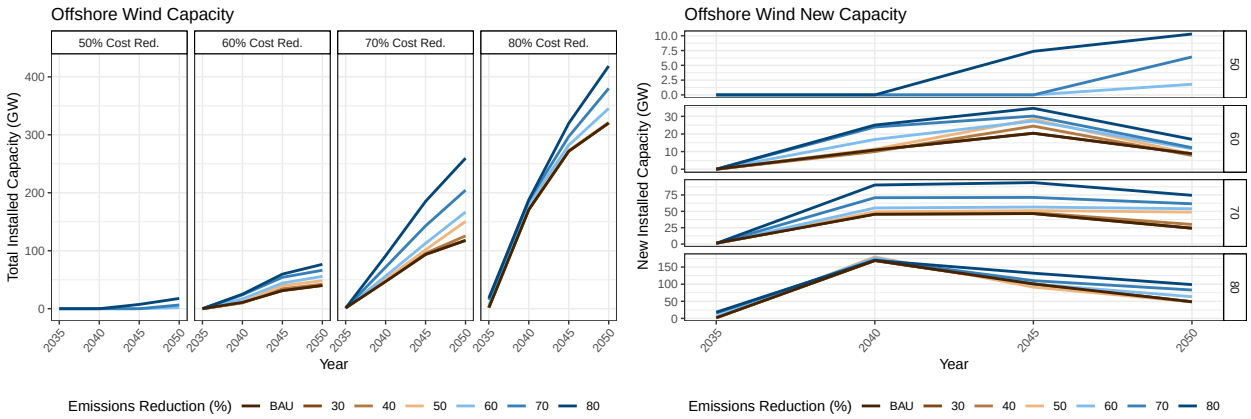
*Note:*
U.S. EIA Annual Energy Outlook 2019

# 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.

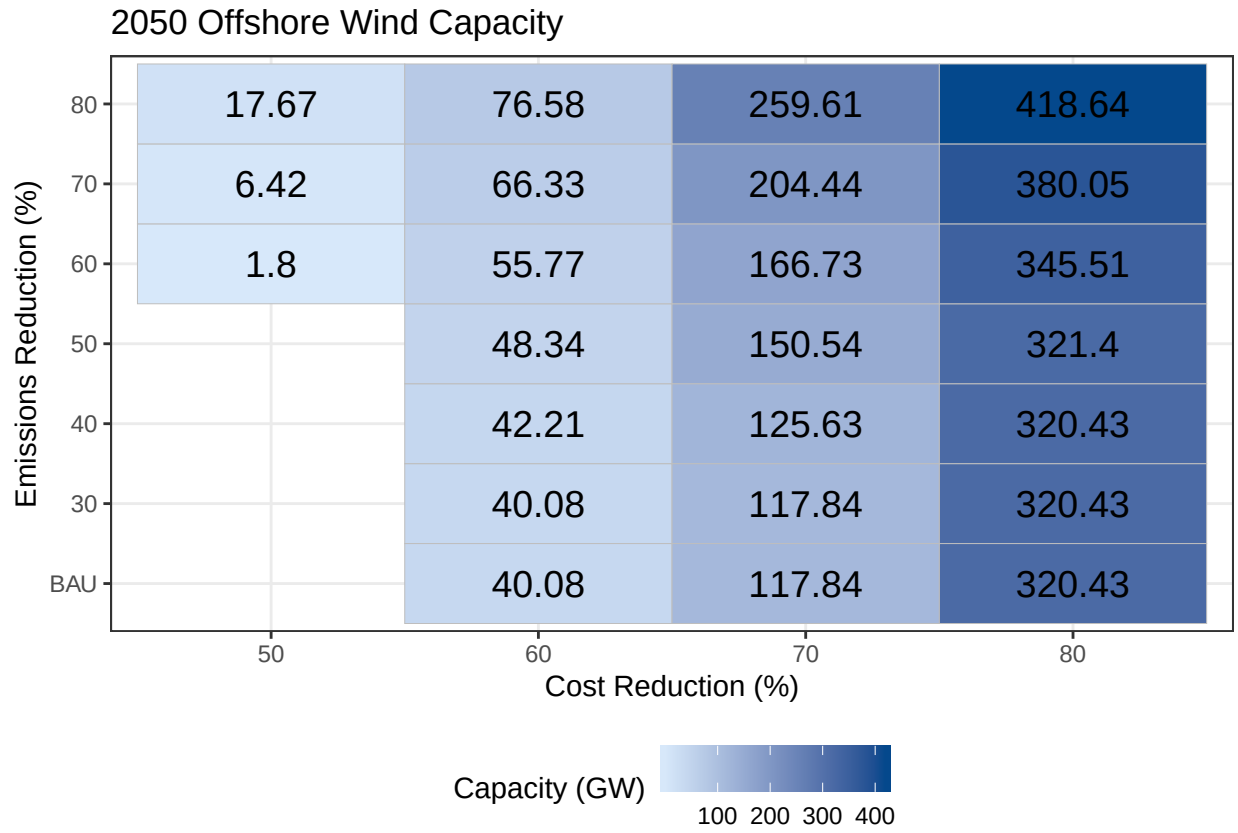
## 5.1 Capacity Buildout

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.



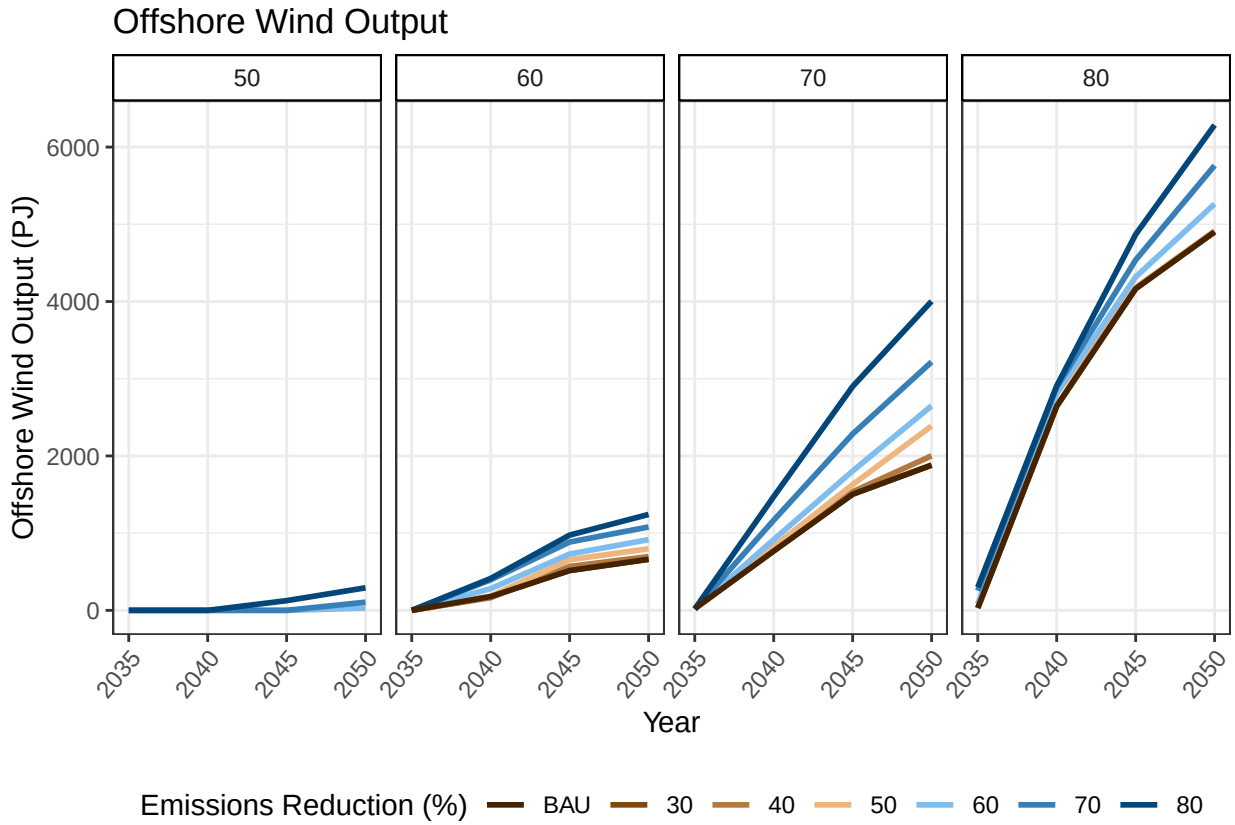

## 5.3 Output

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

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 |

of offshore wind. All generated electricity is utilized in the modeled scenarios.

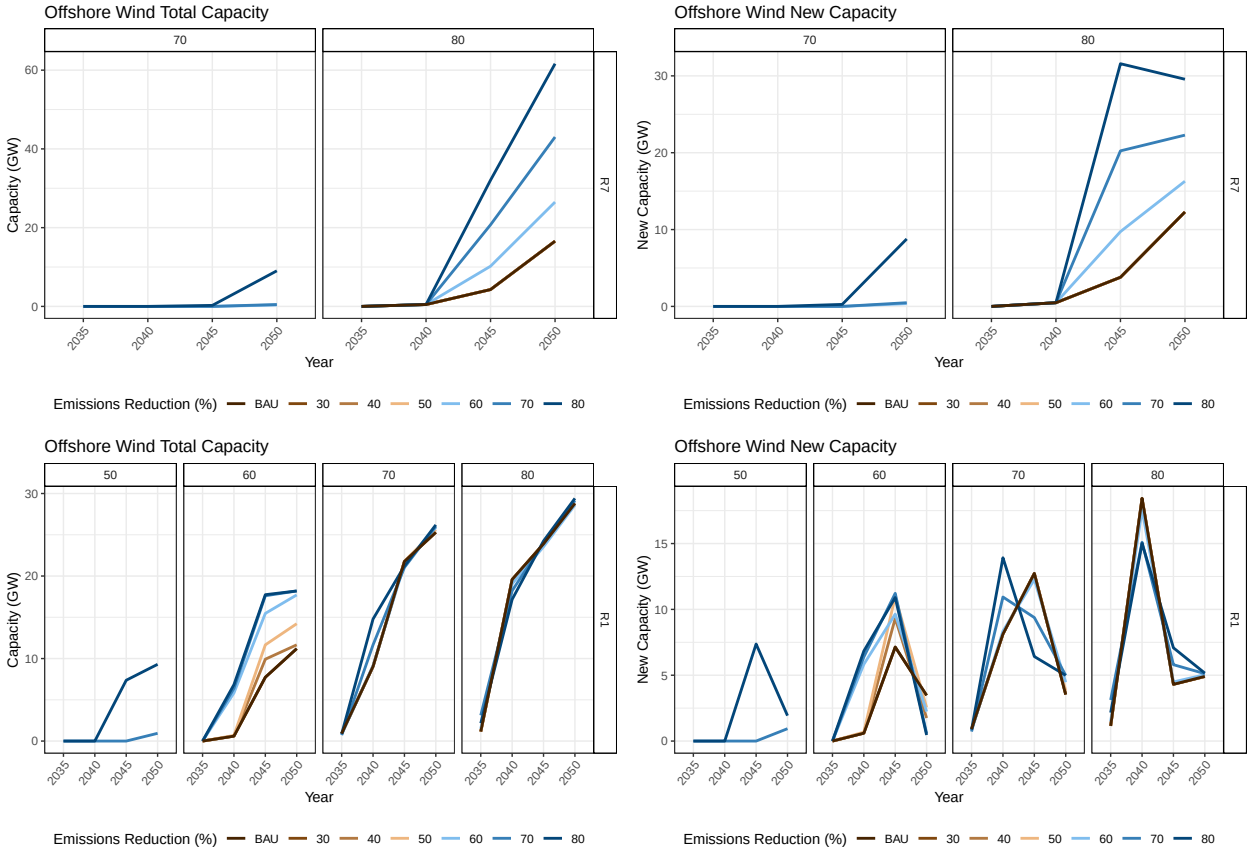


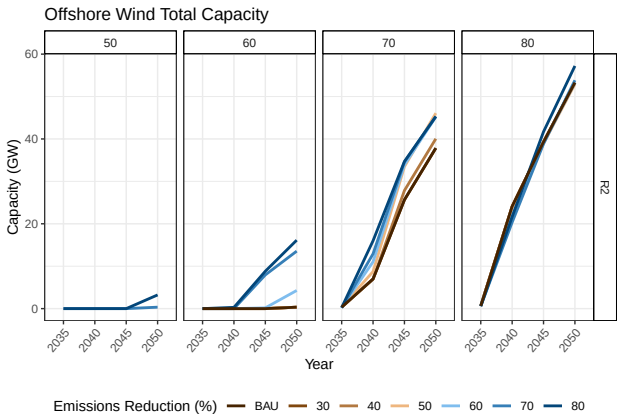

## 5.4 Regions

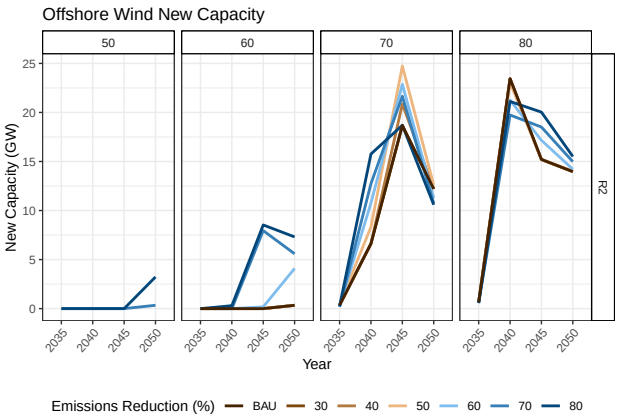
Cumulative and new addition offshore wind capacity by region. Regions are listed from least to highest electricity output.

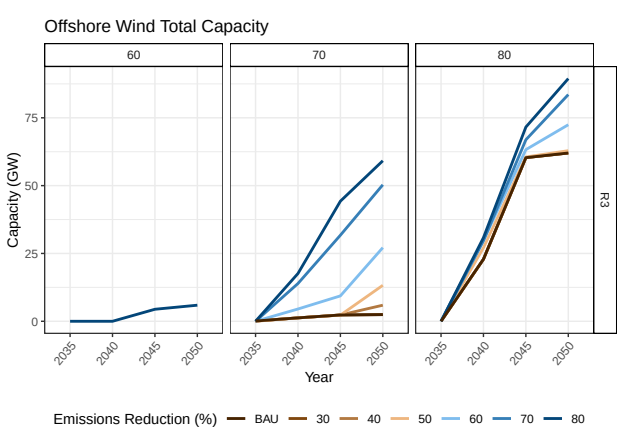
Table 3: Offshore Wind Total Output (PJ): 2050

| 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 |

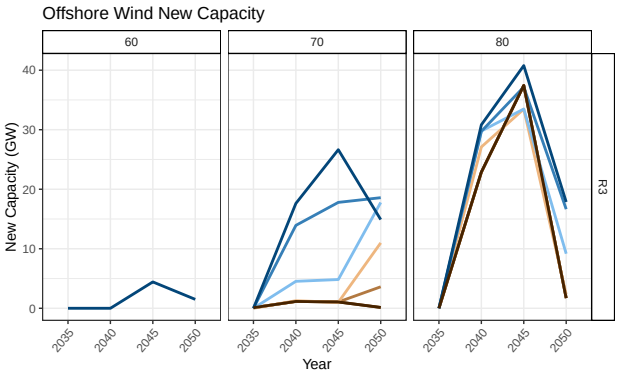


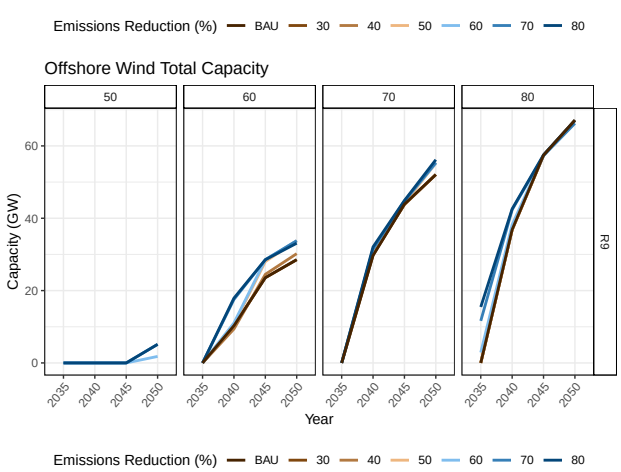

Offshore Wind Total Capacity
50
60
70
80
Capacity (GW)
0
20
40
60
2035
2040
2045
2050
Year
R2


Offshore Wind New Capacity
50
60
70
80
New Capacity (GW)
0
5
10
15
20
25
2035
2040
2045
2050
Year
R2

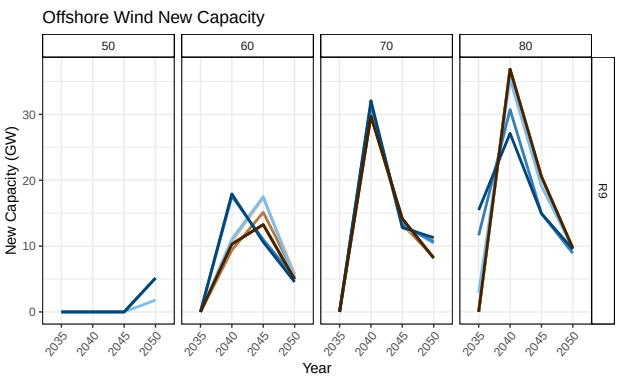

Emissions Reduction (%)
BAU
30
40
50
60
70
80


Offshore Wind Total Capacity
60
70
80
Capacity (GW)
0
25
50
75
2035
2040
2045
2050
Year
R3

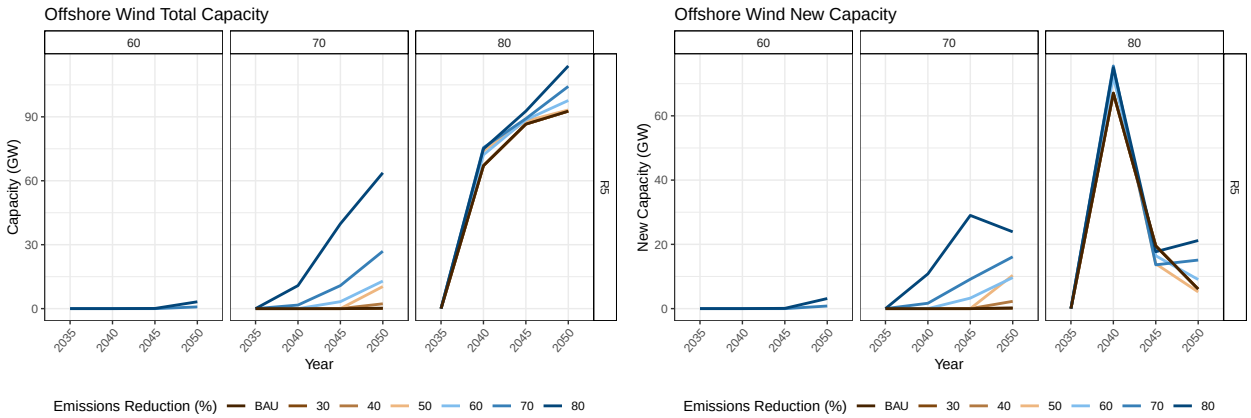

Offshore Wind New Capacity
60
70
80
New Capacity (GW)
0
10
20
30
40
2035
2040
2045
2050
Year
R3


Emissions Reduction (%)
BAU
30
40
50
60
70
80


Offshore Wind Total Capacity
50
60
70
80
Capacity (GW)
0
20
40
60
2035
2040
2045
2050
Year
R9


Offshore Wind New Capacity
50
60
70
80
New Capacity (GW)
0
10
20
30
2035
2040
2045
2050
Year
R9


Emissions Reduction (%)
BAU
30
40
50
60
70
80




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

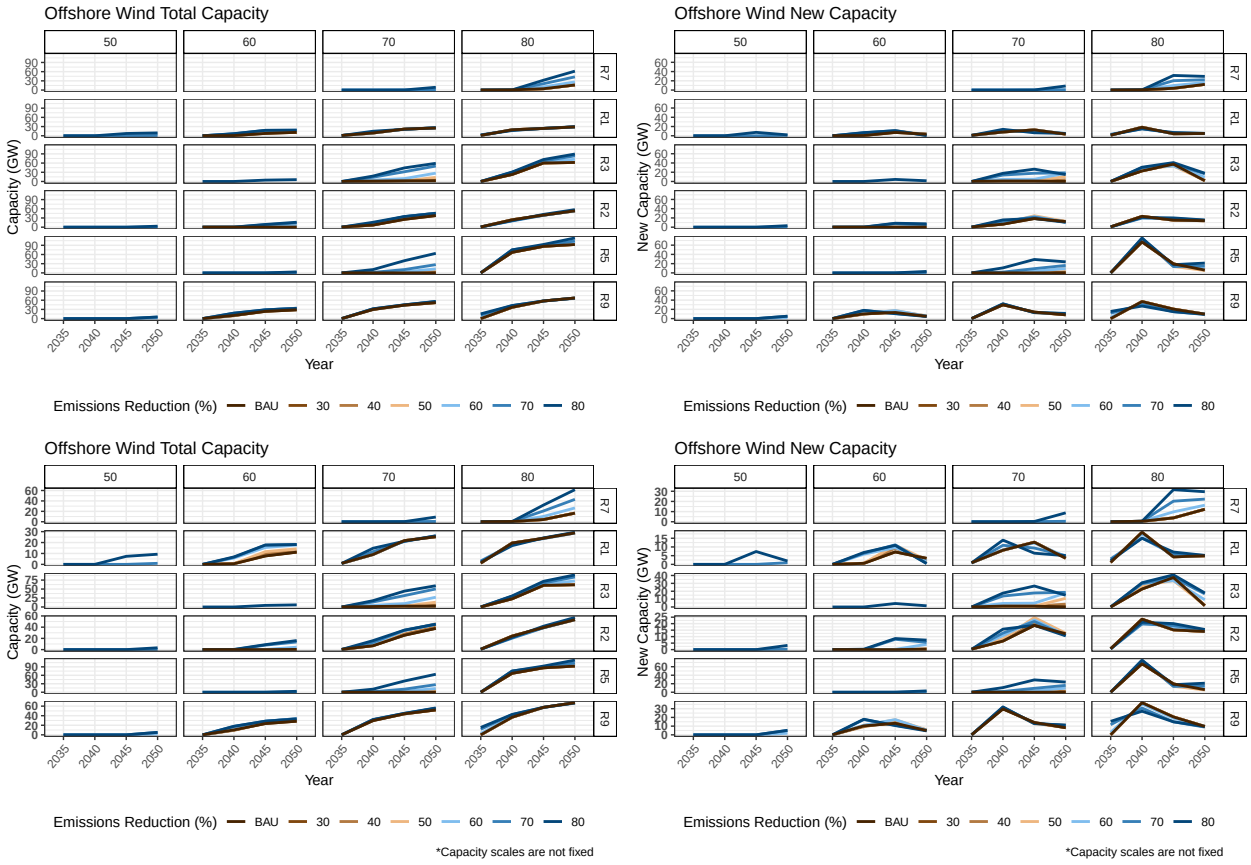


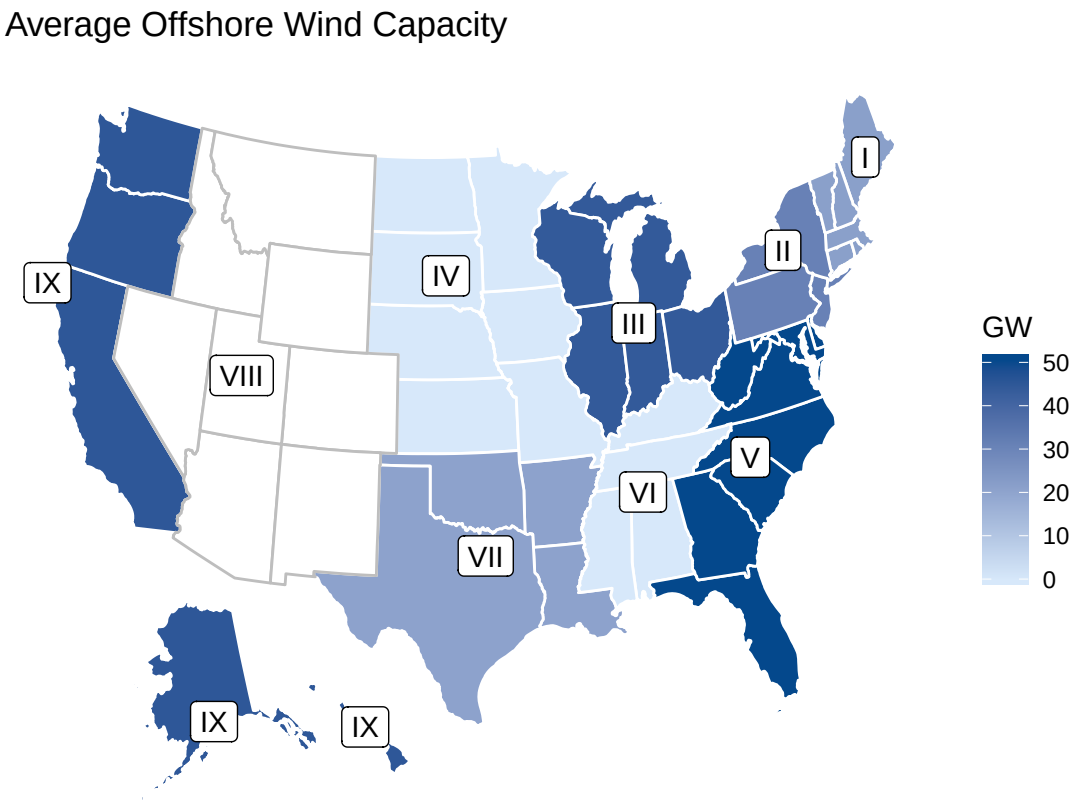

Table 4: Average Installed Capacity (GW)

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

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 |

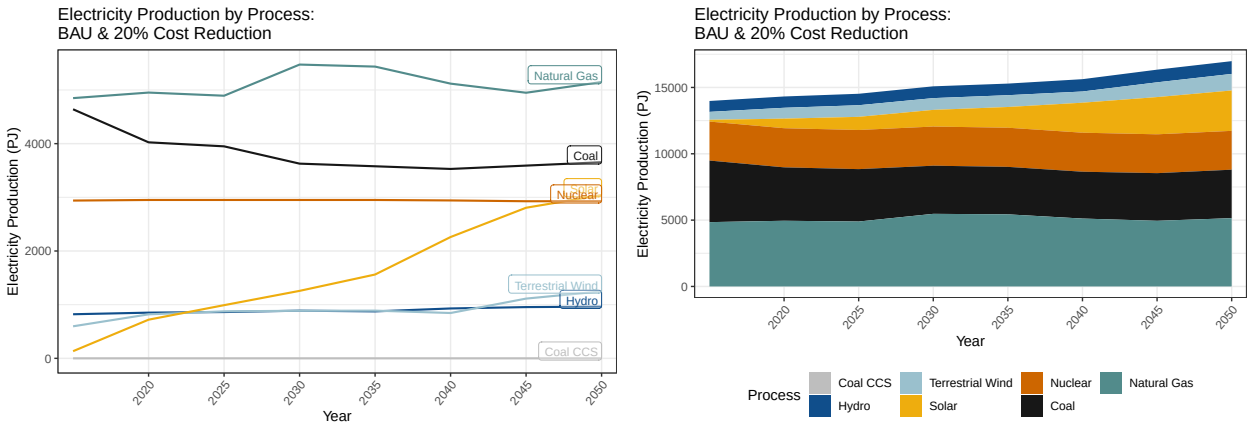
Map of average total capacity




# 6 Grid Mix

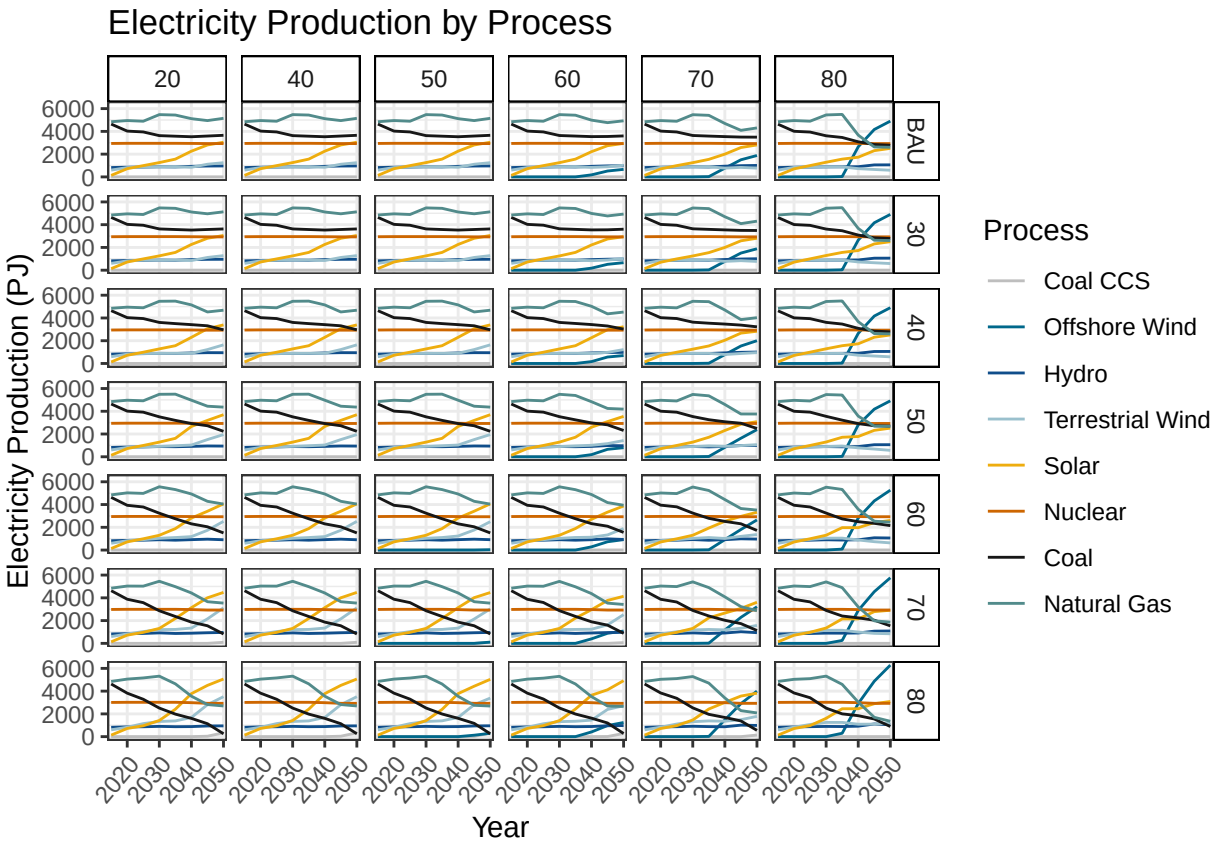
## 6.1 Baseline Production

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

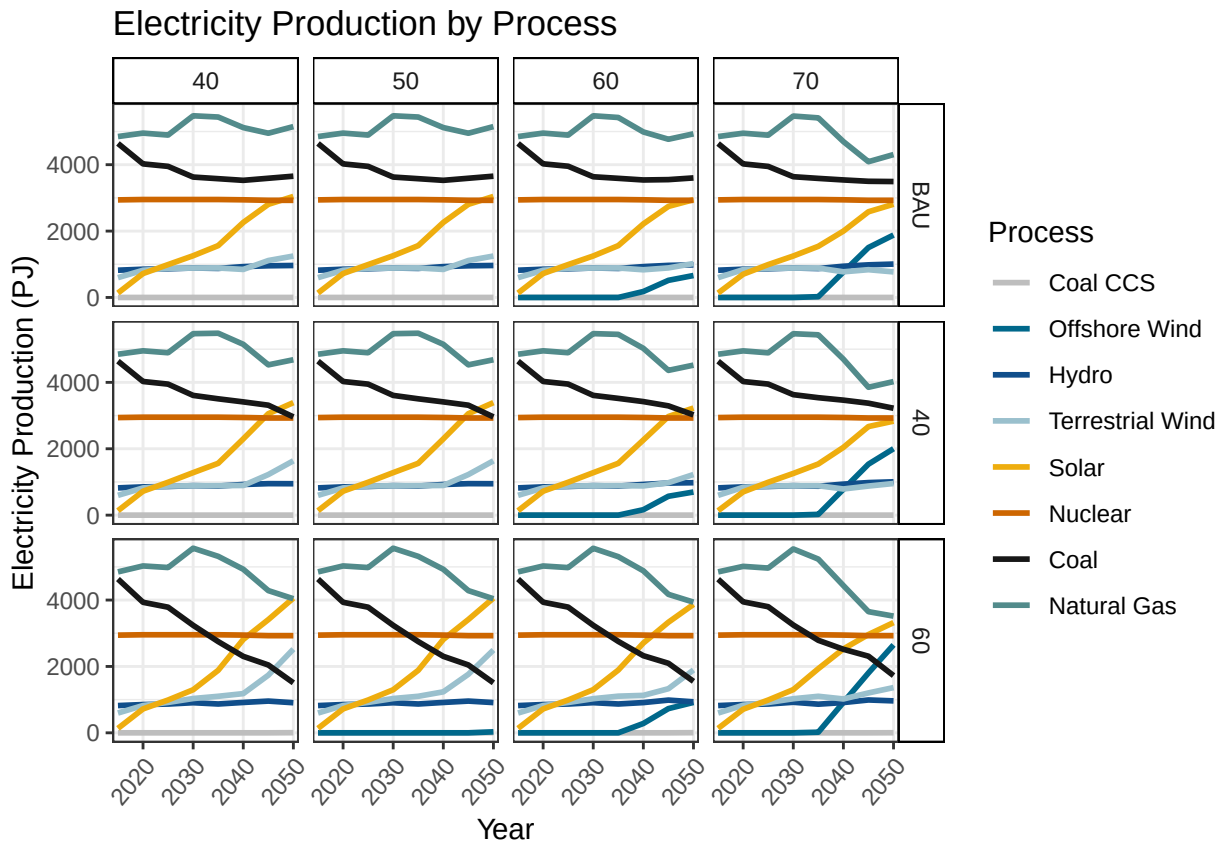



## 6.2 All Scenarios

Complete Set

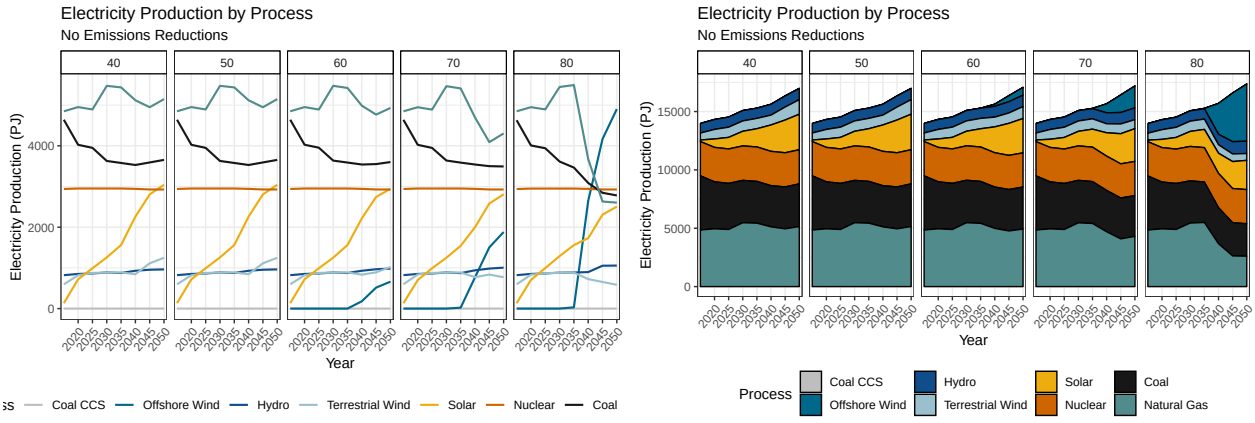



Parsed Set

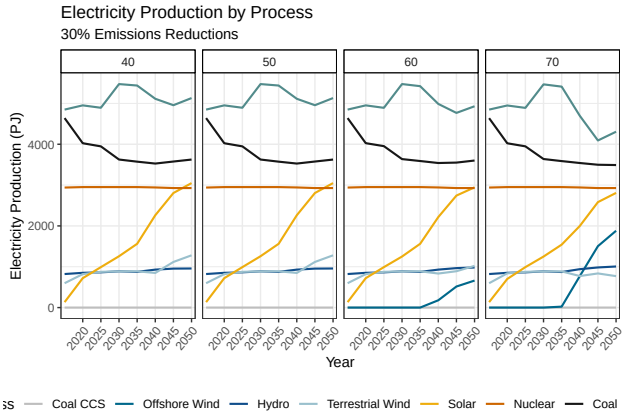


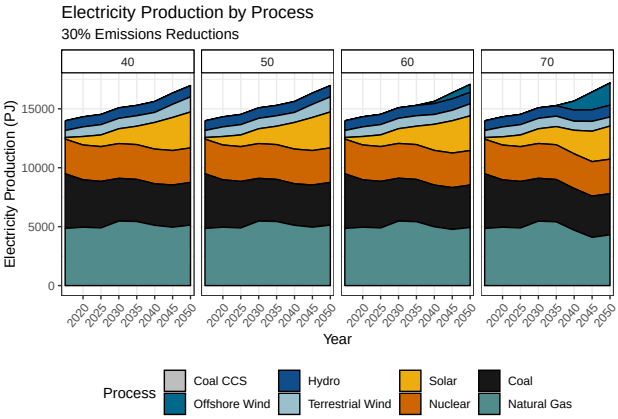

## 6.3 Emissions Cap

BAU emissions

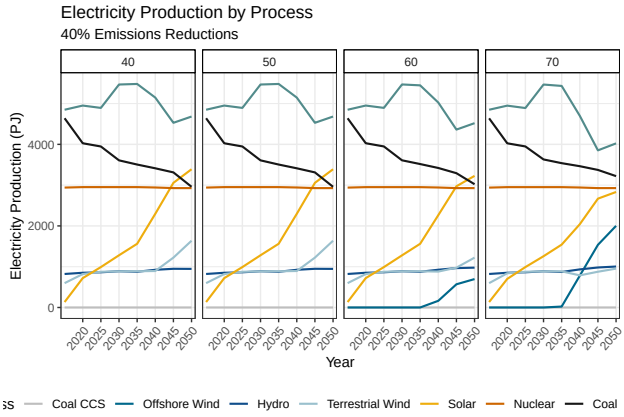


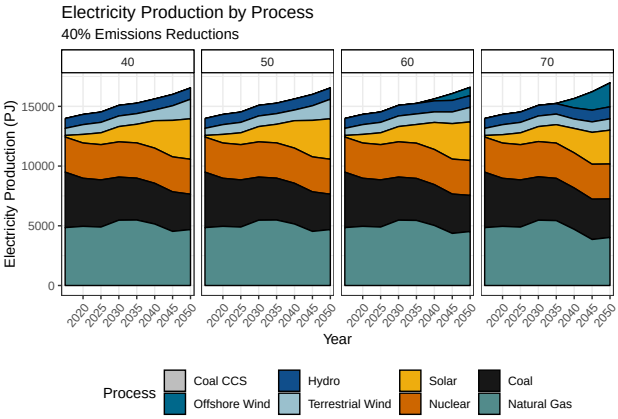

30% emissions reduction



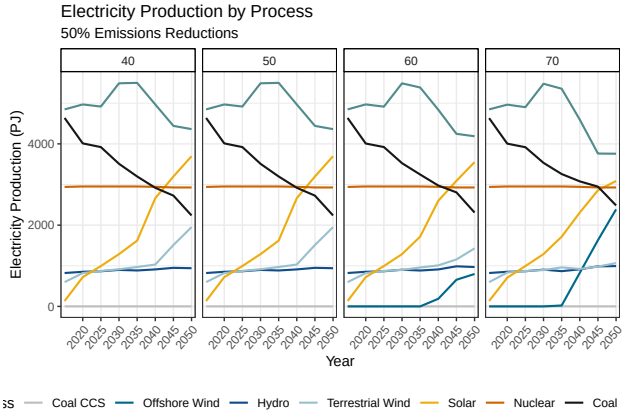



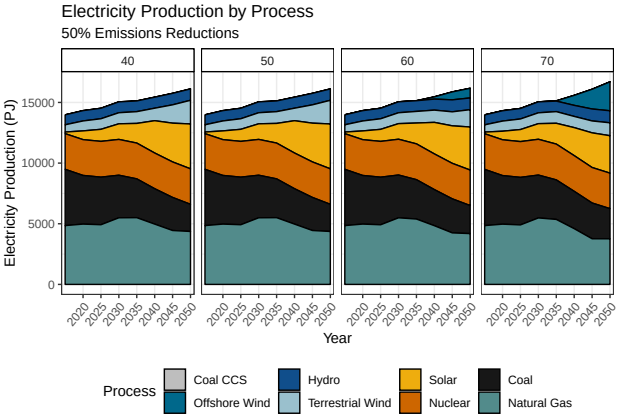

## 40% emissions reduction



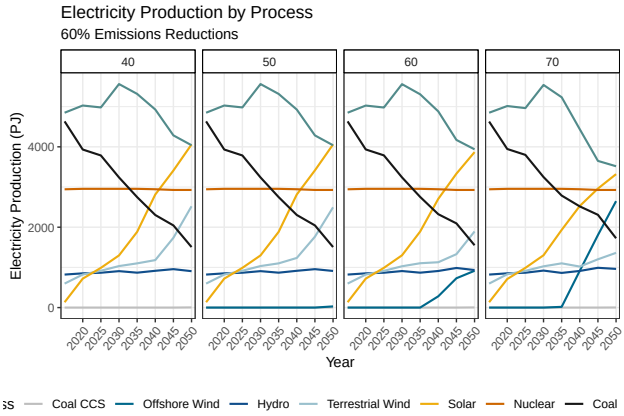



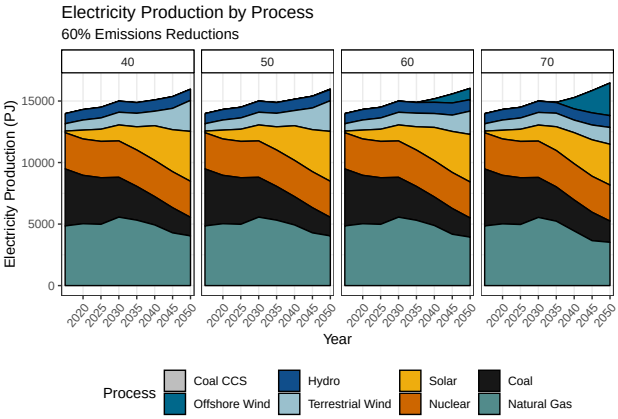

## 50% emissions reduction



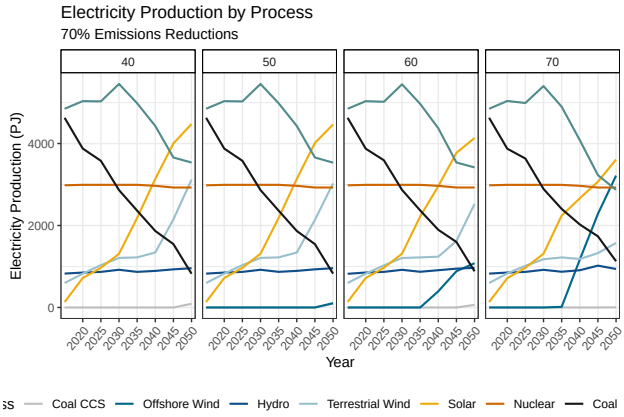



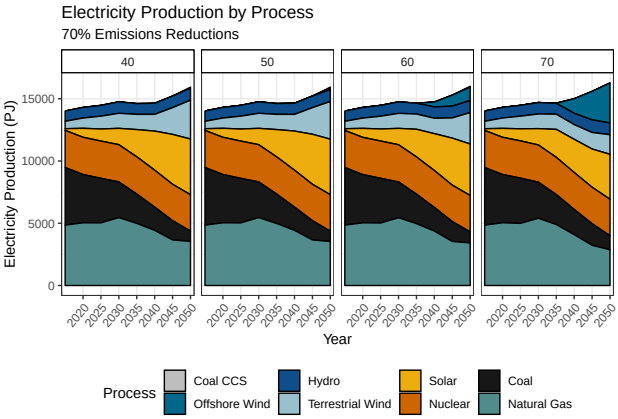

## 60% emissions reduction



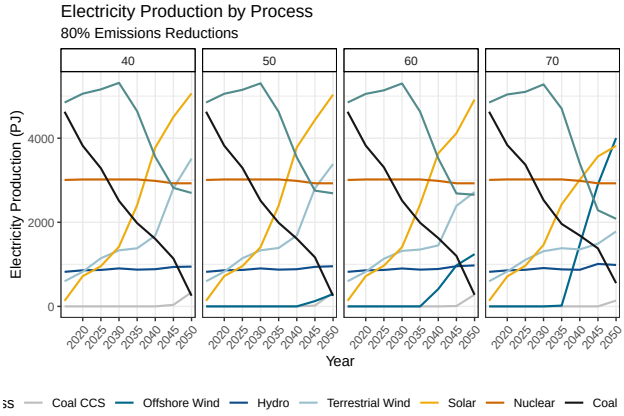



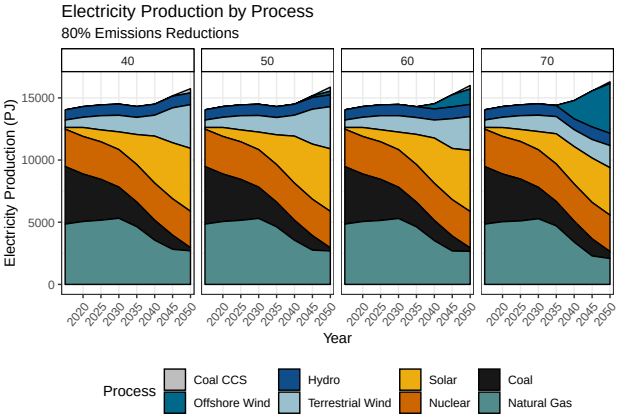

70% emissions reduction



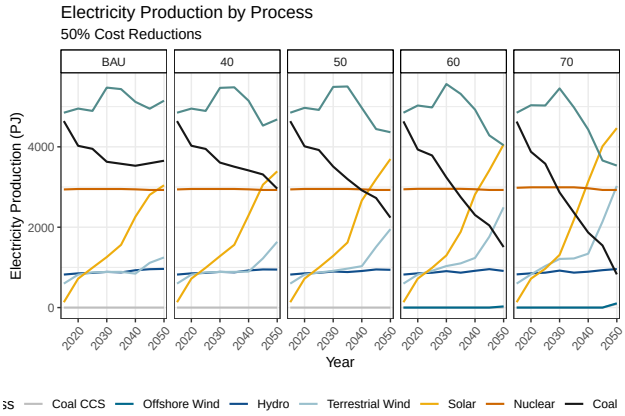

80% emissions reduction

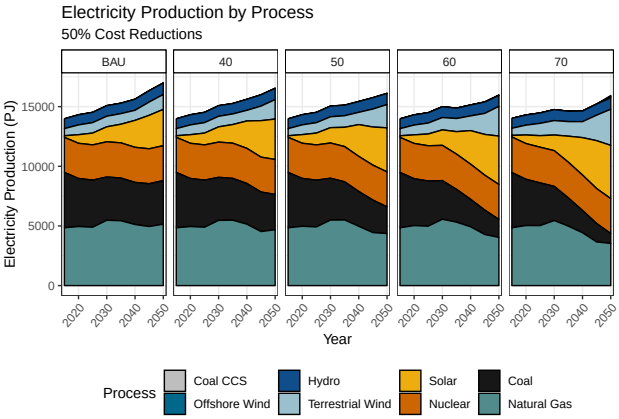


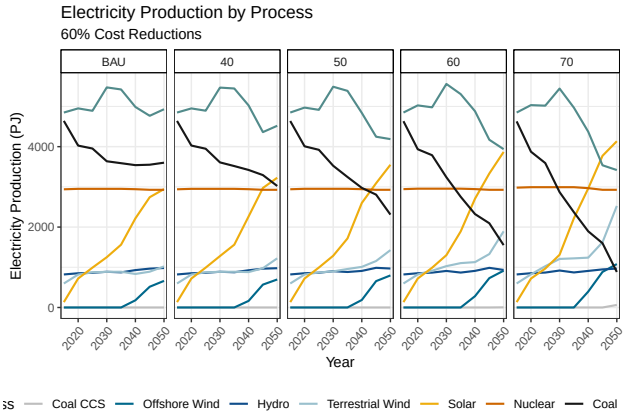

## 6.4 Cost Reductions

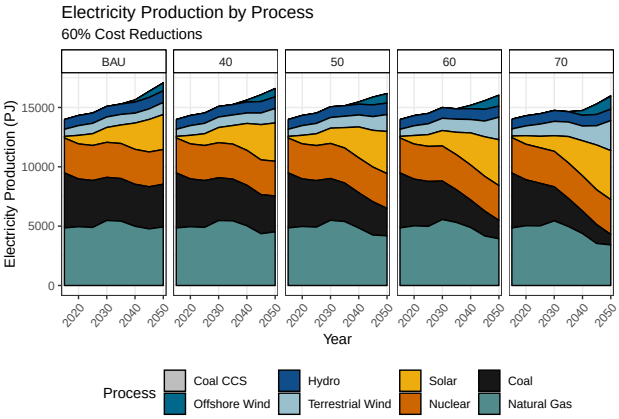
50% cost reduction



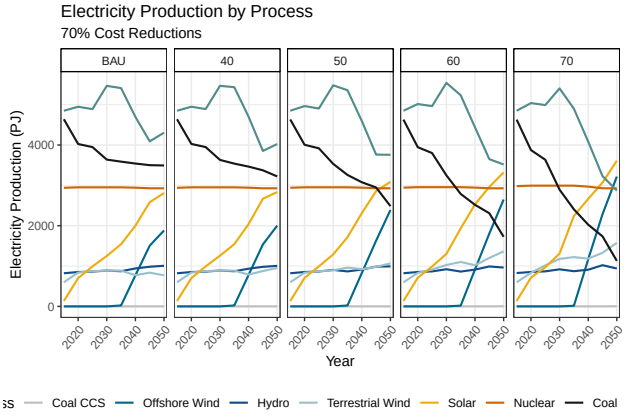



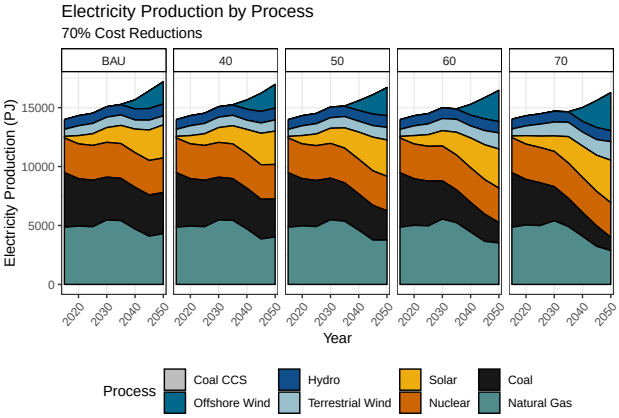

## 60% cost reduction



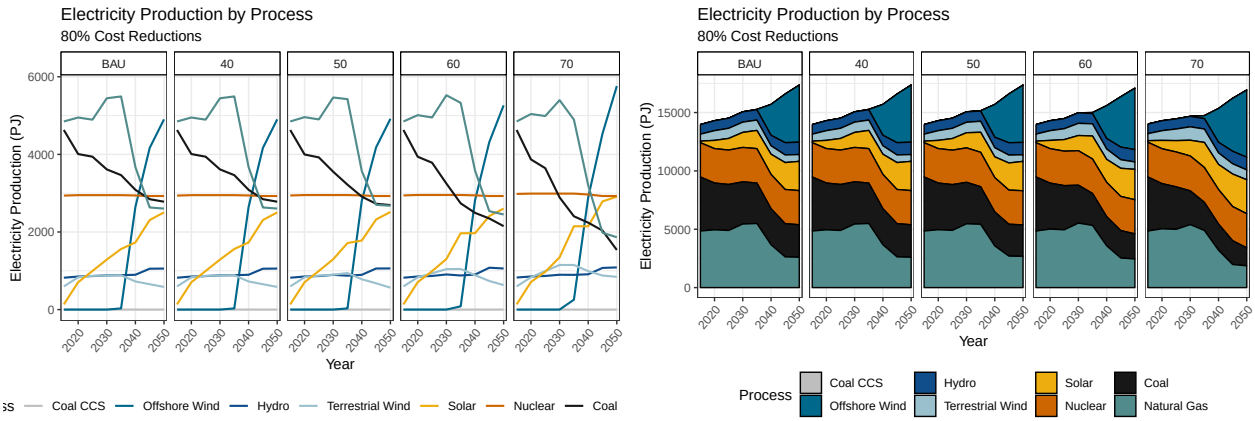




## 70% cost reduction

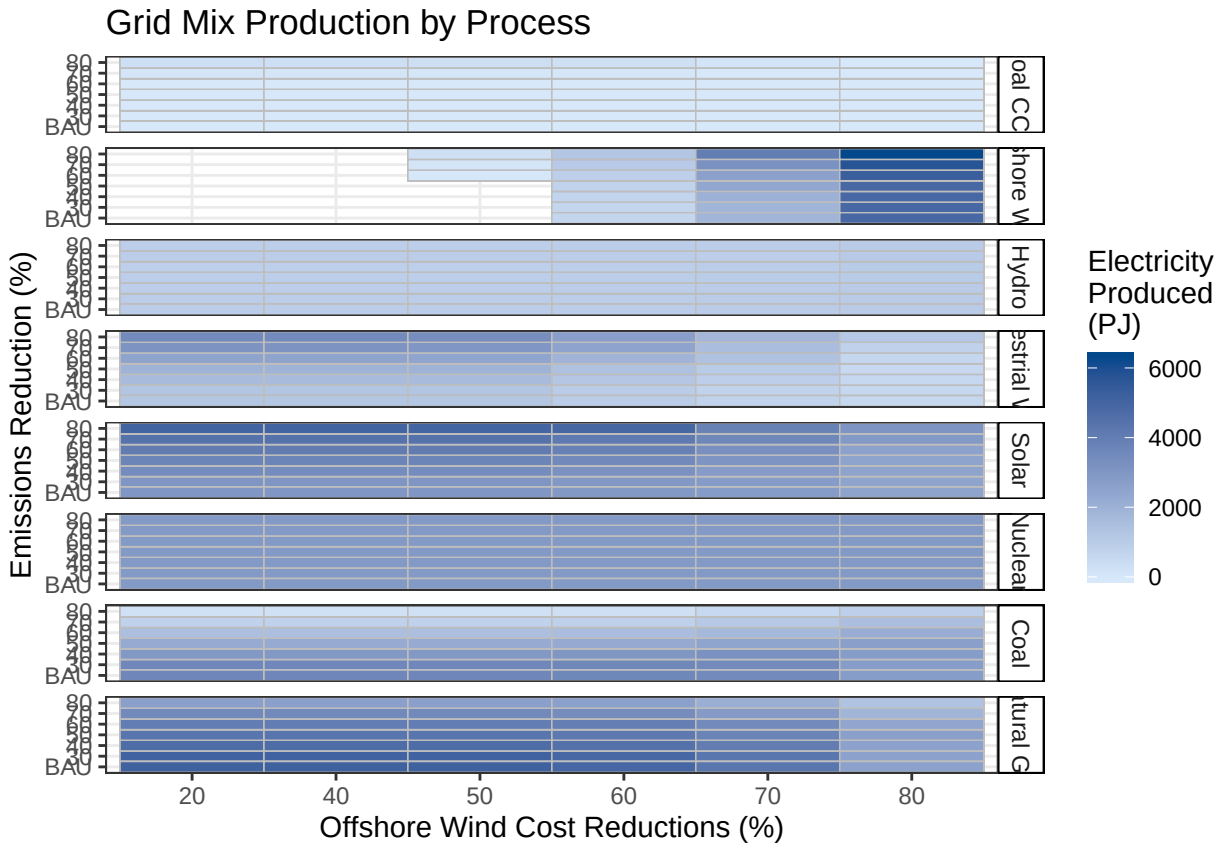


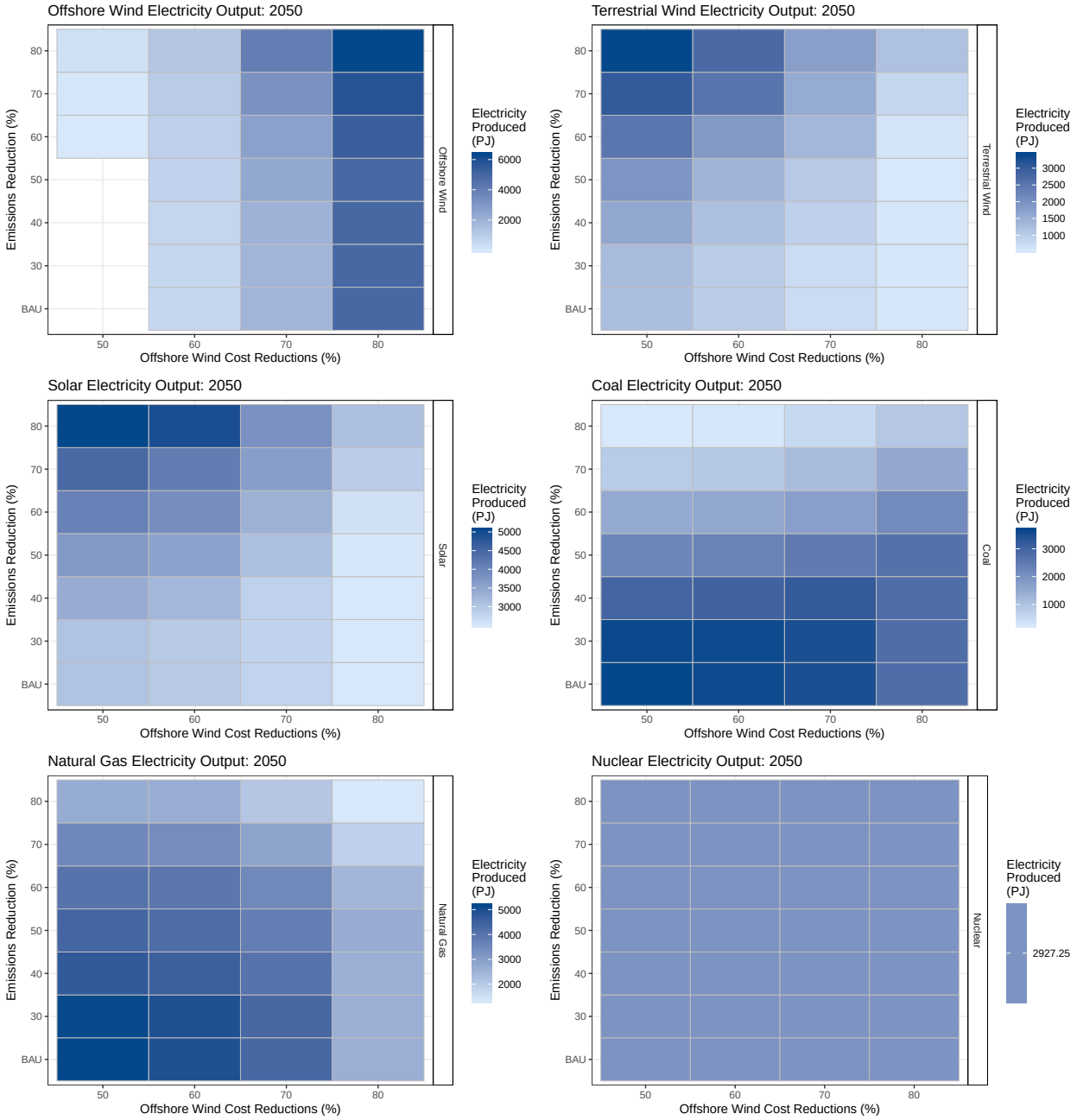



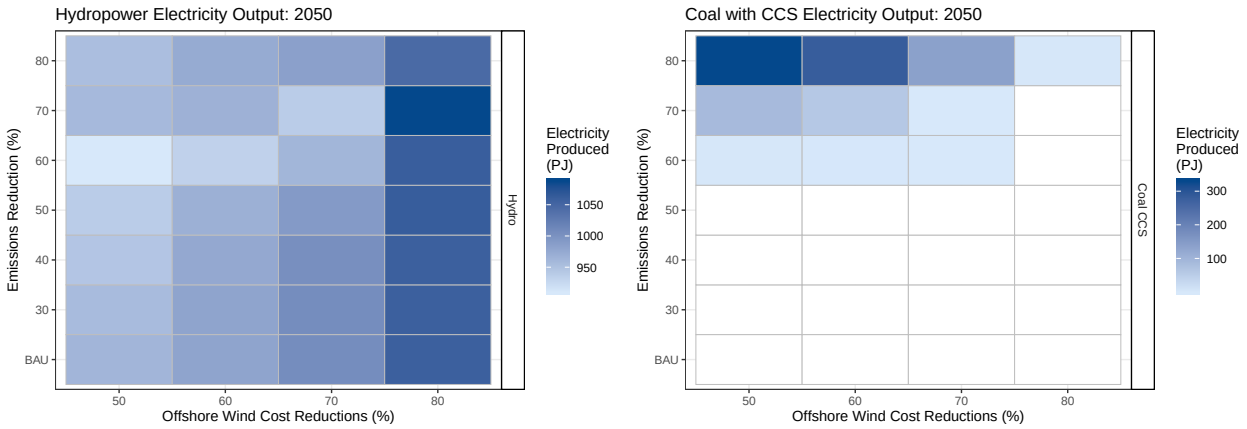

## 80% cost reduction


Electricity Production by Process
80% Cost Reductions
BAU
40
50
60
70
Electricity Production (PJ)
Year
Coal CCS
Offshore Wind
Hydro
Terrestrial Wind
Solar
Nuclear
Coal
Natural Gas
Process

## 6.5 Heatmaps

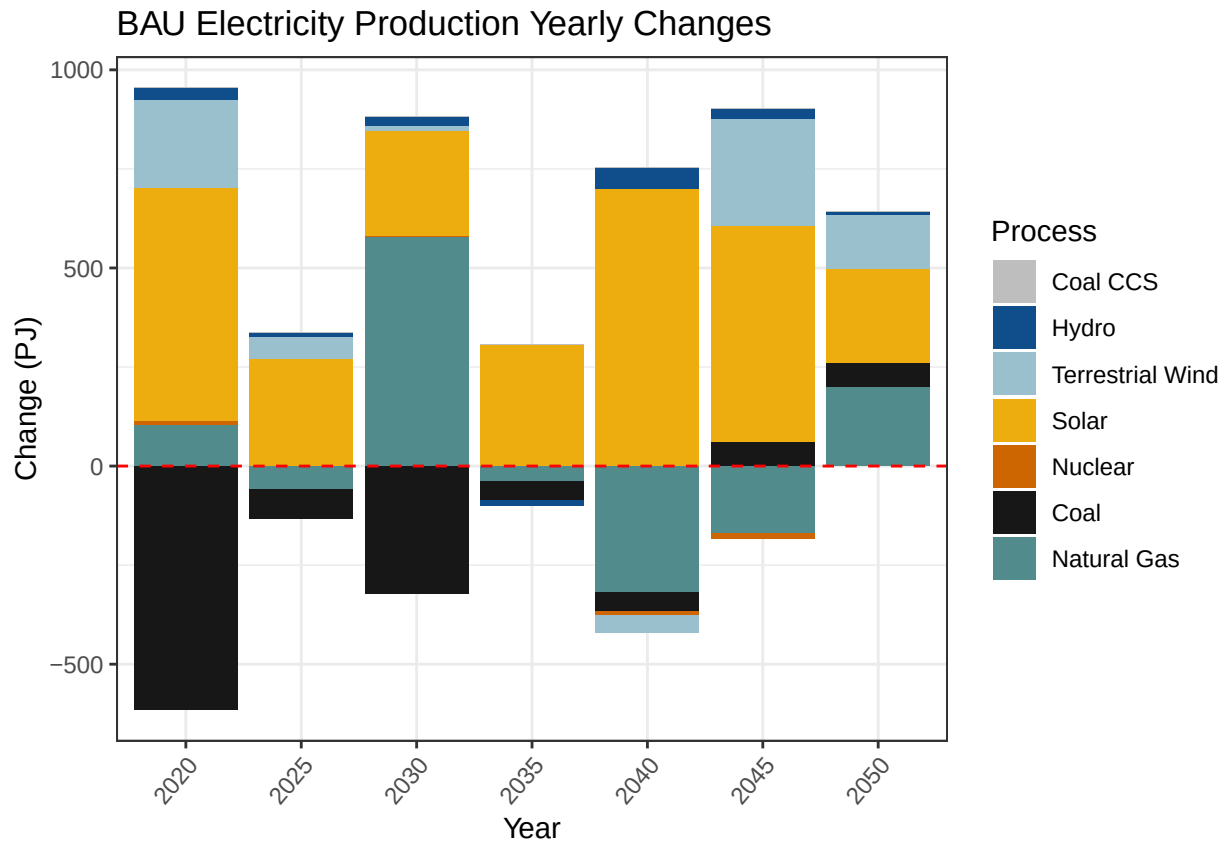

Grid Mix Production by Process
Emissions Reduction (%)
Offshore Wind Cost Reductions (%)
BAU
20
40
50
60
70
80
Hydro
Solar
Coal
Electricity Produced (PJ)
6000
4000
2000
0


Offshore Wind Electricity Output: 2050
Terrestrial Wind Electricity Output: 2050
Solar Electricity Output: 2050
Coal Electricity Output: 2050
Natural Gas Electricity Output: 2050
Nuclear Electricity Output: 2050
Emissions Reduction (%)
Offshore Wind Cost Reductions (%)
Electricity Produced (PJ)
Offshore Wind
Terrestrial Wind
Solar
Coal
Natural Gas
Nuclear
BAU
2927.25



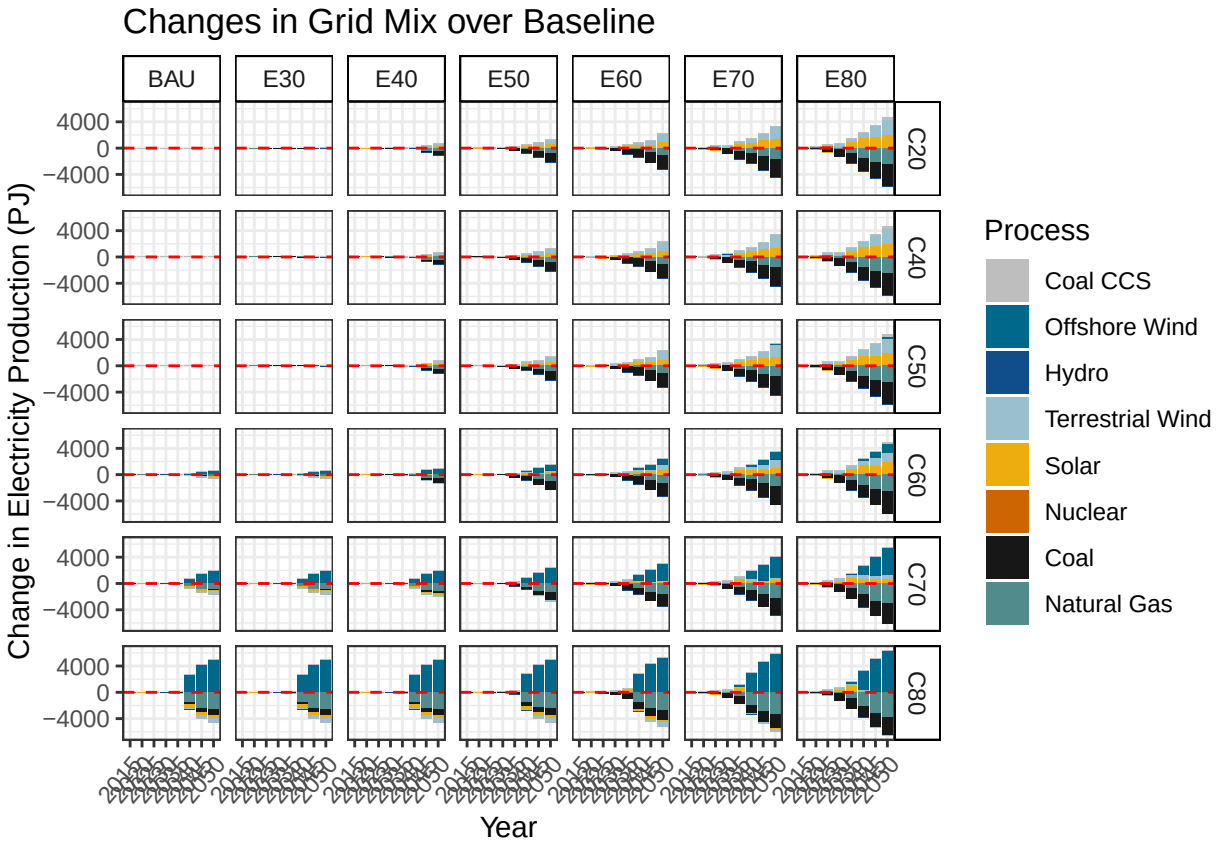

## 6.6 Retirements and Additions

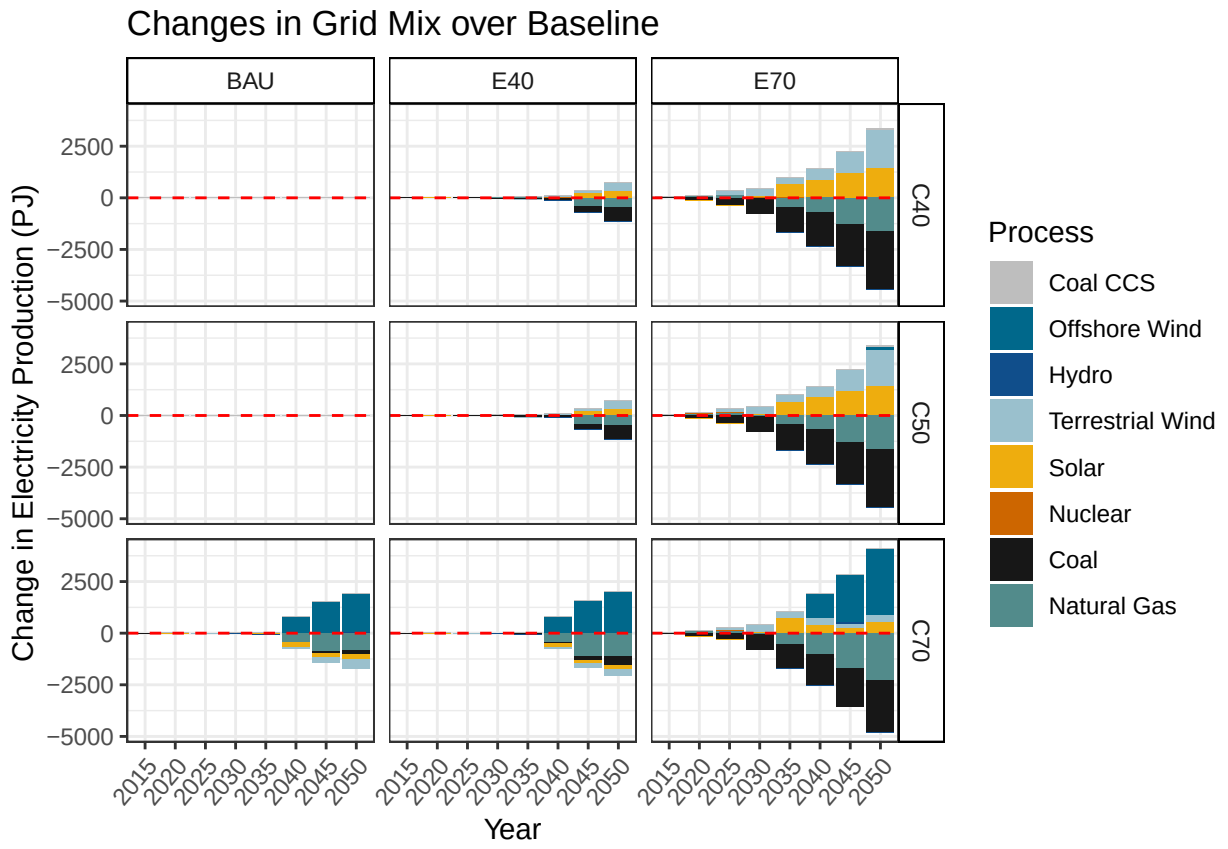
Basecase year-on-year changes in the grid mix. Shows the modeled fluctuations in generation. All following quantifications of grid mix changes are as compared to these changes in the basecase.



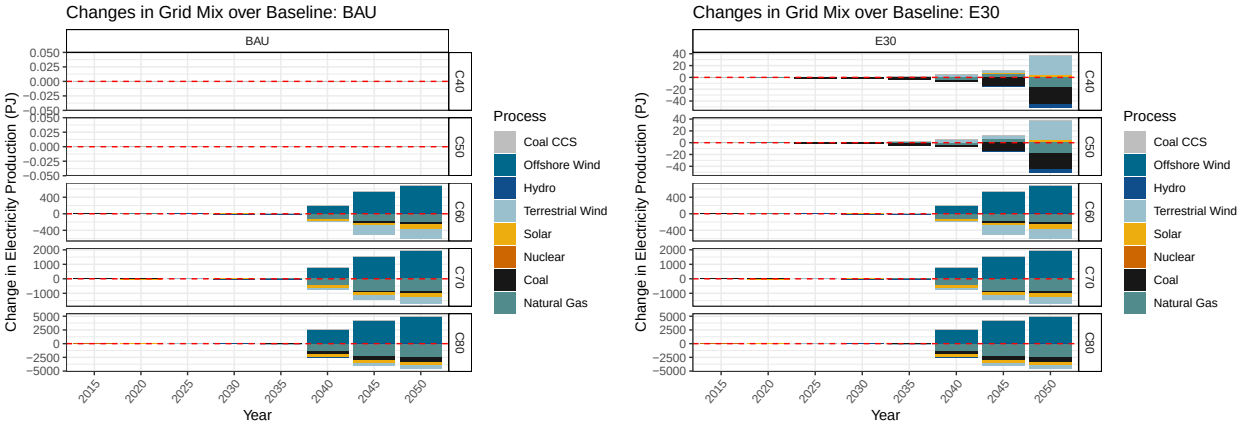

## 6.7 Changes Over Baseline

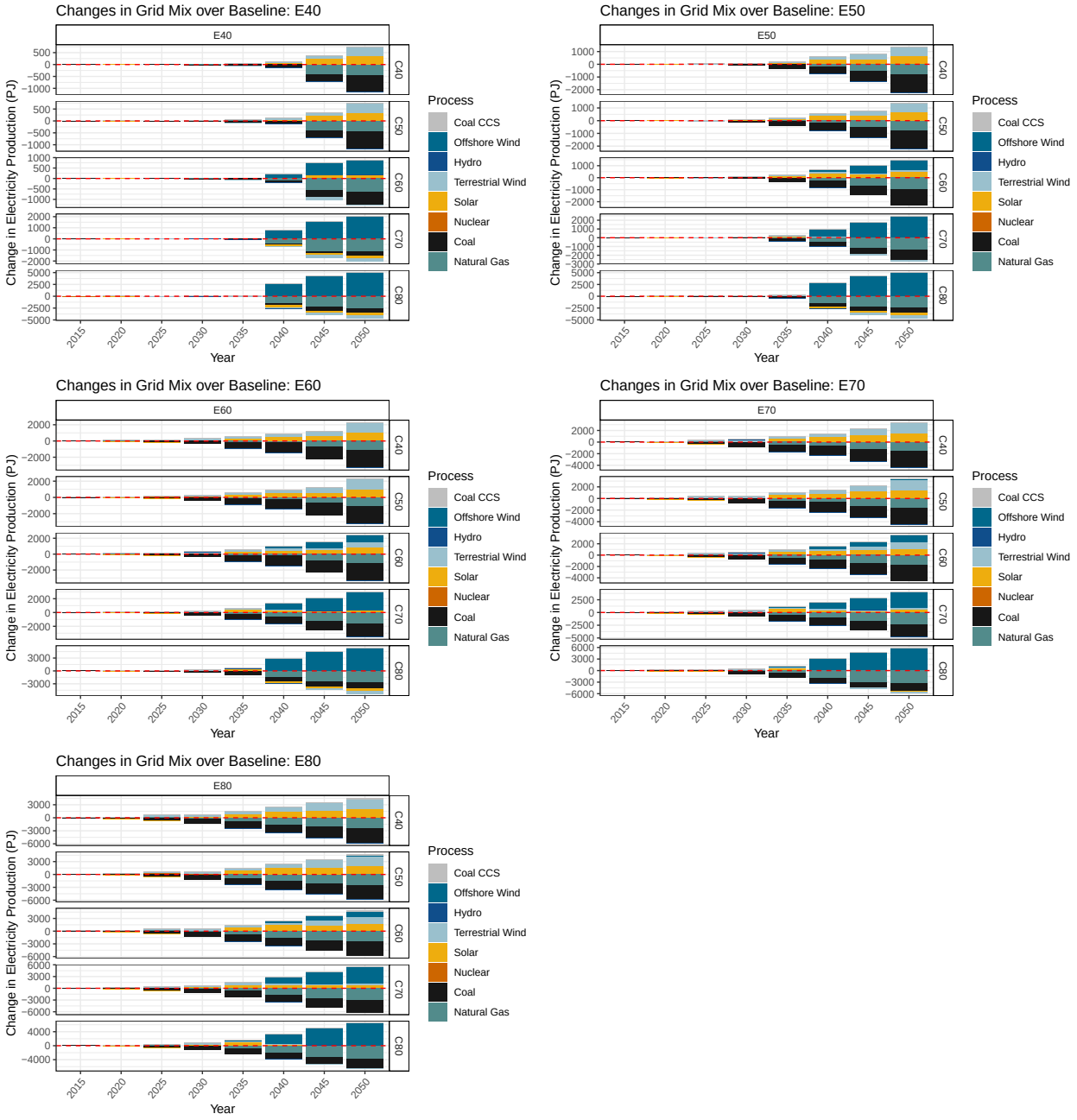
Summary Graph


Changes in Grid Mix over Baseline
BAU
E30
E40
E50
E60
E70
E80
C20
C40
C50
C60
C70
C80
4000
0
−4000
Change in Electricity Production (PJ)
2015
2020
2025
2030
2035
2040
2045
2050
Year
Process
Coal CCS
Offshore Wind
Hydro
Terrestrial Wind
Solar
Nuclear
Coal
Natural Gas

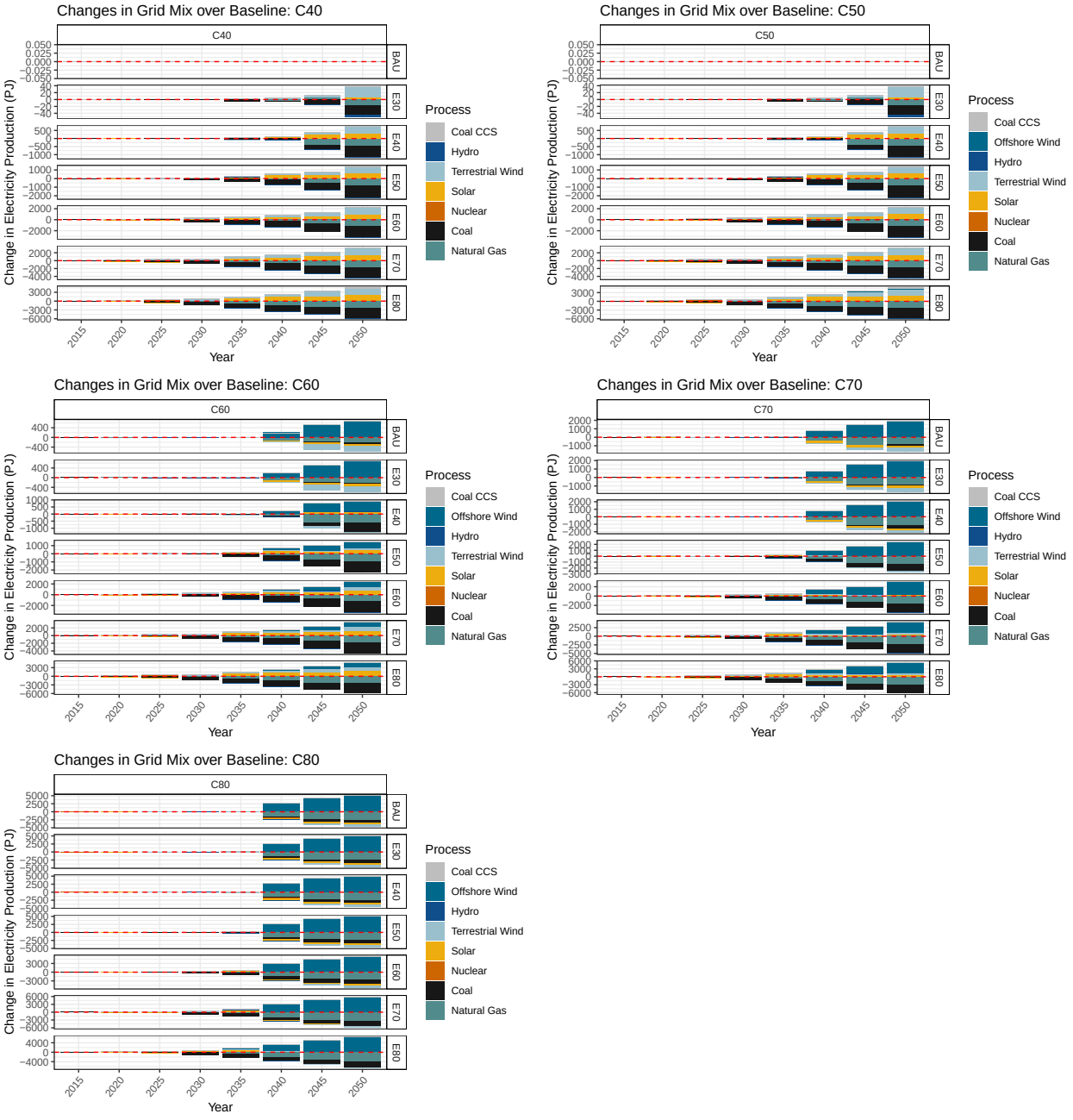



By Emissions Reduction %



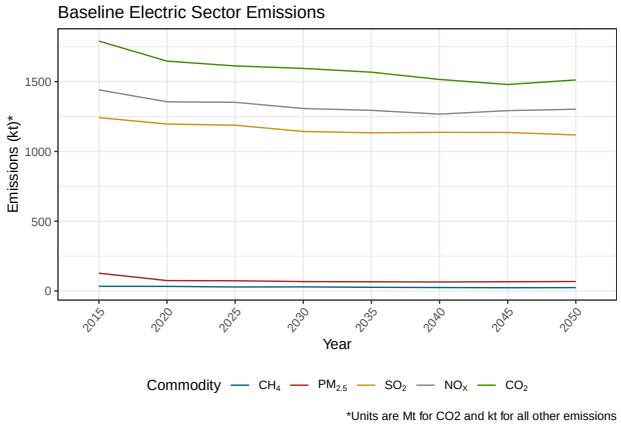


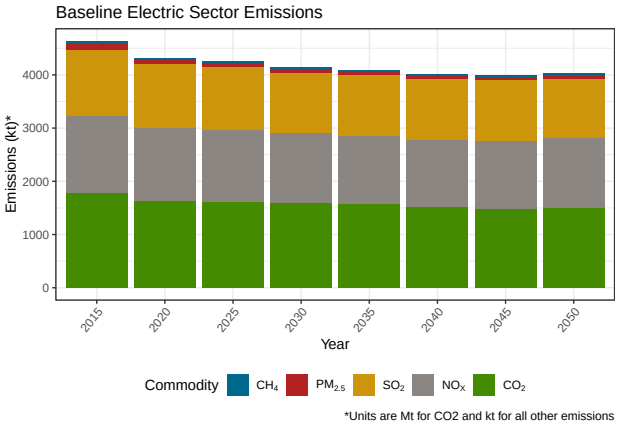

By Cost Reduction %


Changes in Grid Mix over Baseline: C40
C40
BAU
E30
E40
E50
E60
E70
E80
Change in Electricity Production (PJ)
Year
Process
Coal CCS
Hydro
Terrestrial Wind
Solar
Nuclear
Coal
Natural Gas
Changes in Grid Mix over Baseline: C50
C50
Changes in Grid Mix over Baseline: C60
C60
Offshore Wind
Changes in Grid Mix over Baseline: C70
C70
Changes in Grid Mix over Baseline: C80
C80

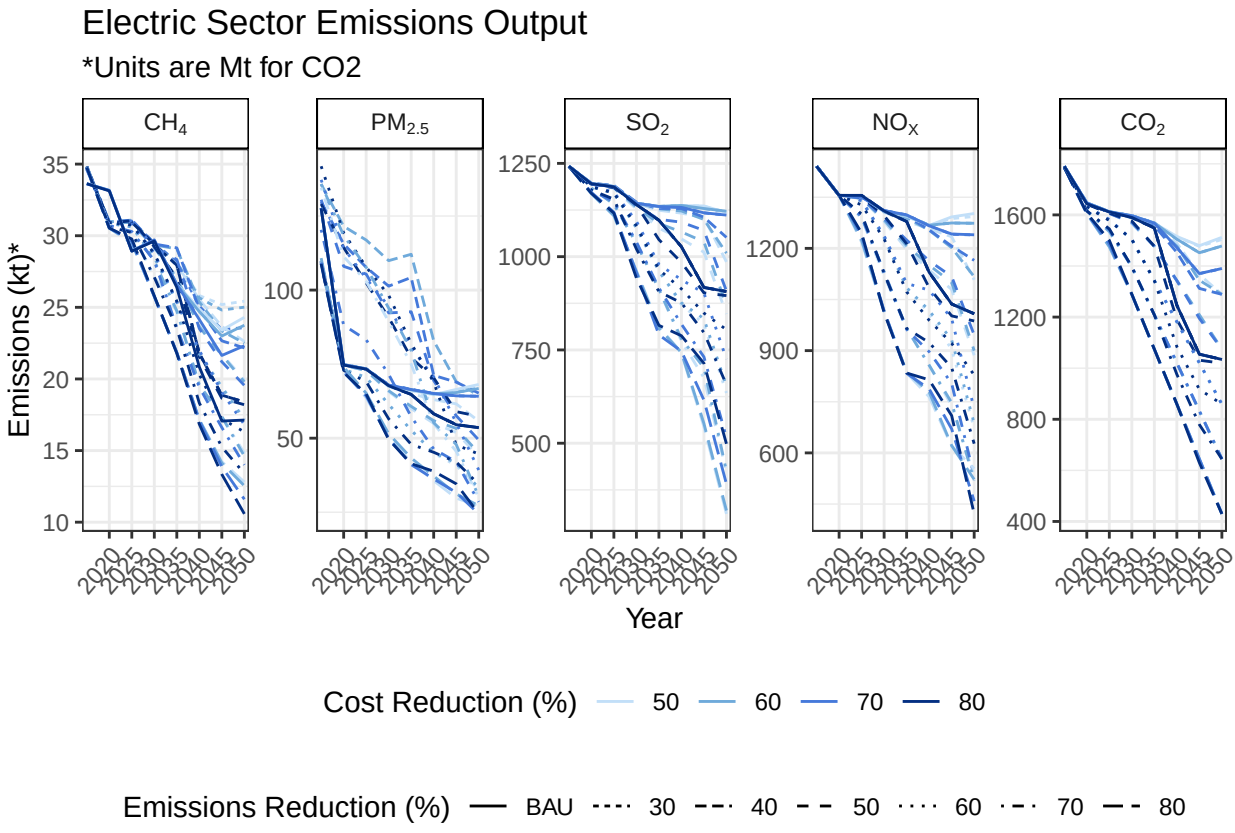
# 7 Emissions

## 7.1 Baseline

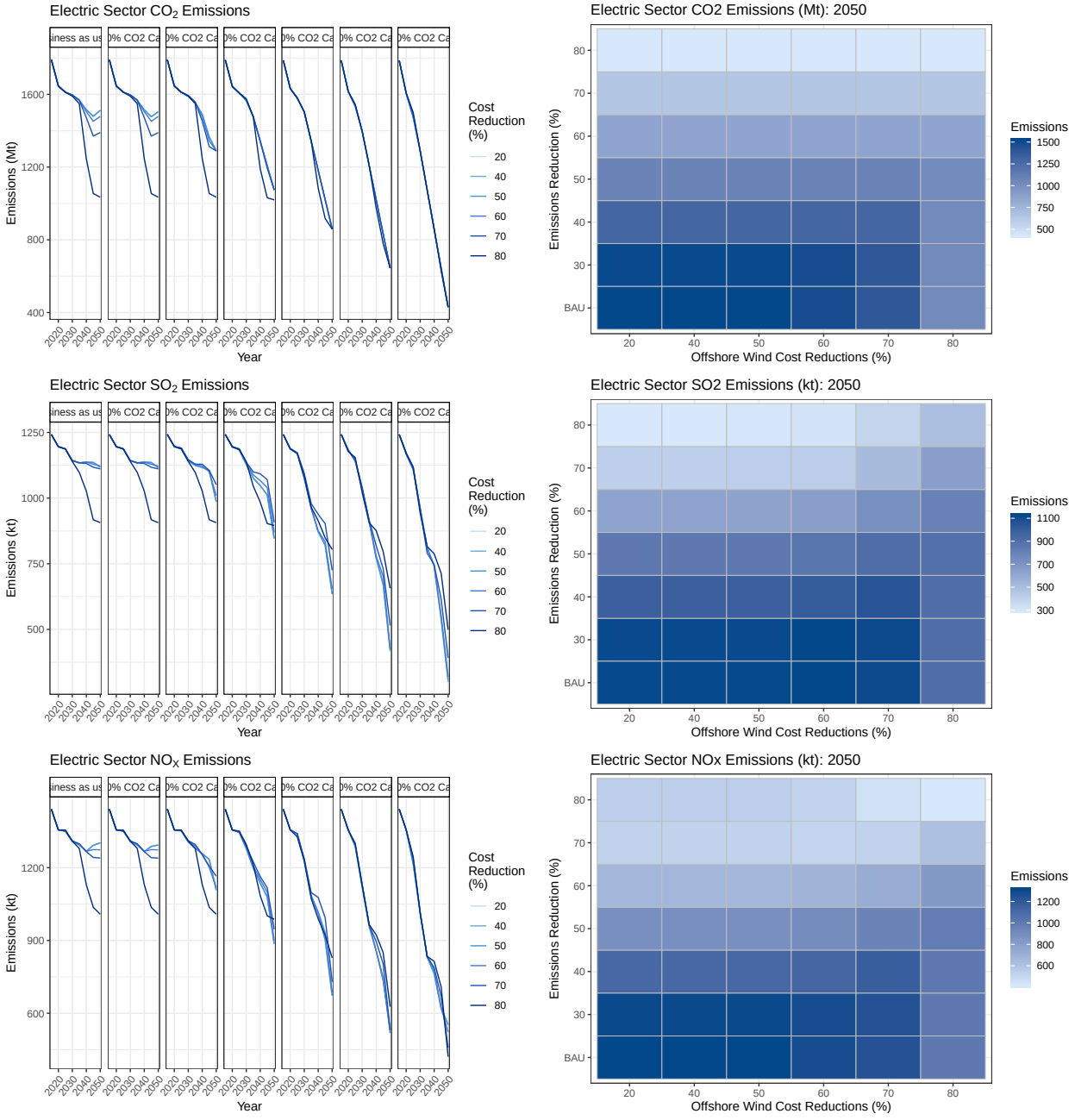


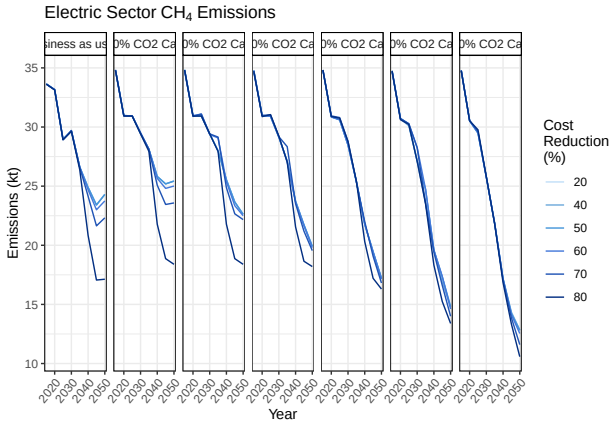



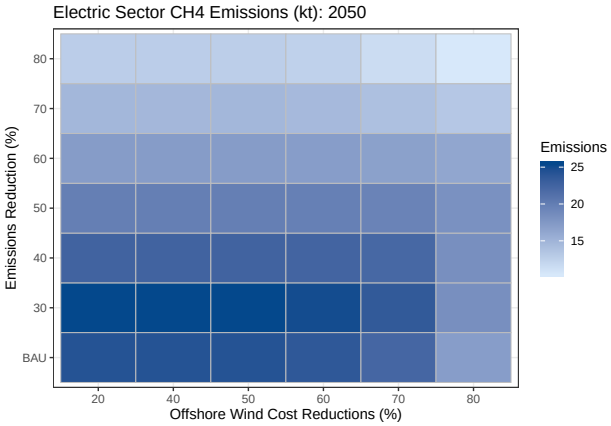

## 7.2 Emissions by Scenario and Commodity

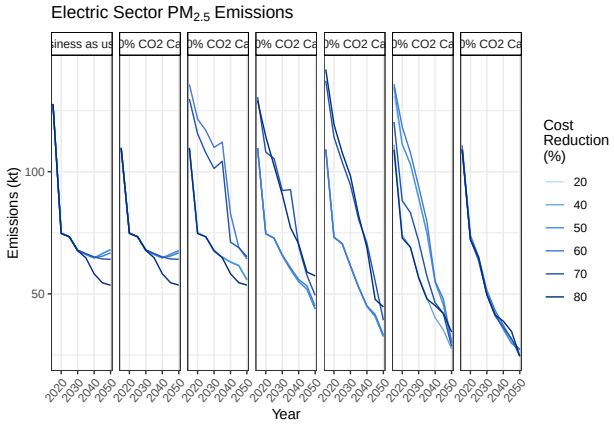


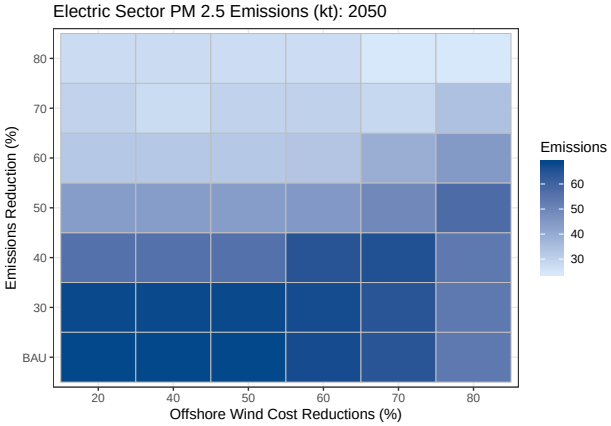
## 7.3 Emissions by Commodity



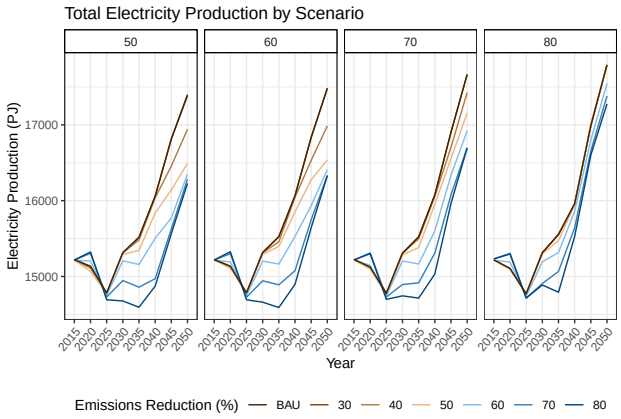


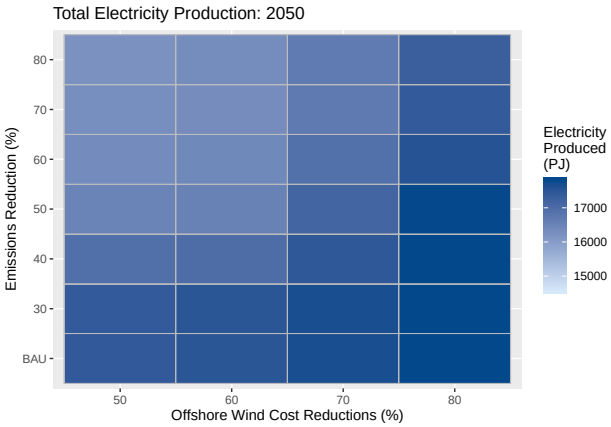




# 8 Total Electricity Production




# 9 Correlation

```
## NULL
```

| | Model 1 | Model 2 | Model 3 |
|---|---|---|---|
| (Intercept) | 141.60 *** | 17079.79 *** | 989.23 *** |
| | (7.86) | (33.59) | (21.74) |
| emred | 24.04 ** | -436.43 *** | -318.36 *** |
| | (8.00) | (39.90) | (22.49) |
| costred | 129.73 *** | 16.90 | |
| | (8.00) | (116.06) | |
| cap2050 | | 354.53 ** | -73.17 ** |
| | | (117.86) | (22.49) |
| N | 28 | 28 | 28 |
| R2 | 0.92 | 0.91 | 0.90 |

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