Offshore Wind Results and Analysis

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11 September, 2019

Contents

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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

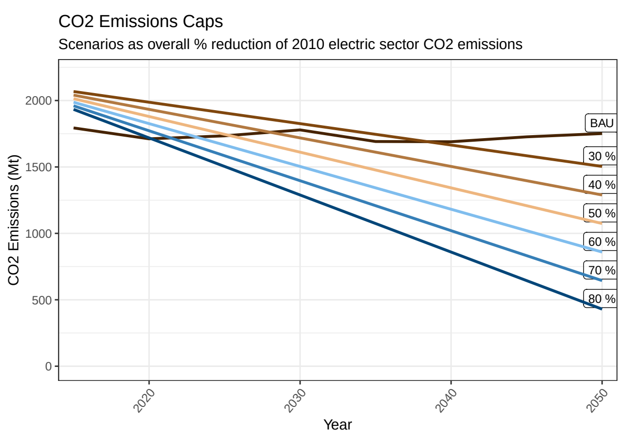
The nested parametric sensitivity analysis was built on combinations of two sets of scenarios:

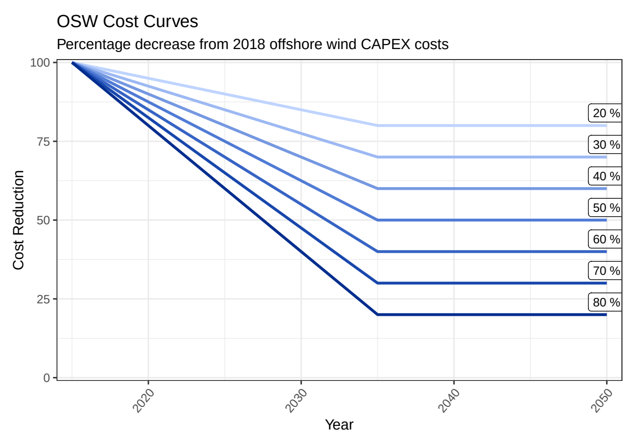
1. Electric sector CO_2 emissions caps, as a linear decrease to a given % decrease from 2010 emissions by 2050

- 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.

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.

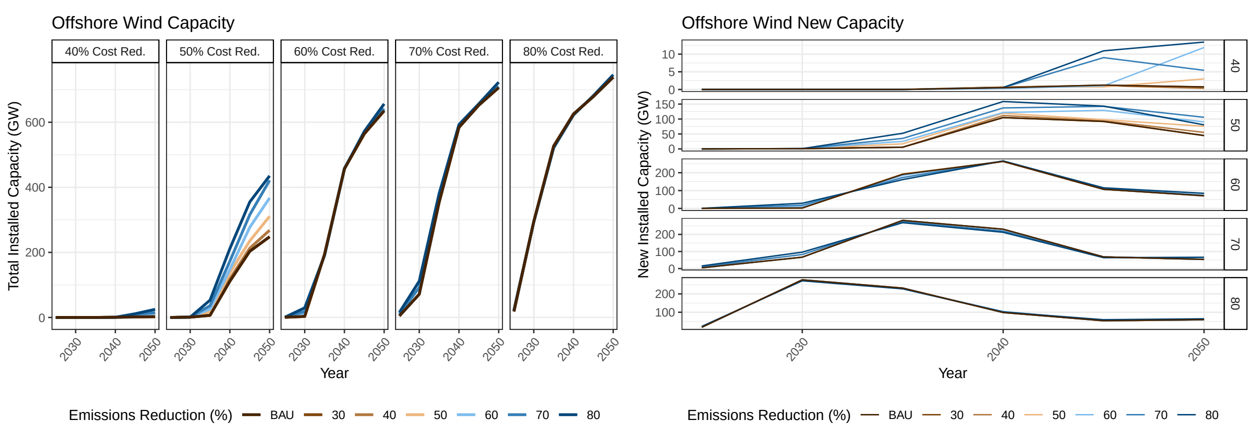
5.1 Capacity Buildout

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

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



5.2 Total Capacity

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

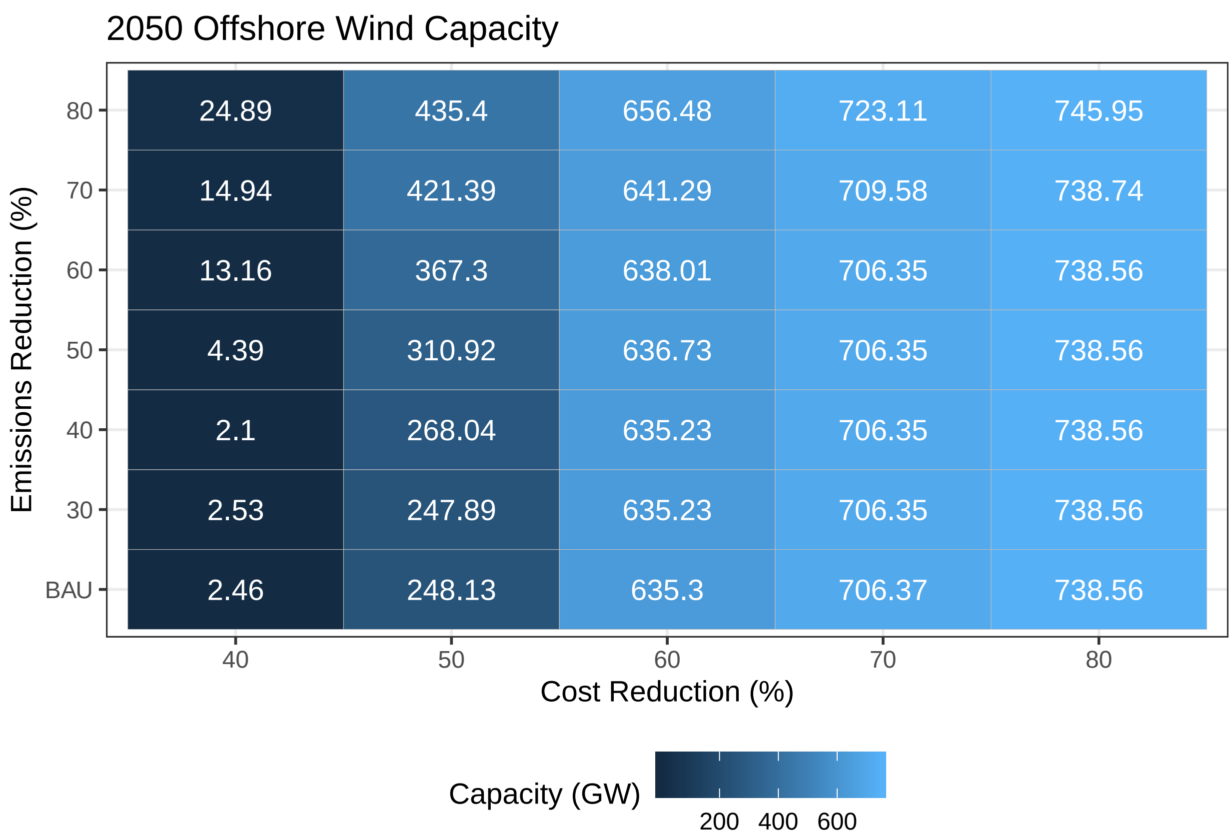


Table 2: Offshore Wind Total Installed Capacity (GW): 2050

Emissions Reduction (%)	Cost Reduction (%)				
	40	50	60	70	80
BAU	2.5	248.1	635.3	706.4	738.6
30	2.5	247.9	635.2	706.4	738.6
40	2.1	268.0	635.2	706.4	738.6
50	4.4	310.9	636.7	706.4	738.6
60	13.2	367.3	638.0	706.4	738.6
70	14.9	421.4	641.3	709.6	738.7
80	24.9	435.4	656.5	723.1	746.0

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.

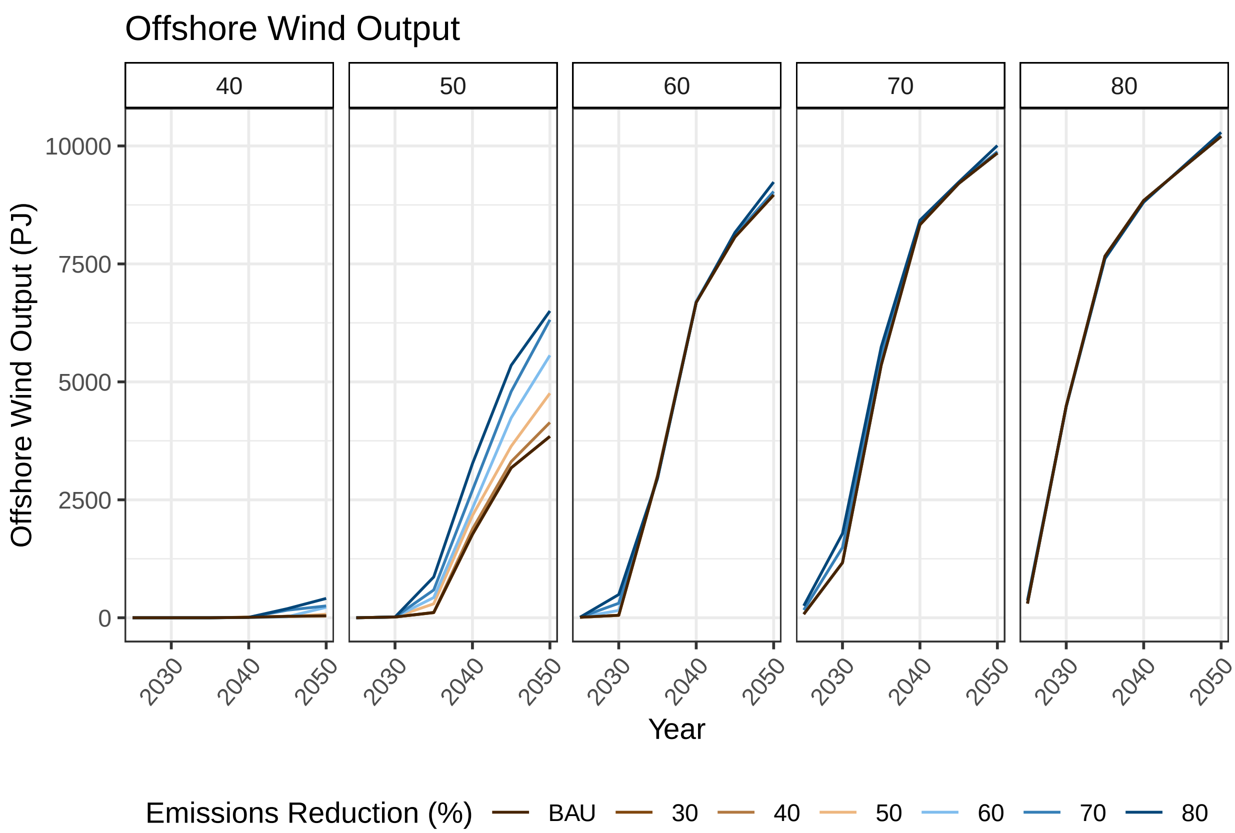
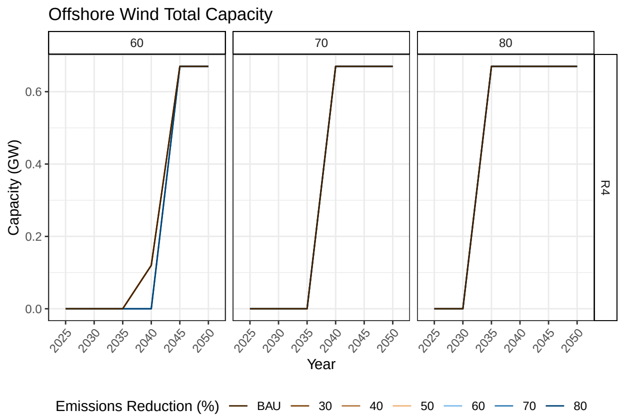


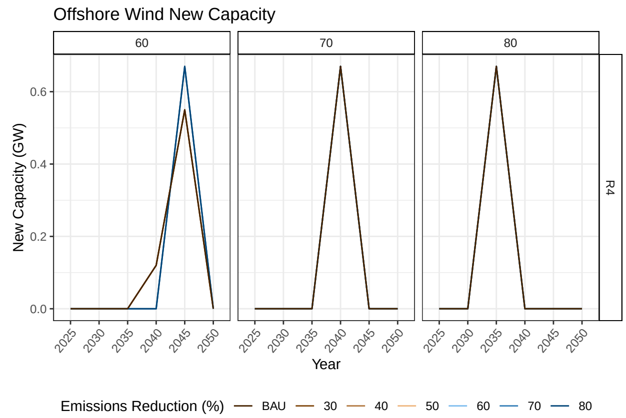
Table 3: Offshore Wind Total Output (PJ): 2050

Emissions Reduction (%)	Cost Reduction (%)				
	40	50	60	70	80
BAU	42.3	3845.4	8962.0	9848.8	10204.0
30	43.4	3841.7	8960.8	9848.5	10204.0
40	36.0	4139.4	8960.8	9848.5	10204.0
50	75.3	4758.1	8977.9	9848.5	10204.0
60	221.0	5562.3	8992.0	9848.5	10204.0
70	250.4	6315.4	9034.2	9880.0	10205.3
80	409.6	6502.2	9235.0	10008.3	10287.1

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
60
70
80
R4
Capacity (GW)
Year
Emissions Reduction (%) BAU 30 40 50 60 70 80


Offshore Wind New Capacity
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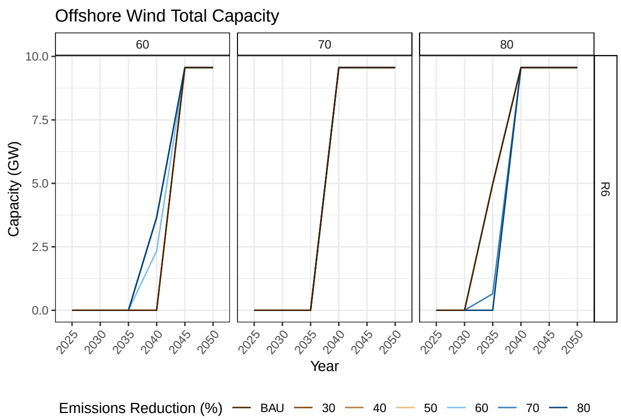
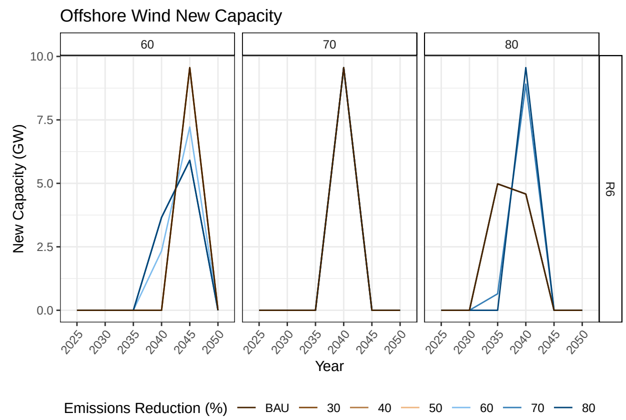
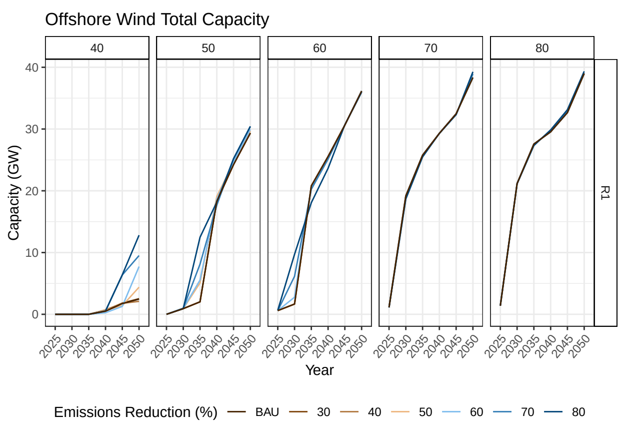
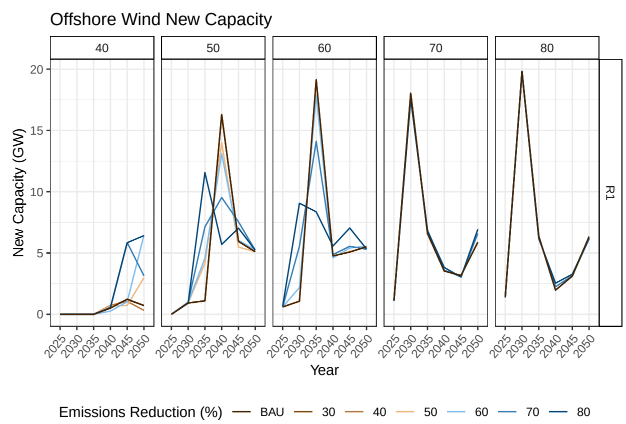
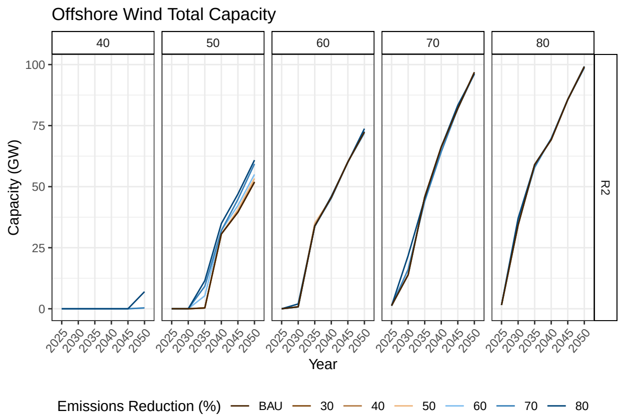
70
80
R4
New Capacity (GW)
Year
Emissions Reduction (%) BAU 30 40 50 60 70 80


Offshore Wind Total Capacity
60
70
80
R6
Capacity (GW)
Year
Emissions Reduction (%) BAU 30 40 50 60 70 80


Offshore Wind New Capacity
60
70
80
R6
New Capacity (GW)
Year
Emissions Reduction (%) BAU 30 40 50 60 70 80


Offshore Wind Total Capacity
40
50
60
70
80
R1
Capacity (GW)
Year
Emissions Reduction (%) BAU 30 40 50 60 70 80


Offshore Wind New Capacity
40
50
60
70
80
R1
New Capacity (GW)
Year
Emissions Reduction (%) BAU 30 40 50 60 70 80


Offshore Wind Total Capacity
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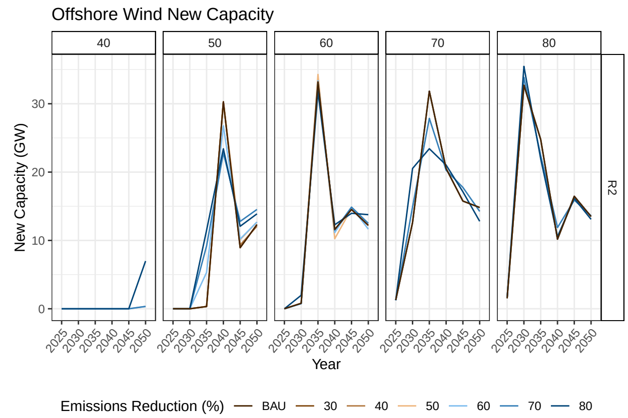
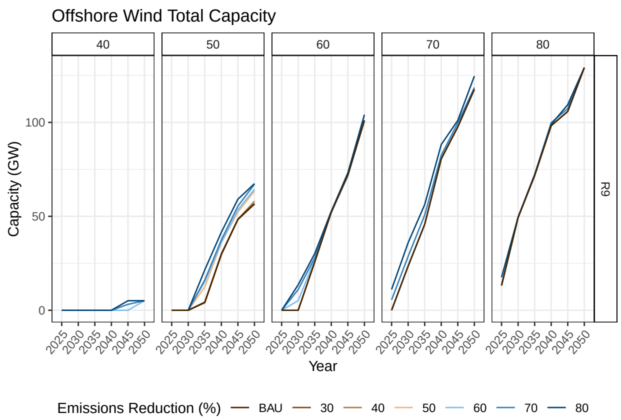
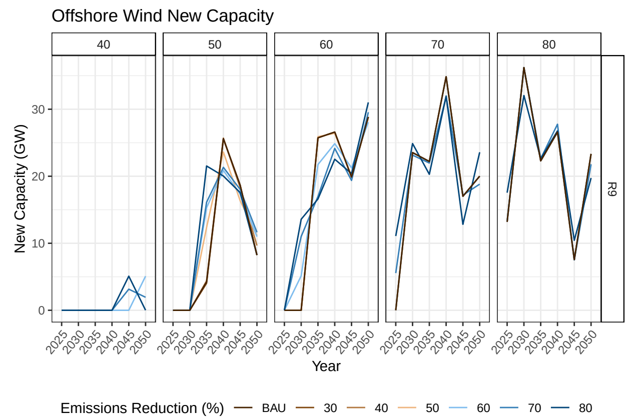
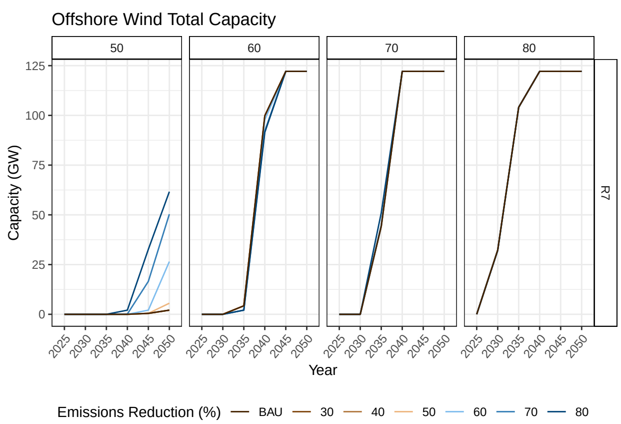
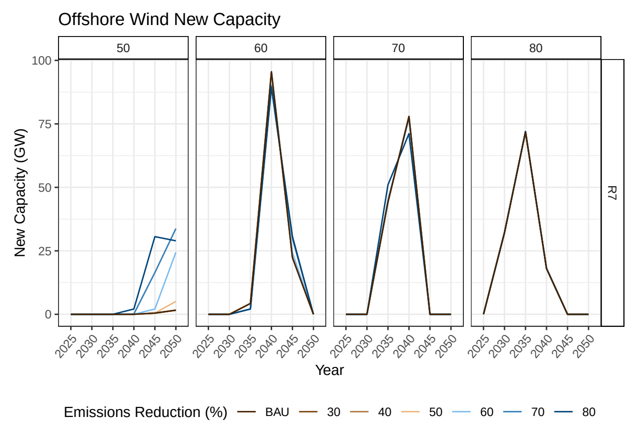
50
60
70
80
R2
Capacity (GW)
Year
Emissions Reduction (%) BAU 30 40 50 60 70 80

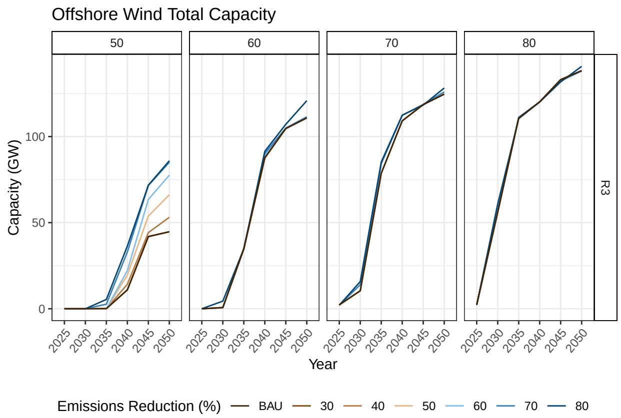

Offshore Wind New Capacity
40
50
60
70
80
R2
New Capacity (GW)
Year
Emissions Reduction (%) BAU 30 40 50 60 70 80

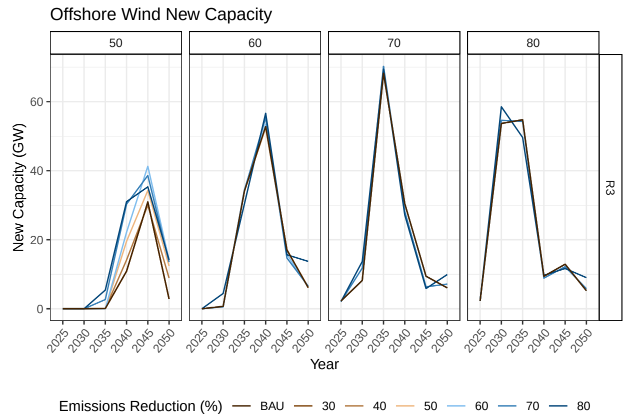

Offshore Wind Total Capacity
40
50
60
70
80
R9
Capacity (GW)
Year
Emissions Reduction (%) BAU 30 40 50 60 70 80

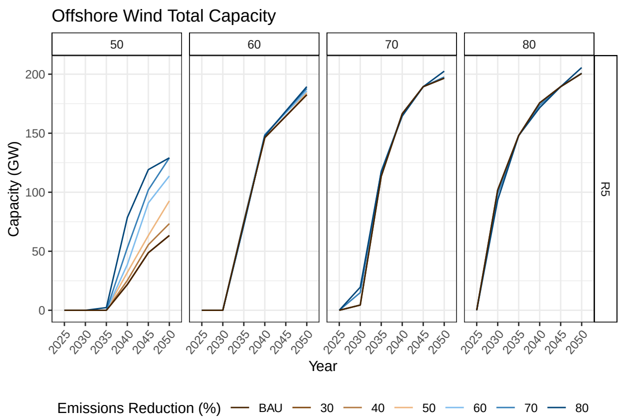

Offshore Wind New Capacity
40
50
60
70
80
R9
New Capacity (GW)
Year
Emissions Reduction (%) BAU 30 40 50 60 70 80

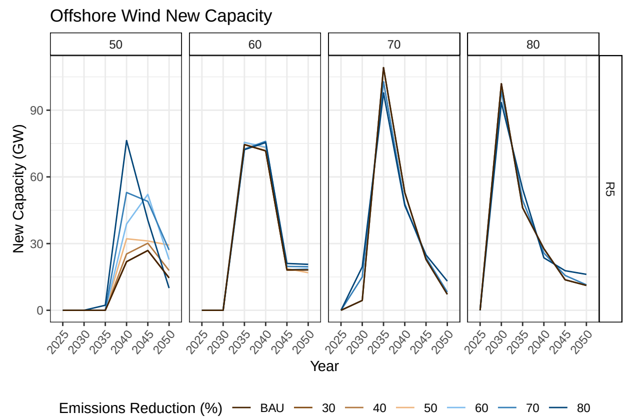

Offshore Wind Total Capacity
50
60
70
80
R7
Capacity (GW)
Year
Emissions Reduction (%) BAU 30 40 50 60 70 80


Offshore Wind New Capacity
50
60
70
80
R7
New Capacity (GW)
Year
Emissions Reduction (%) BAU 30 40 50 60 70 80

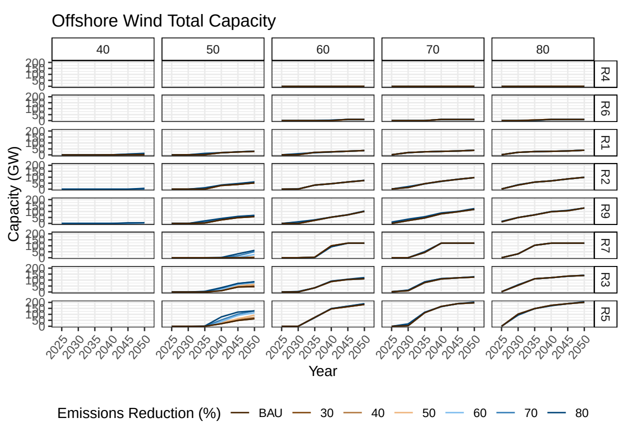


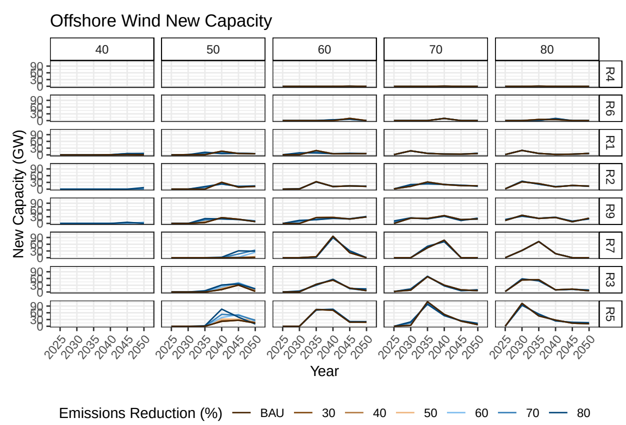


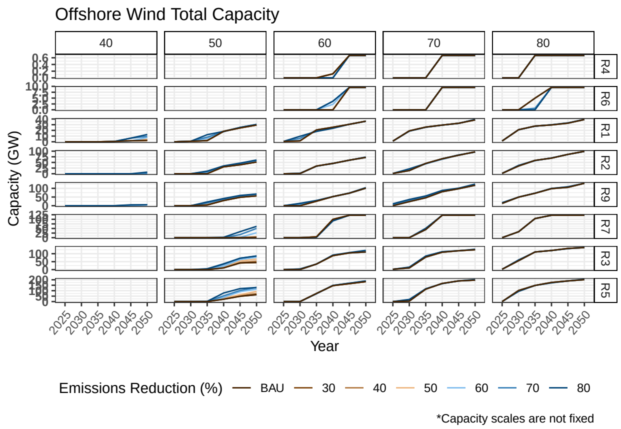




Cumulative and new addition offshore wind capacity by region, emissions reduction, and cost reduction.







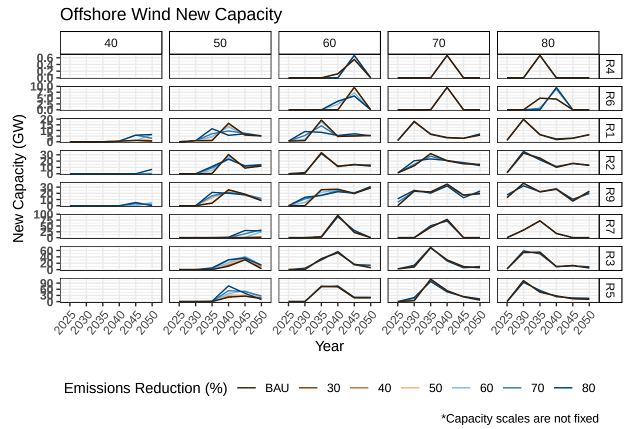


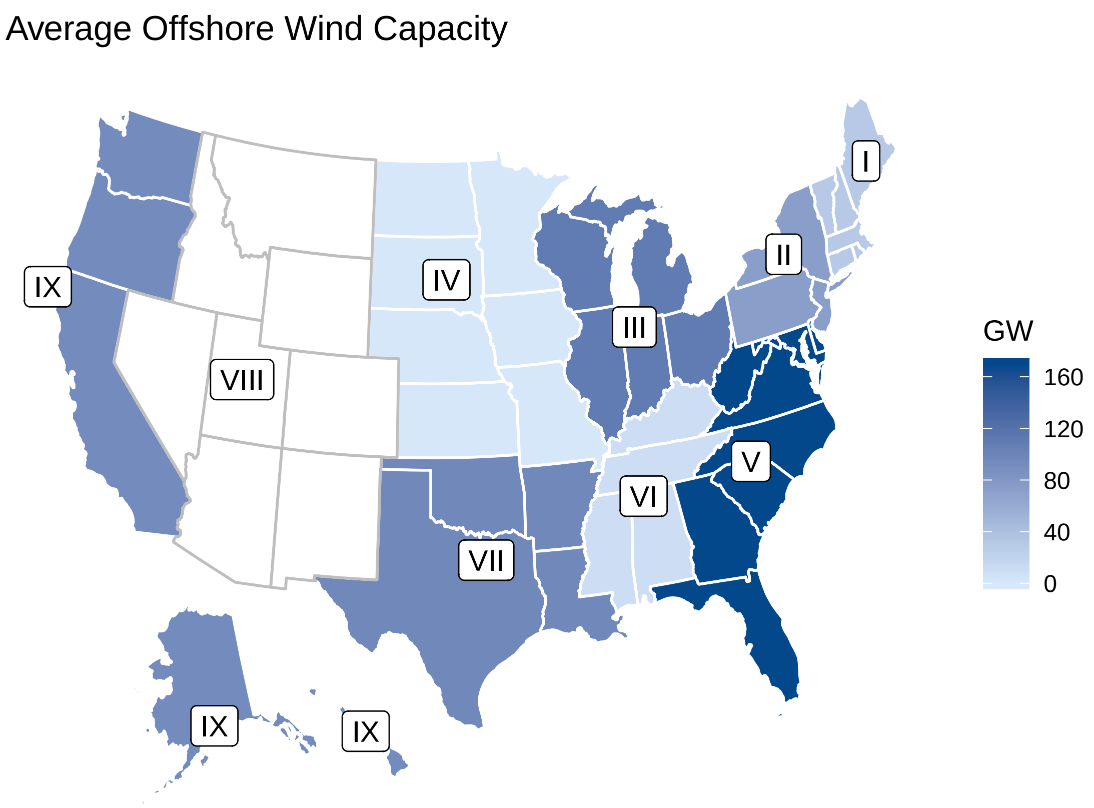
Table 4: Average Installed Capacity (GW)

Region	2050 Total
R4	0.67000
R6	9.56000
R1	29.88514
R2	73.21452
R9	93.38871
R7	96.97286
R3	110.37893
R5	169.72857

Table 5: Average Electricity Output (PJ)

Region	2050 Total
R4	5.85375
R6	68.65600
R1	96.99500
R2	224.66953
R9	284.79601
R3	326.76062
R7	485.47903
R5	526.62200

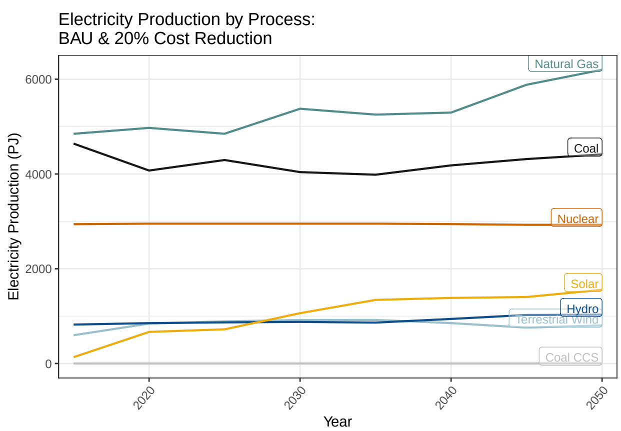
Map of average total capacity

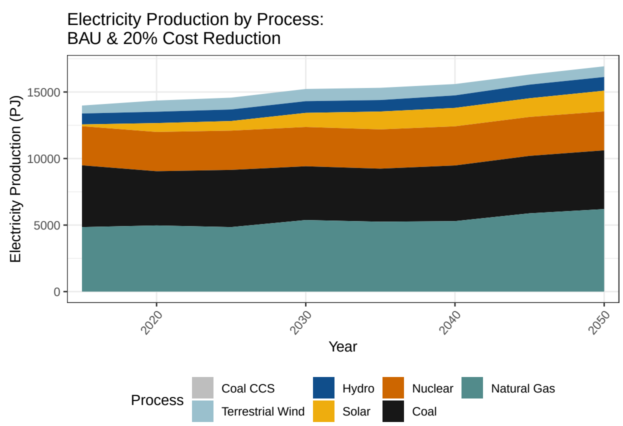


6 Grid Mix

6.1 Baseline Production

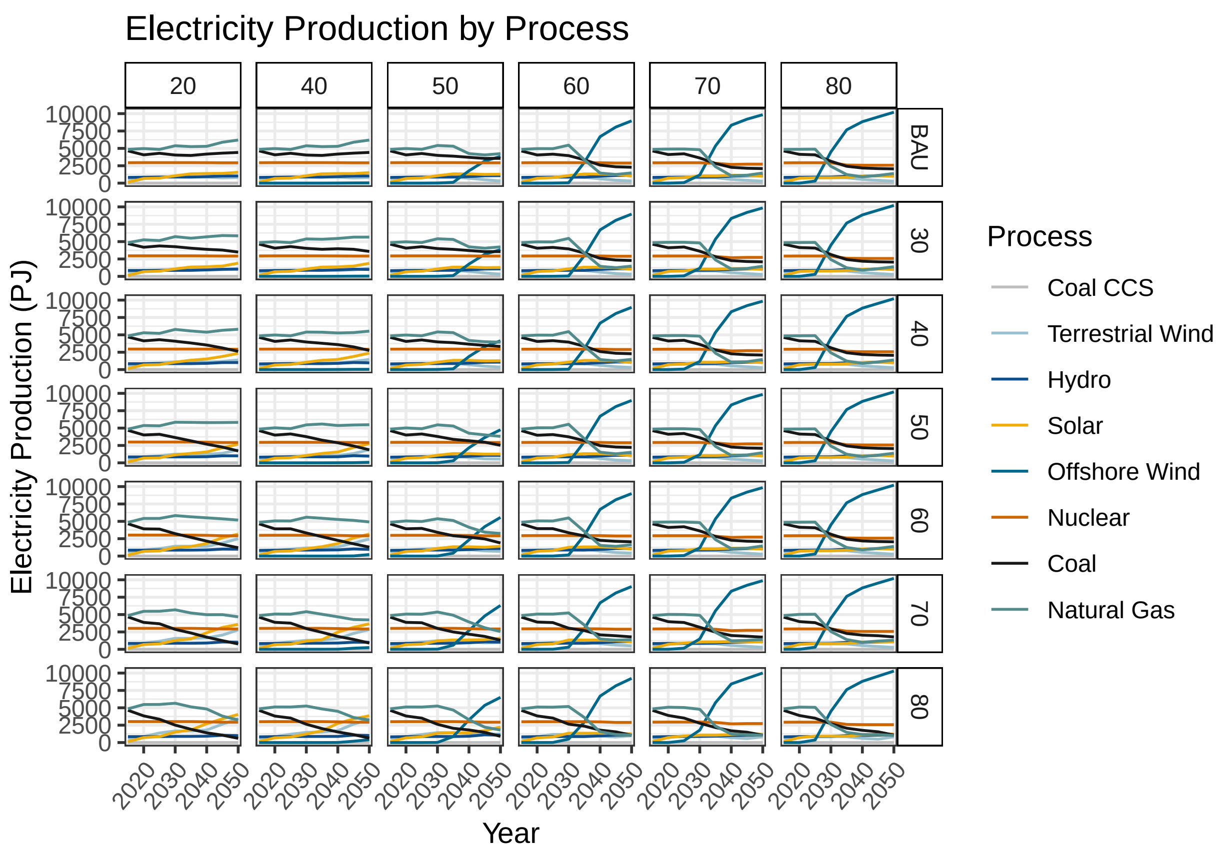
Grid mix without any offshore wind cost reduction or emissions cap.



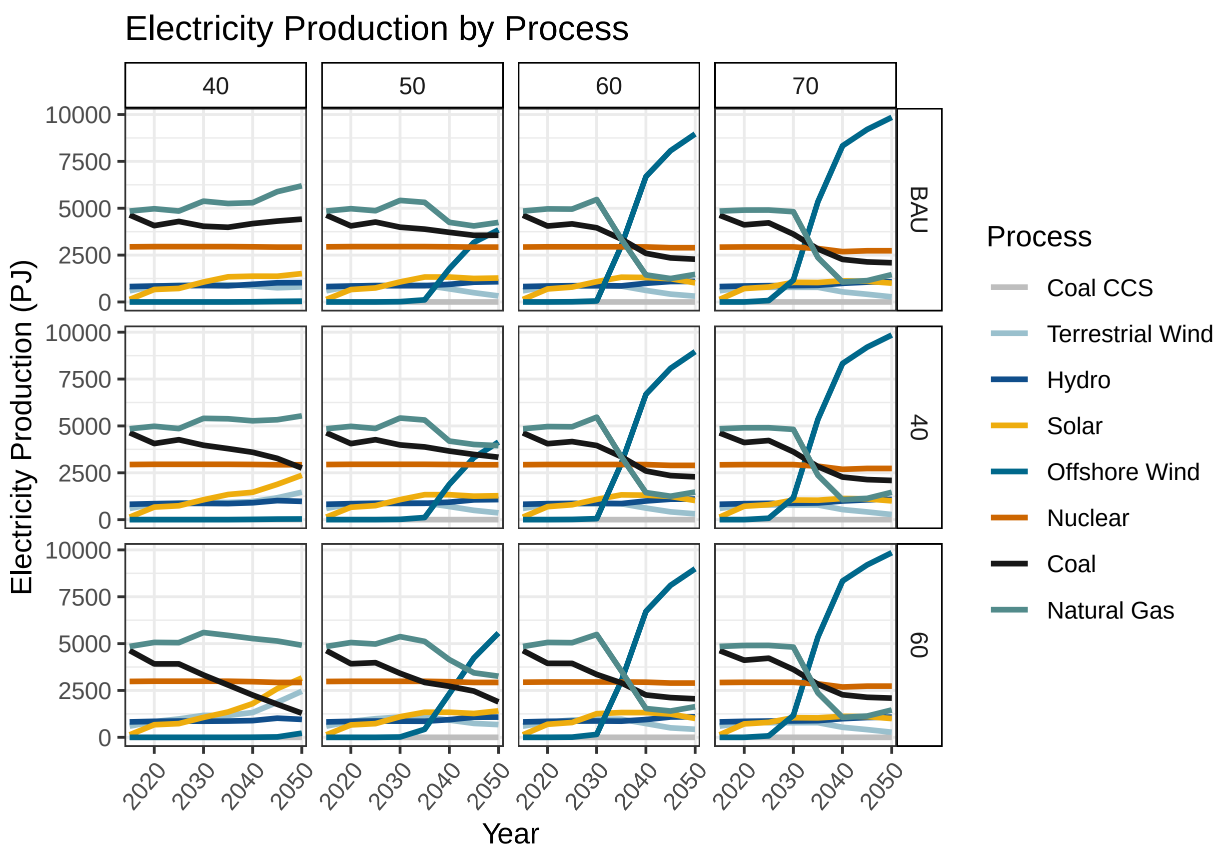


6.2 All Scenarios

Complete Set

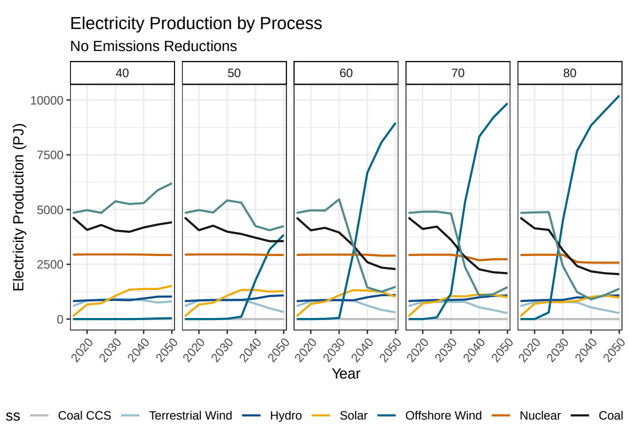

Electricity Production by Process
20
40
50
60
70
80
BAU
30
40
50
60
70
80
10000
7500
5000
2500
0
Electricity Production (PJ)
2020
2030
2040
2050
Year
Process
Coal CCS
Terrestrial Wind
Hydro
Solar
Offshore Wind
Nuclear
Coal
Natural Gas

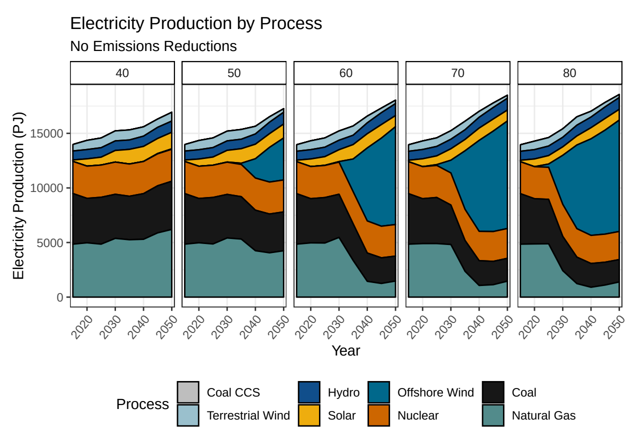
Parsed Set



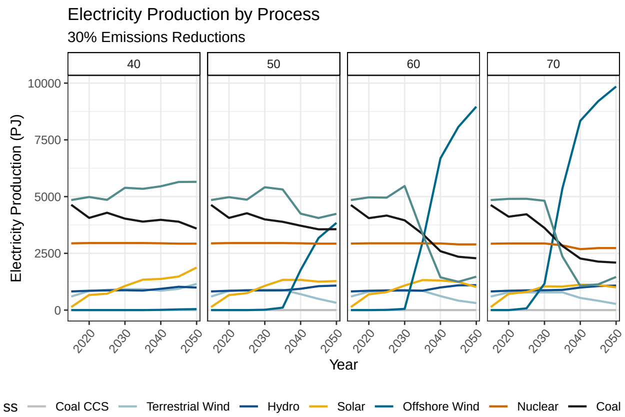
6.3 Emissions Cap

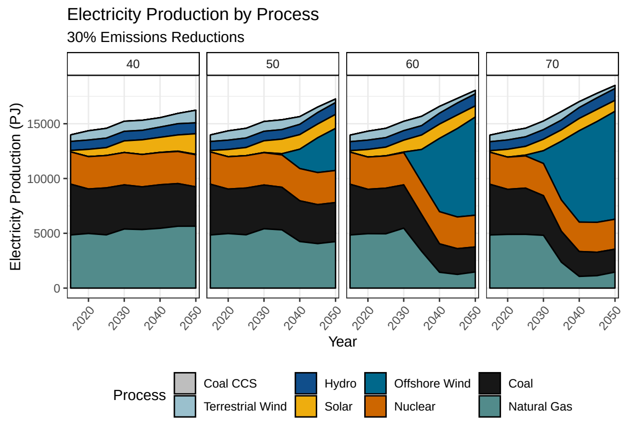
BAU emissions



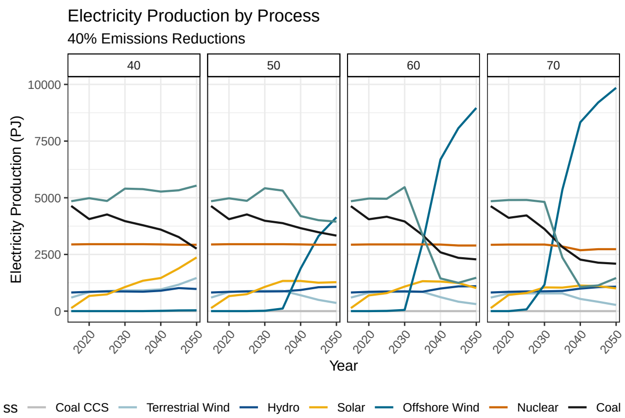


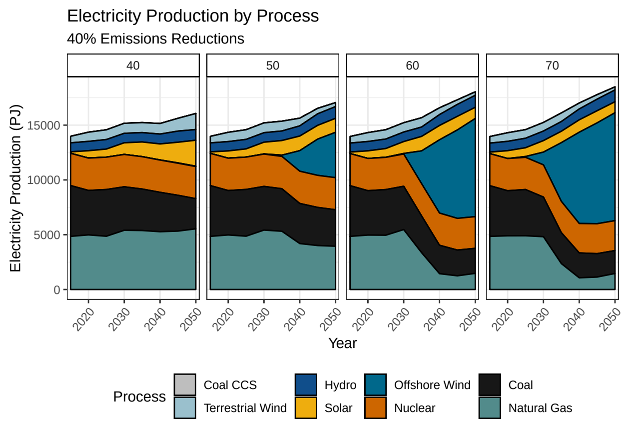
30% emissions reduction



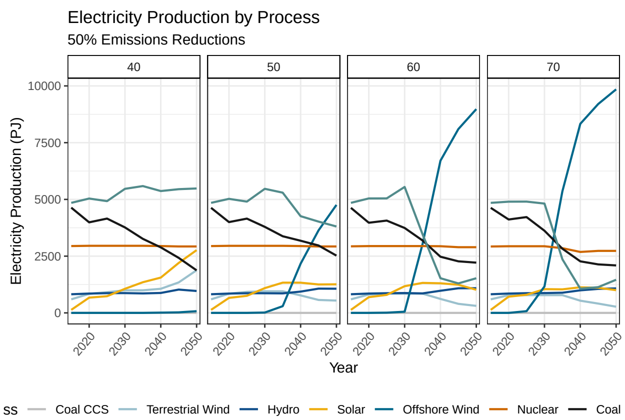


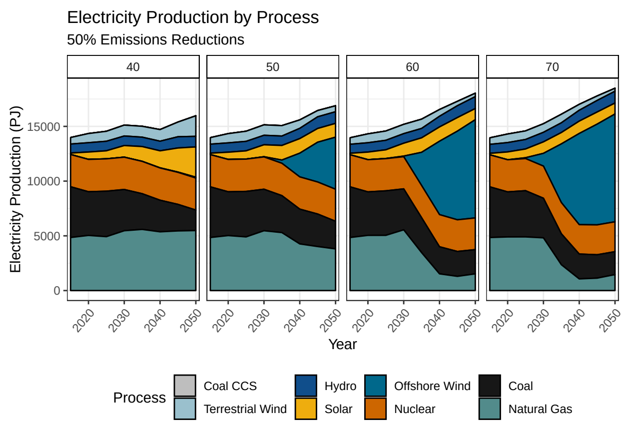
40% emissions reduction



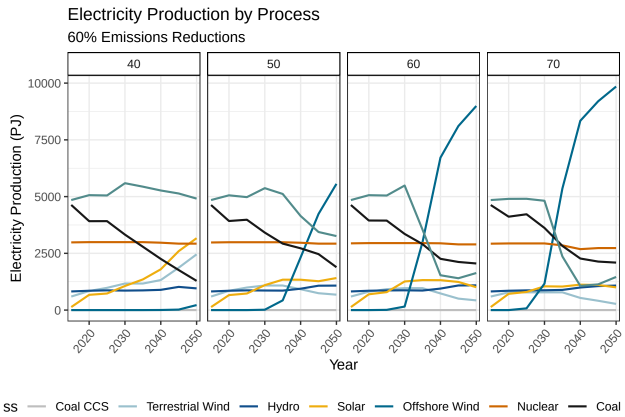


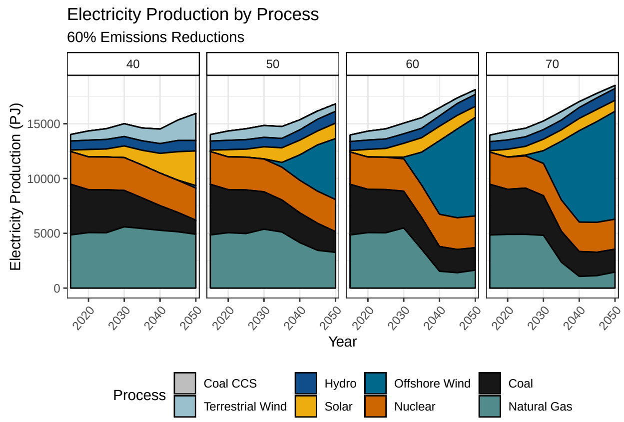
50% emissions reduction



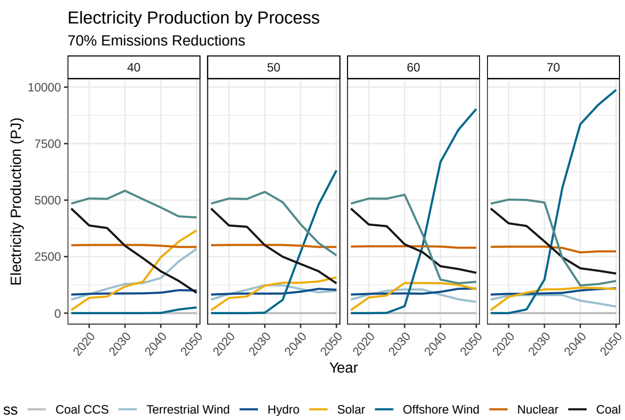


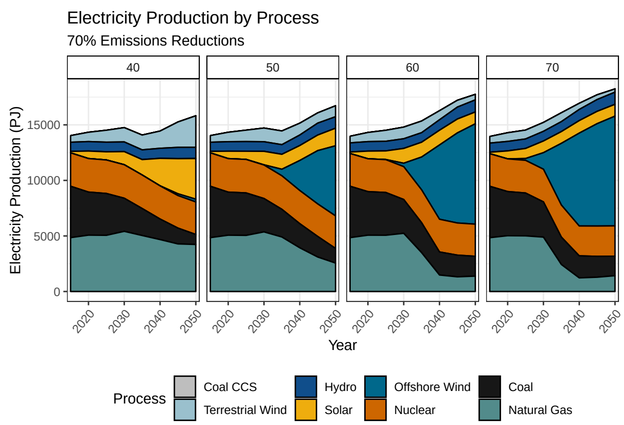
60% emissions reduction



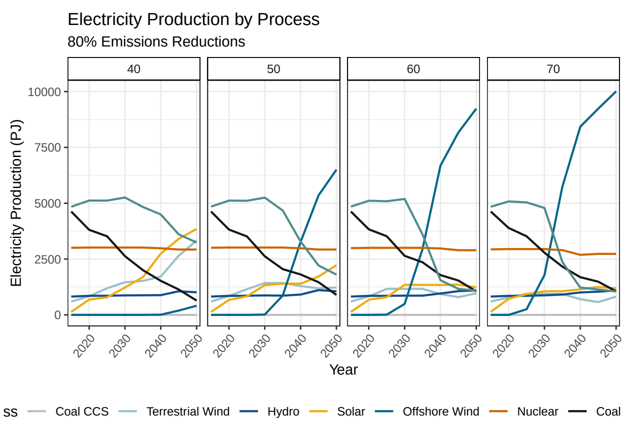


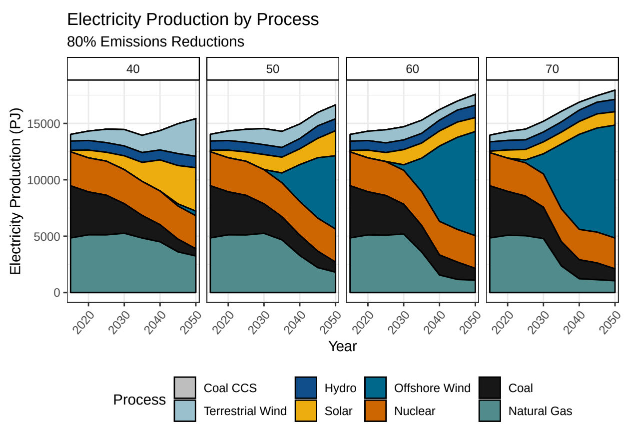
70% emissions reduction





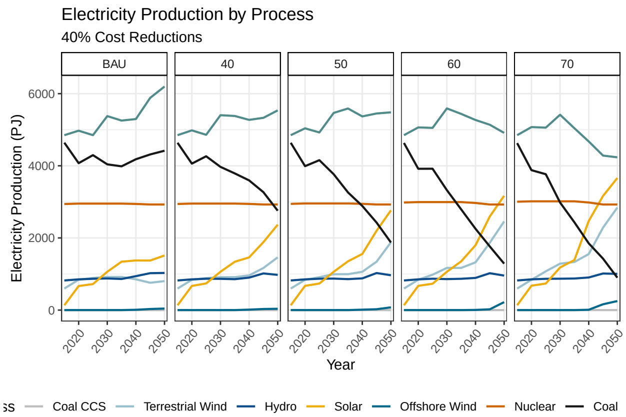
80% emissions reduction

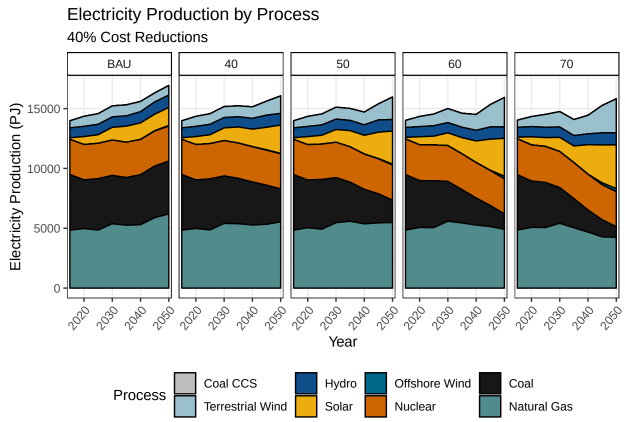




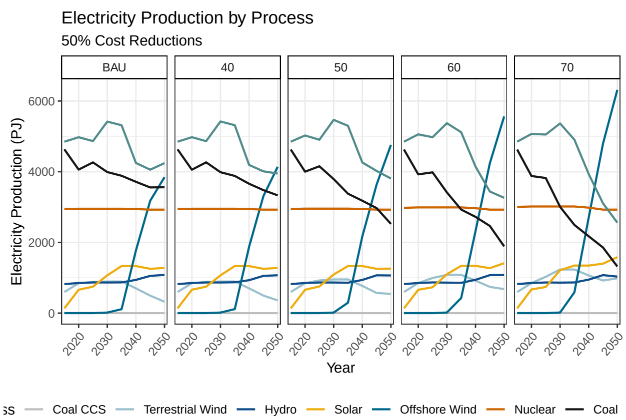
6.4 Cost Reductions

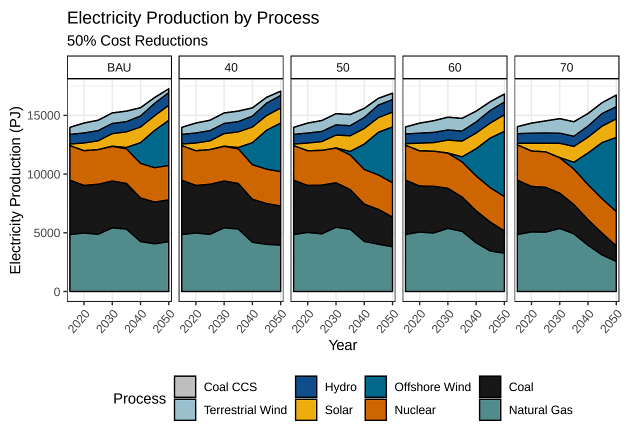
40% cost reduction



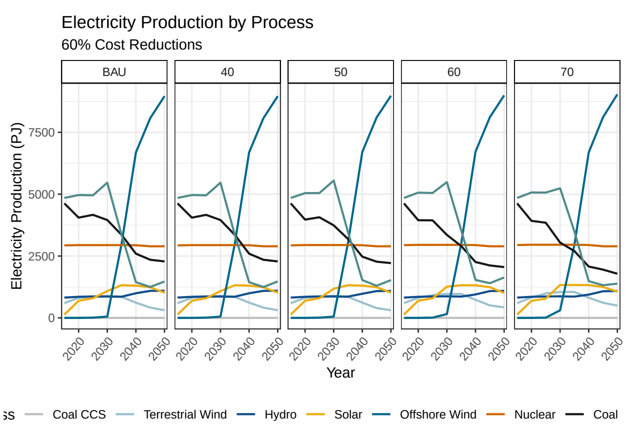


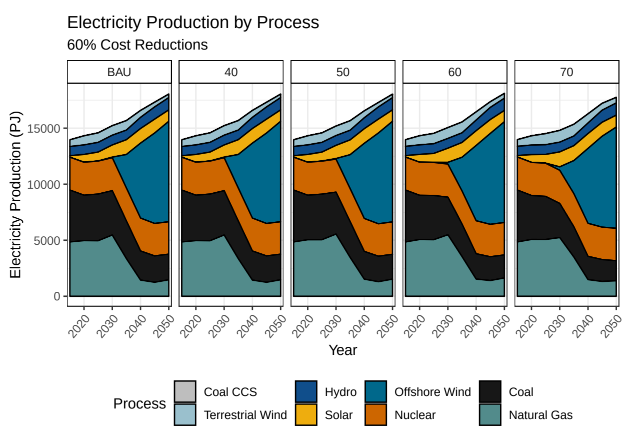
50% cost reduction



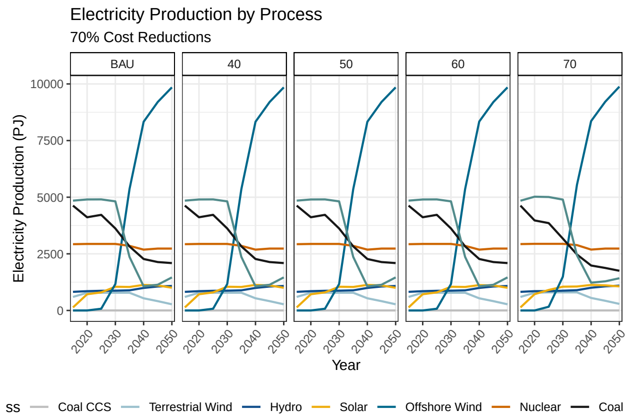


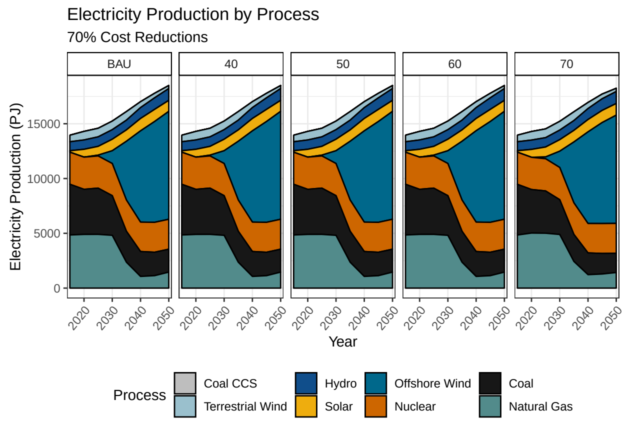
60% cost reduction



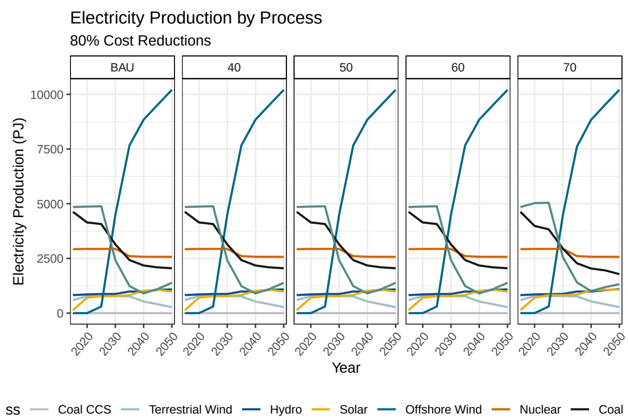


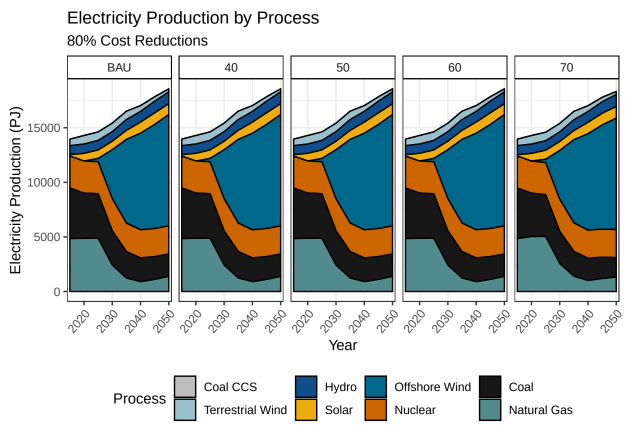
70% cost reduction



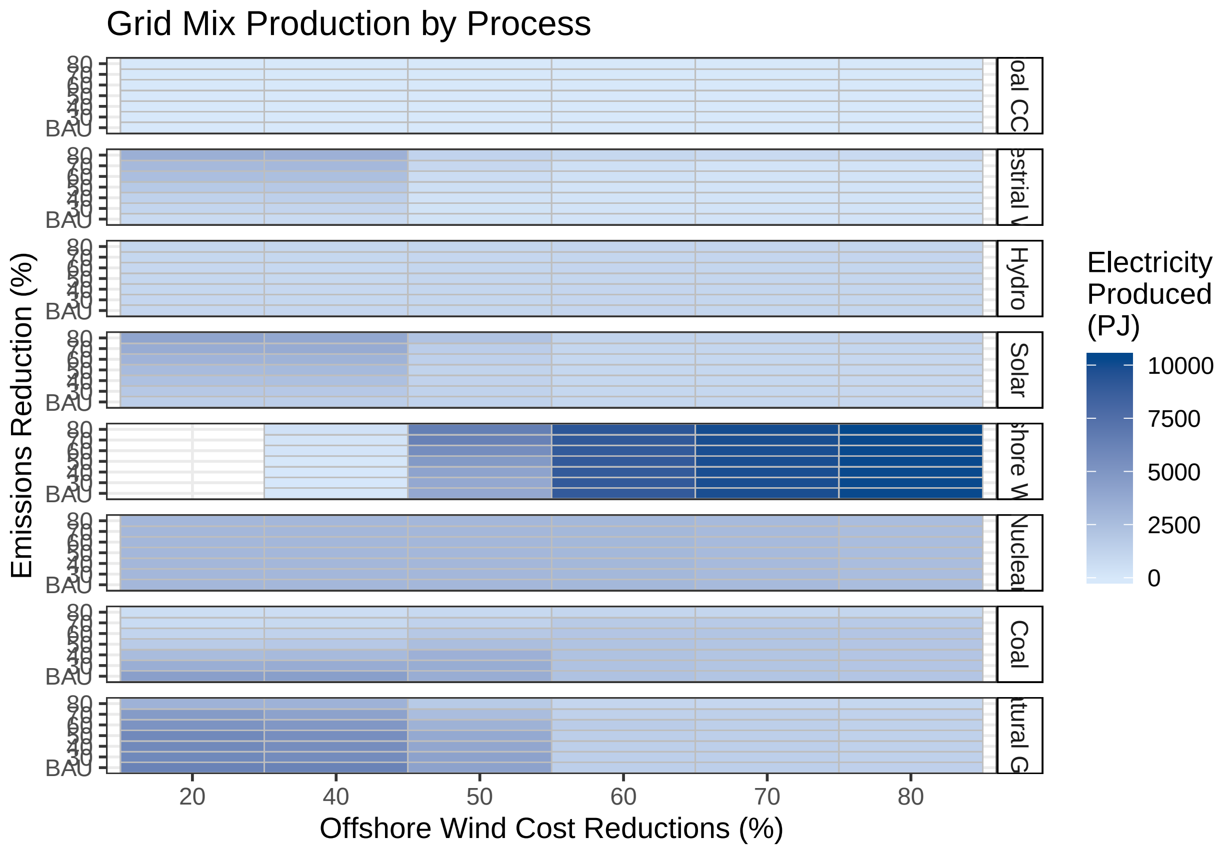


80% cost reduction

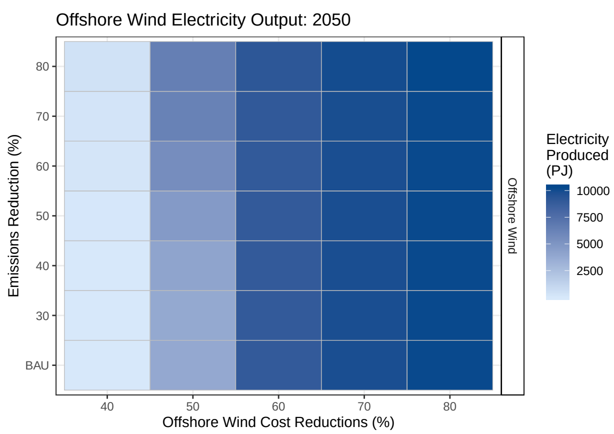




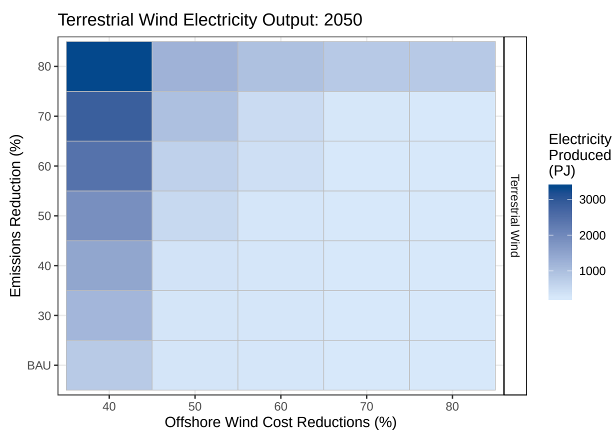
6.5 Heatmaps



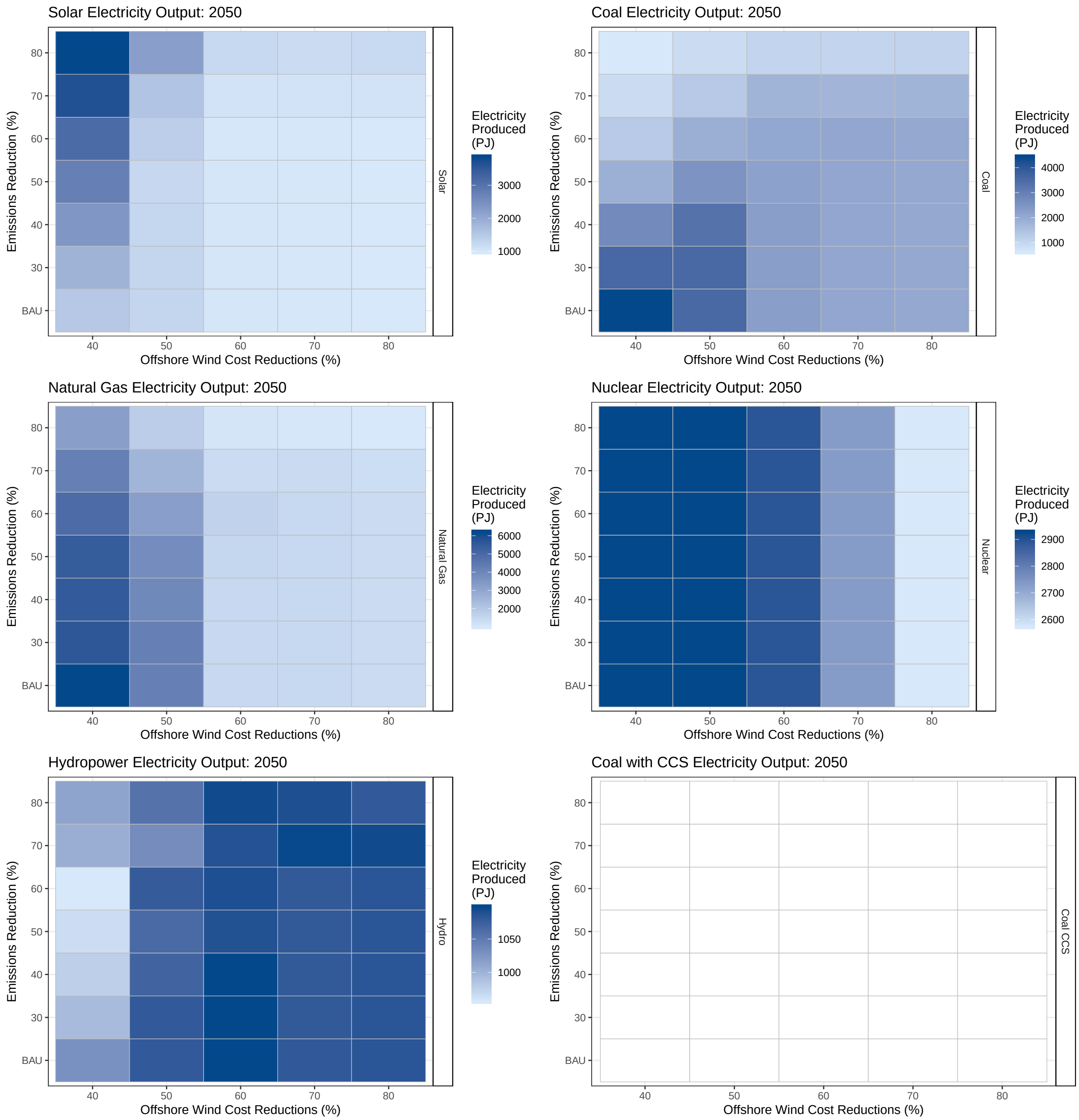
Grid Mix Production by Process
Emissions Reduction (%)
Offshore Wind Cost Reductions (%)
20
40
50
60
70
80
BAU
Hydro
Solar
Coal
Electricity Produced (PJ)
10000
7500
5000
2500
0



Offshore Wind Electricity Output: 2050
Emissions Reduction (%)
Offshore Wind Cost Reductions (%)
Offshore Wind
Electricity Produced (PJ)
10000
7500
5000
2500

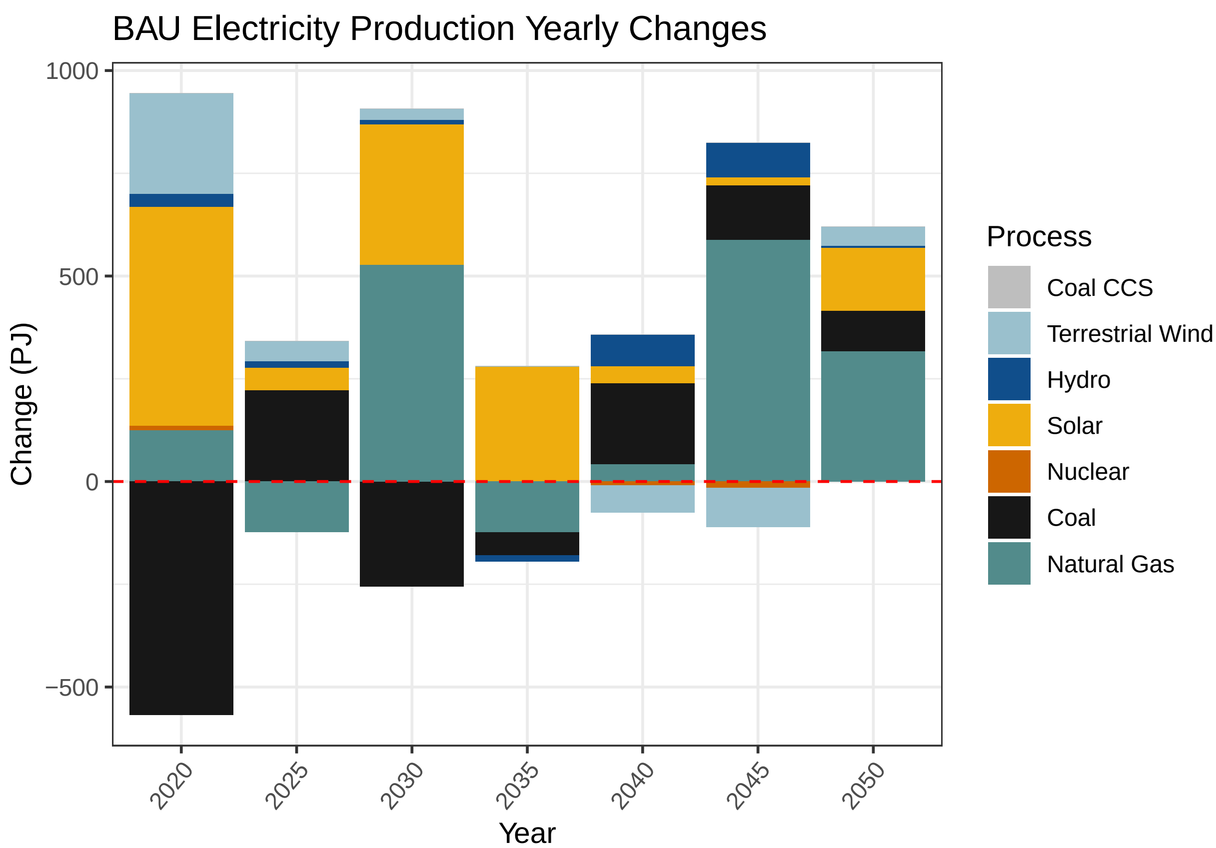


Terrestrial Wind Electricity Output: 2050
Emissions Reduction (%)
Offshore Wind Cost Reductions (%)
Terrestrial Wind
Electricity Produced (PJ)
3000
2000
1000



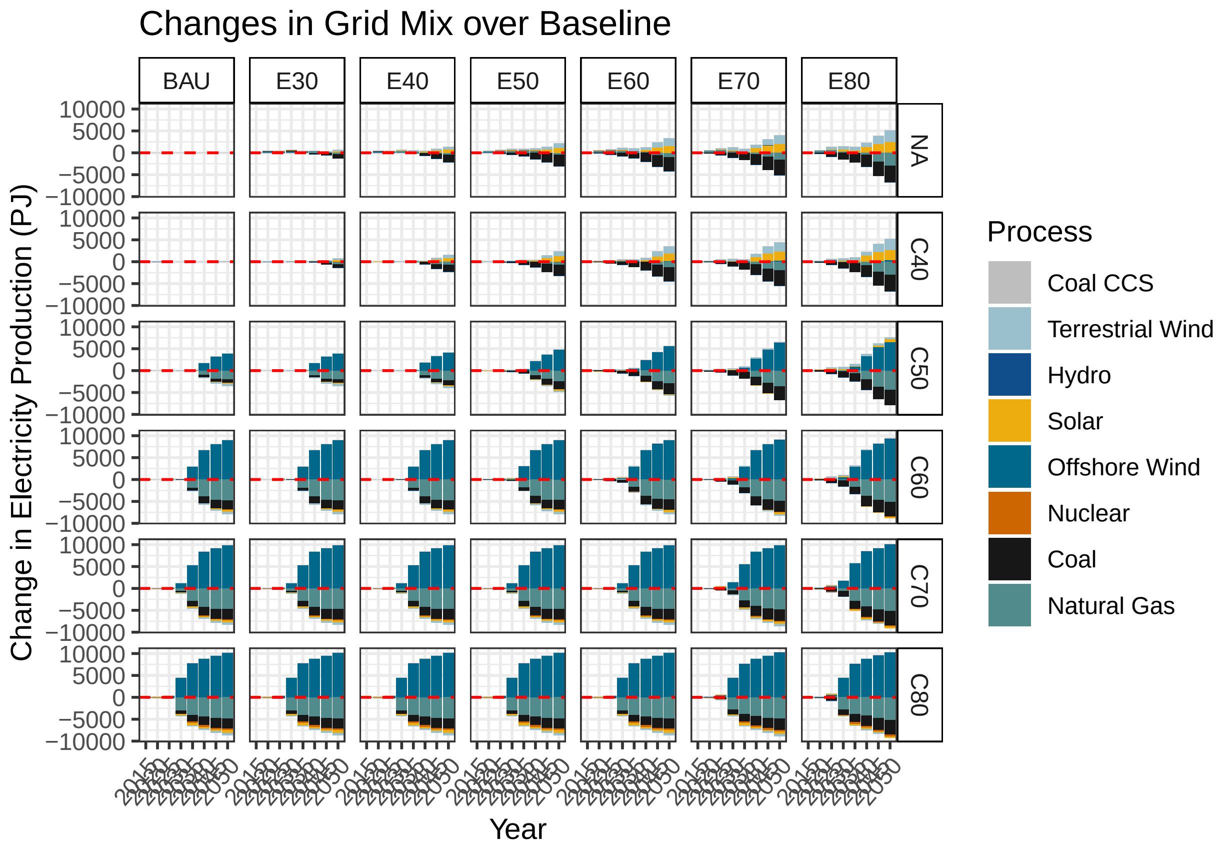
6.6 Retirements and Additions

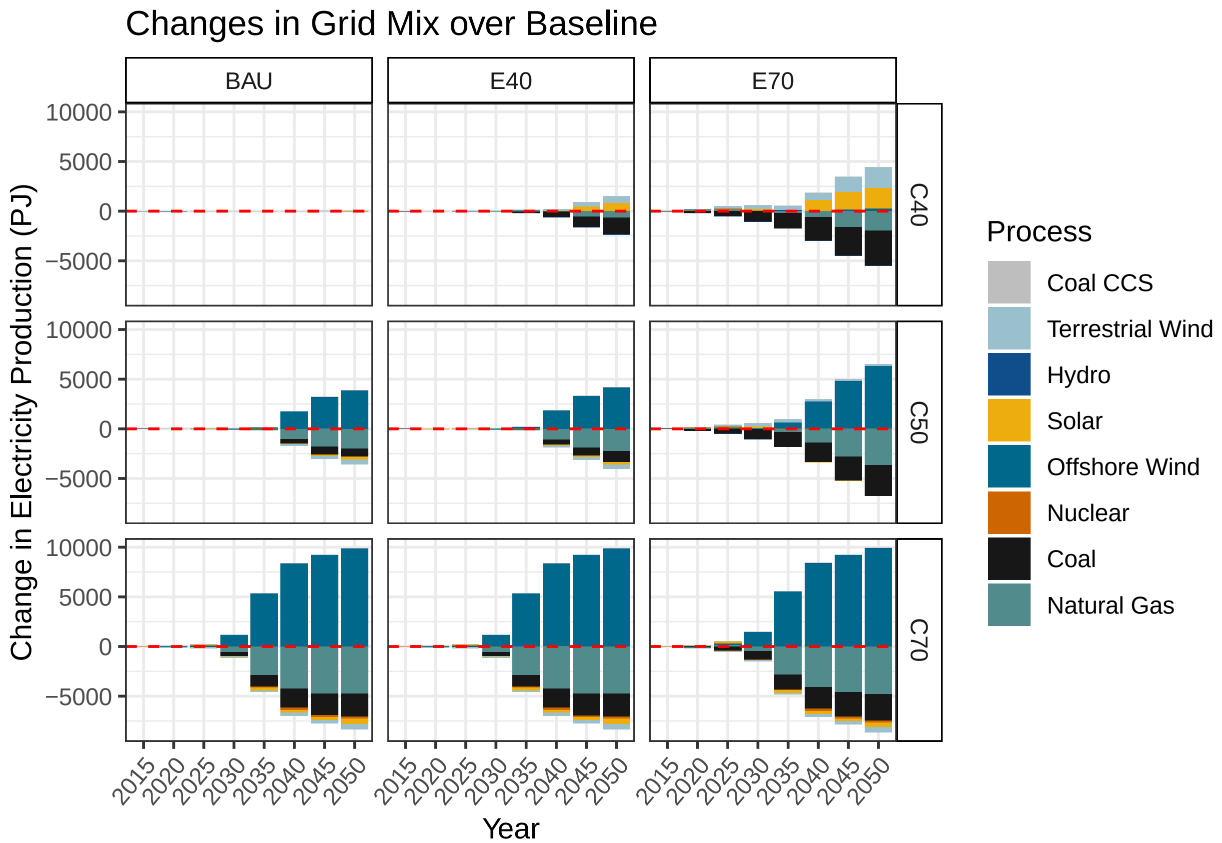
Basecase year-on-year changes in the grid mix. Shows the modeled fluctuations in generation. All following quantifications of grid mix changes are as compared to these changes in the basecase.



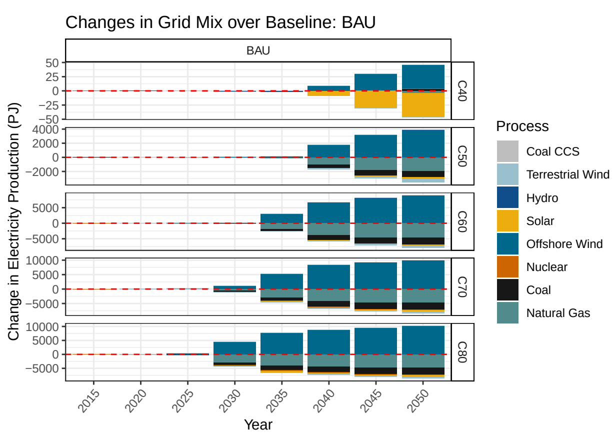
6.7 Changes Over Baseline

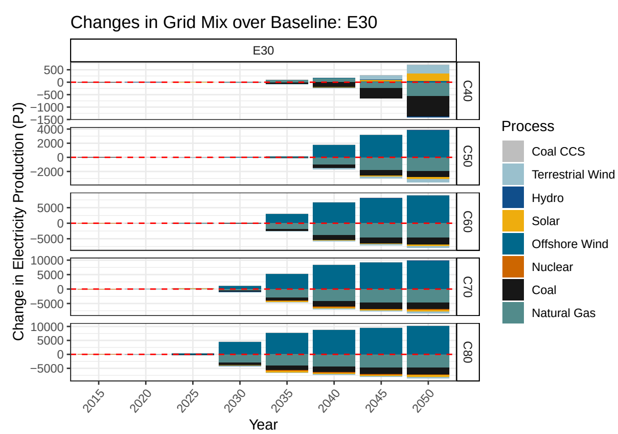
Summary Graph

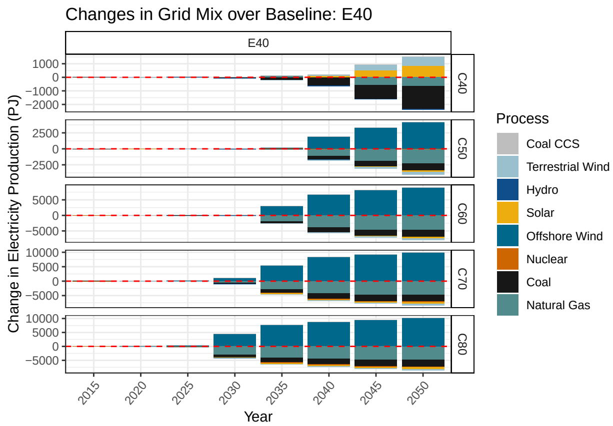

Changes in Grid Mix over Baseline
BAU
E30
E40
E50
E60
E70
E80
NA
C40
C50
C60
C70
C80
10000
5000
0
−5000
−10000
Change in Electricity Production (PJ)
Year
Process
Coal CCS
Terrestrial Wind
Hydro
Solar
Offshore Wind
Nuclear
Coal
Natural Gas

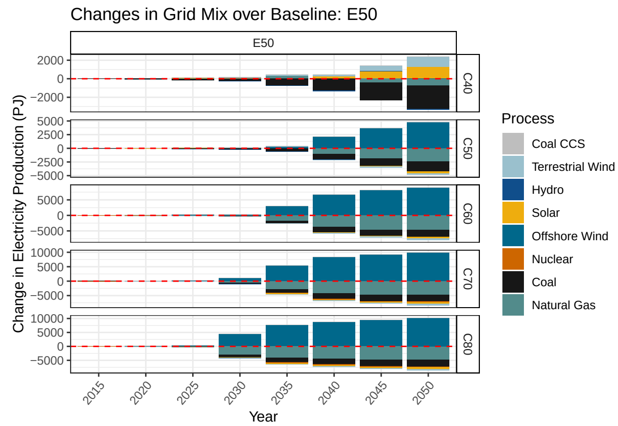


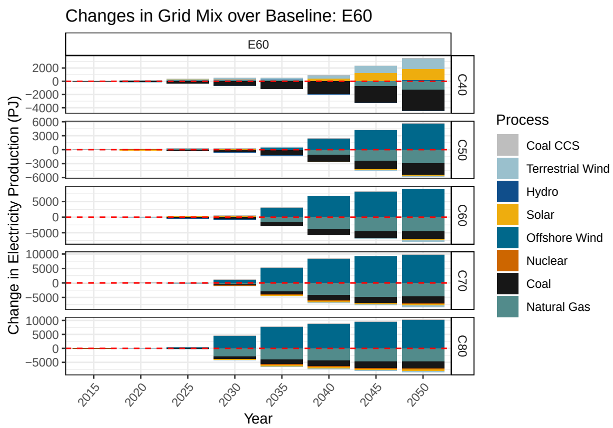
By Emissions Reduction %

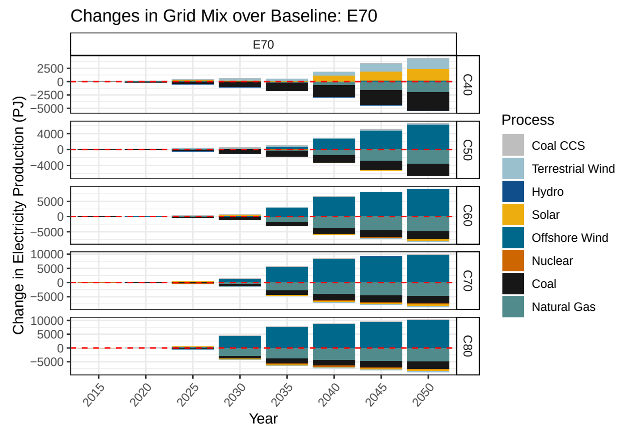


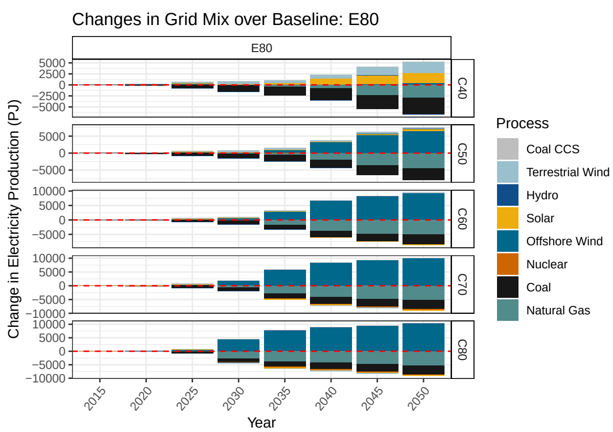






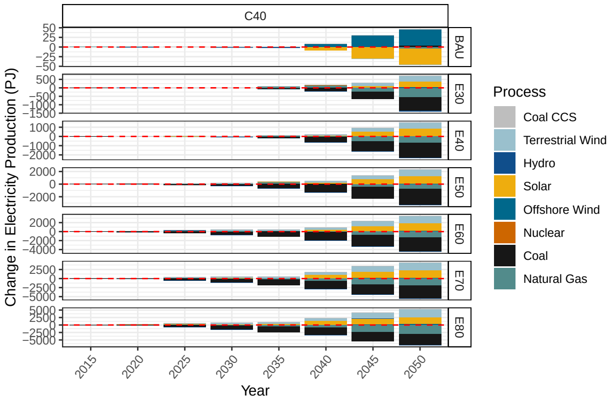




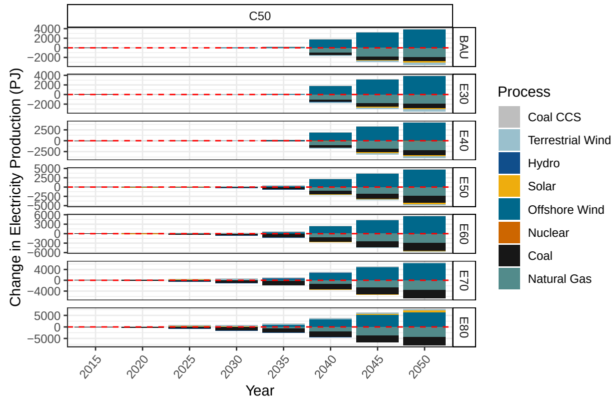


By Cost Reduction %

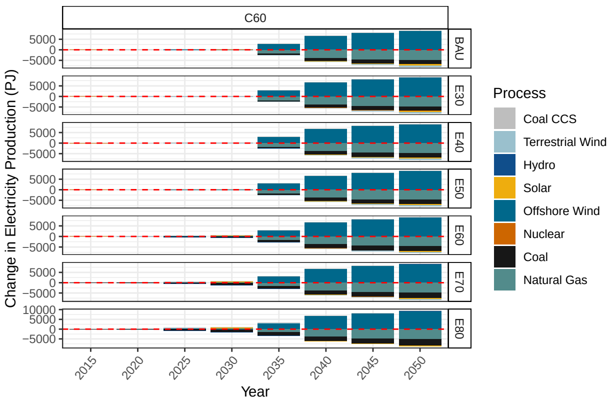
Changes in Grid Mix over Baseline: C40



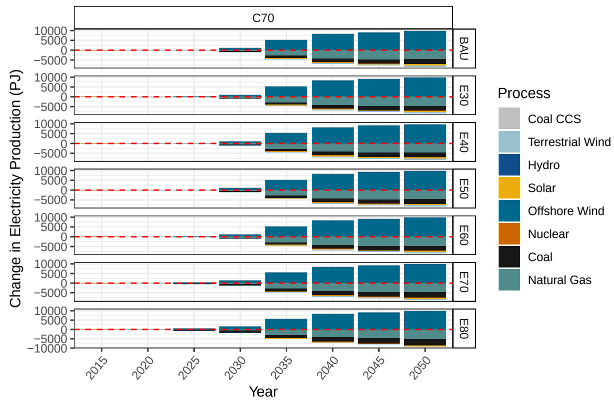
Changes in Grid Mix over Baseline: C50



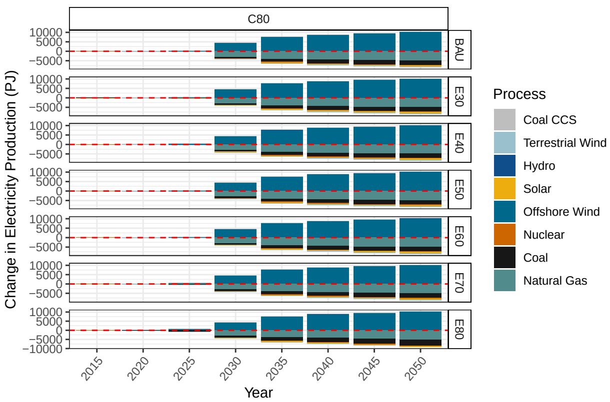
Changes in Grid Mix over Baseline: C60



Changes in Grid Mix over Baseline: C70

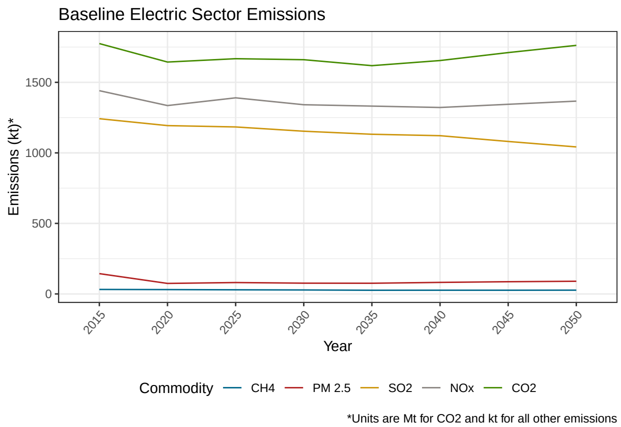


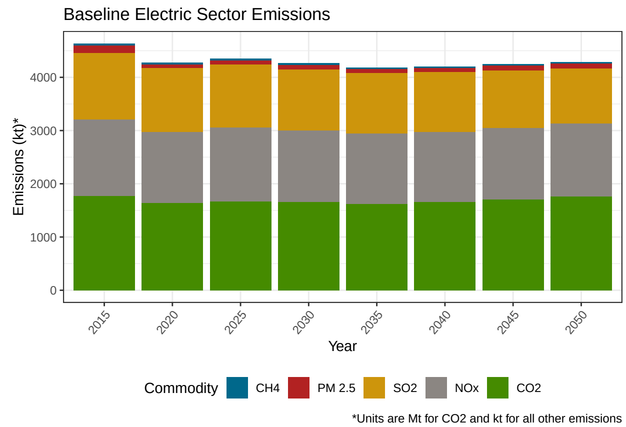
Changes in Grid Mix over Baseline: C80



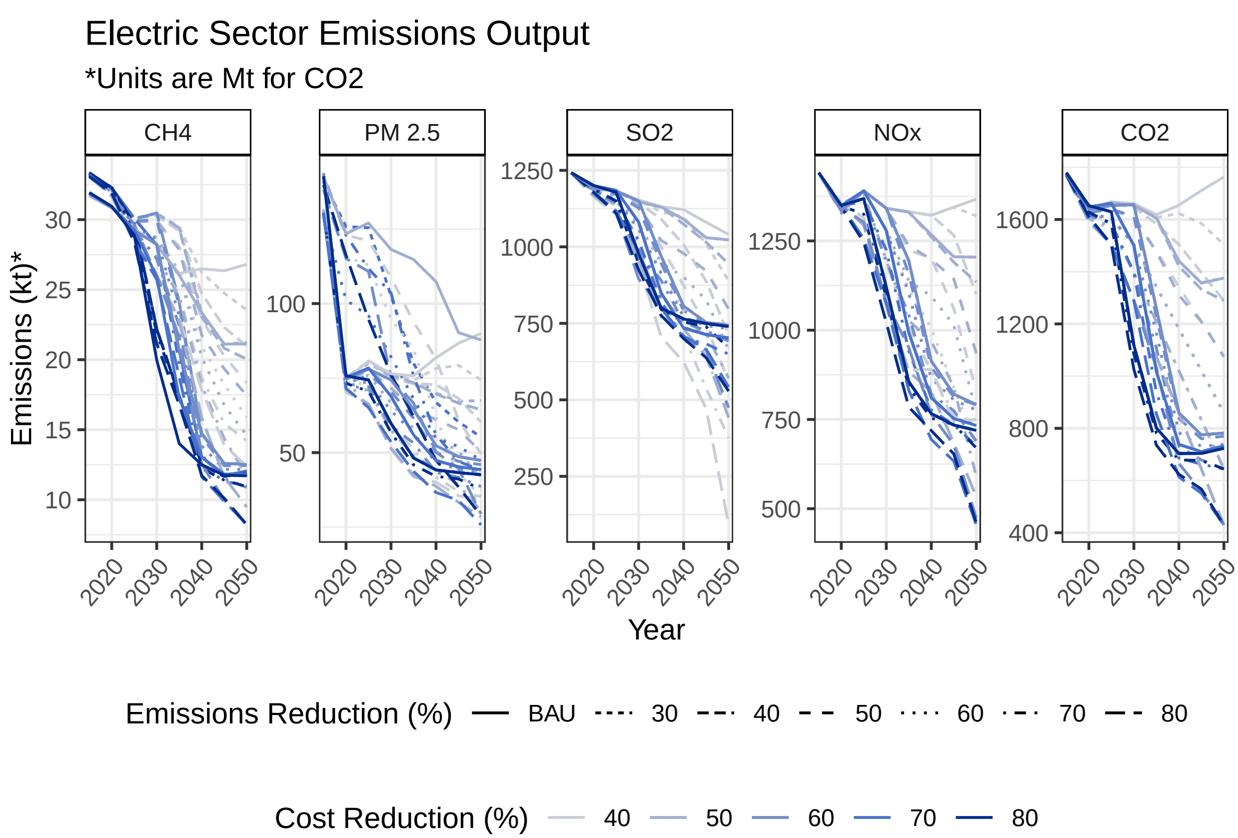
7 Emissions

7.1 Baseline





7.2 Emissions by Scenario and Commodity



8 Total Electricity Production

	emred	costred	2050cap
statistic	c(S = 6051.93861168052)	c(S = 126.15744830328)	c(S = 0)
parameter	NULL	NULL	NULL
p.value	0.382157974623978	1.3462791522123e-25	0
estimate	c(rho = 0.152389550184802)	c(rho = 0.982330889593378)	c(rho = 1)
null.value	c(rho = 0)	c(rho = 0)	c(rho = 0)
alternative	two.sided	two.sided	two.sided
method	Spearman's rank correlation rho	Spearman's rank correlation rho	Spearman's rank correlation rho
data.name	X[[i]] and oswcor$'2050cap'	X[[i]] and oswcor$'2050cap'	X[[i]] and oswcor$'2050cap'