

Offshore Wind Results and Analysis

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1 Disclosure

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

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

2 Setup

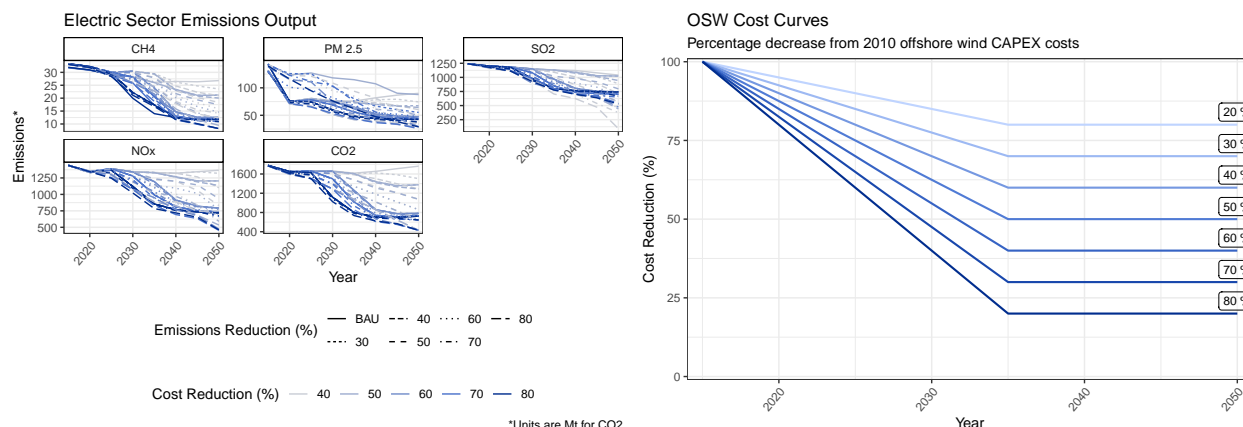
Three scripts are loaded into this markdown document to allow for analysis of the data. The setup script loads the library, creates generalized functions, and creates global variables for color scales and factors. The data script loads the excel spreadsheet with all of the results data and performs the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

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

3 Scenarios

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

1. Electric sector CO₂ emissions caps, as a linear decrease to a given % decrease from 2010 emissions by 2050
 - Business and usual emissions represent approximately a 20% reduction in CO₂ emissions
2. Cost reductions of offshore wind, as a linear decrease to a given % decrease from 2010 costs by 2035, then level costs to 2050
 - A 20% cost reduction is used as the base case, assuming very conservative technological advancement and little benefit of economies of scale
 - Cost curves are set to resolve by 2035 as estimated based on NREL LCOE cost projections for offshore wind



4 LCOE

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

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

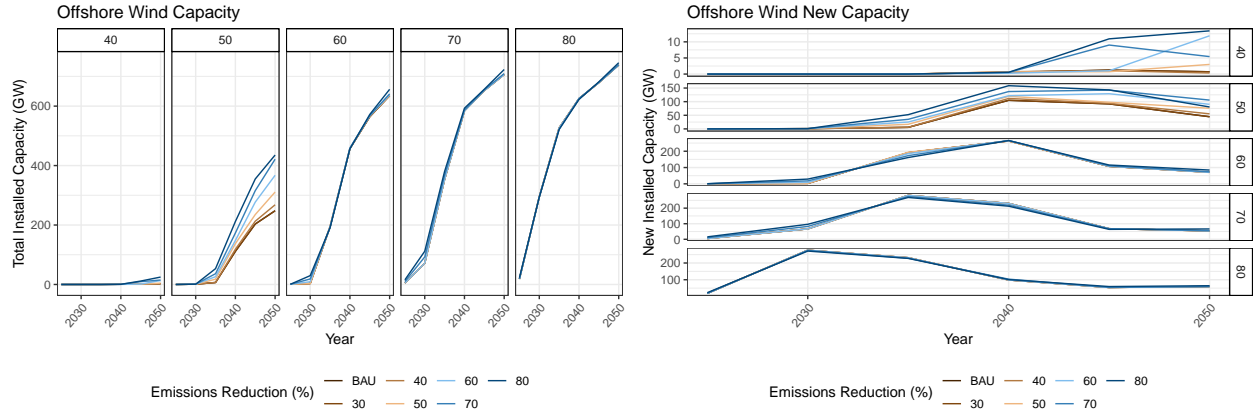
Cumulative and new addition offshore wind capacity across all nine census regions, by cost and emissions reduction scenario.

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

Note:

U.S. EIA Annual Energy Outlook 2019



5.2 Total Capacity

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

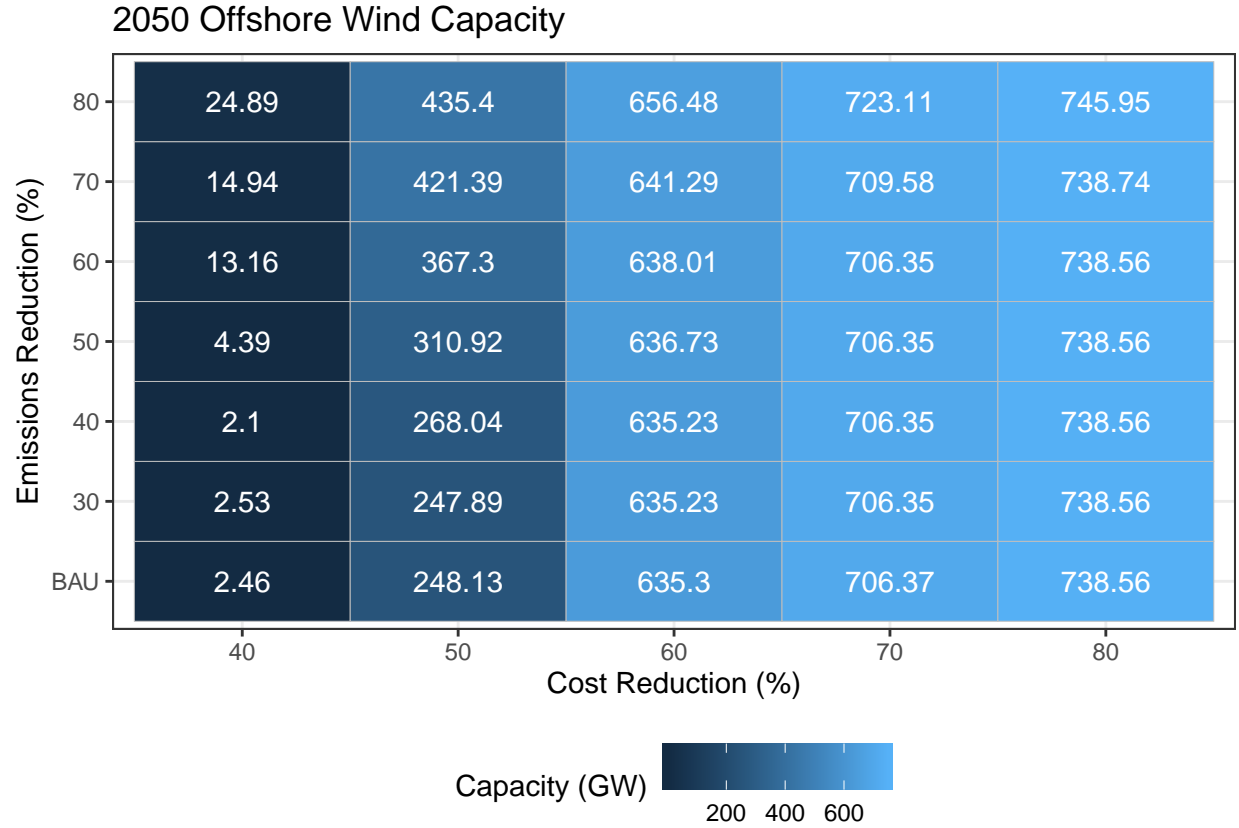


Table 2: Offshore Wind Total Installed Capacity (GW): 2050

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.

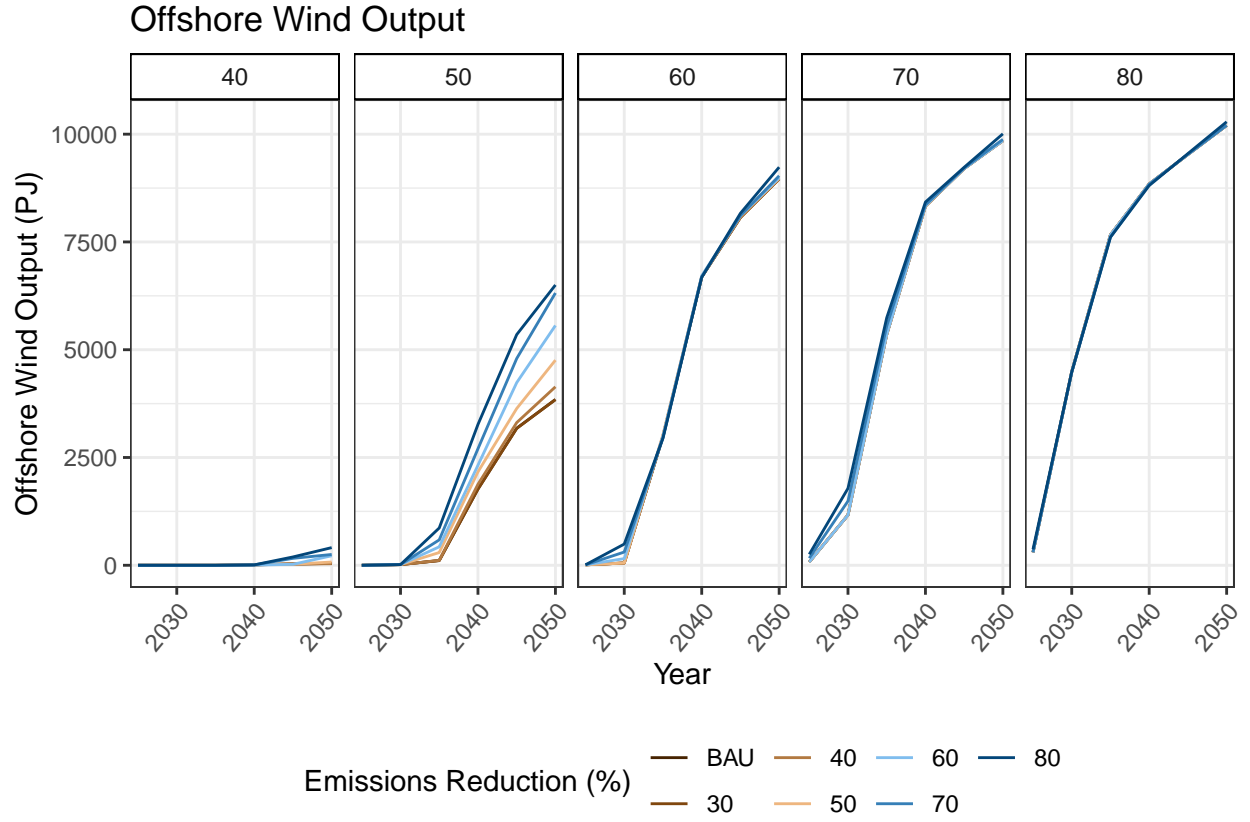
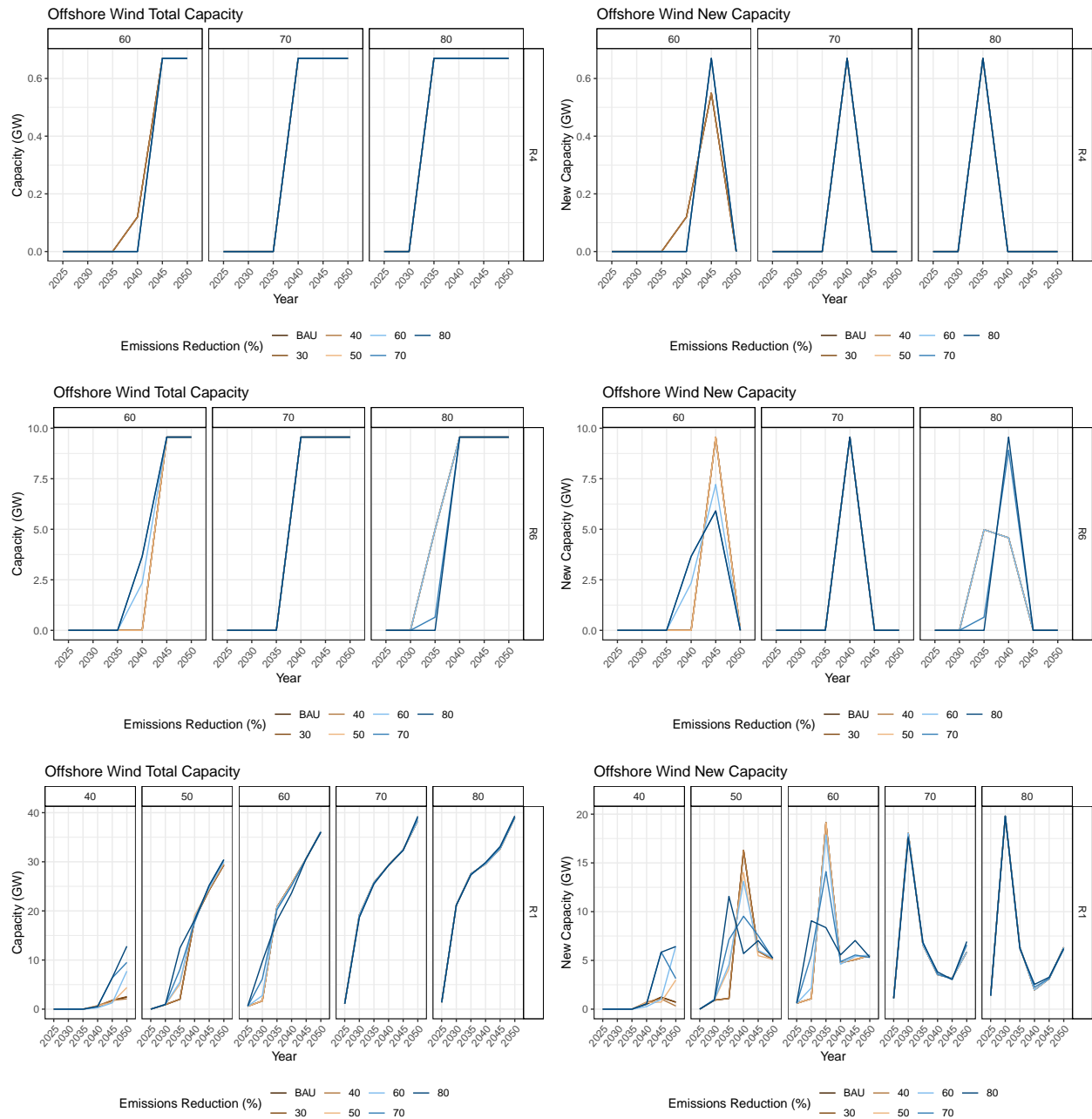


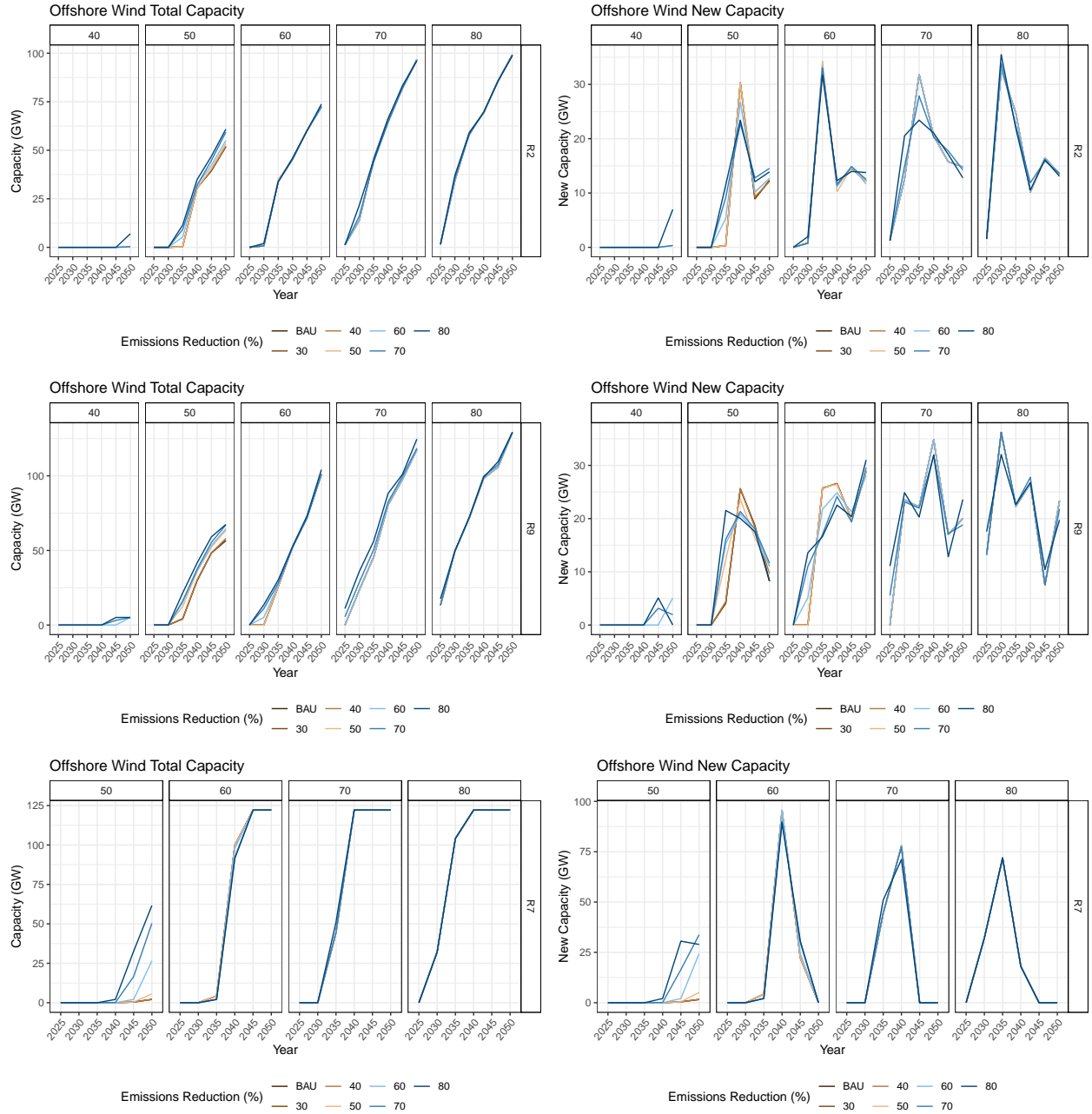
Table 3: Offshore Wind Total Output (PJ): 2050

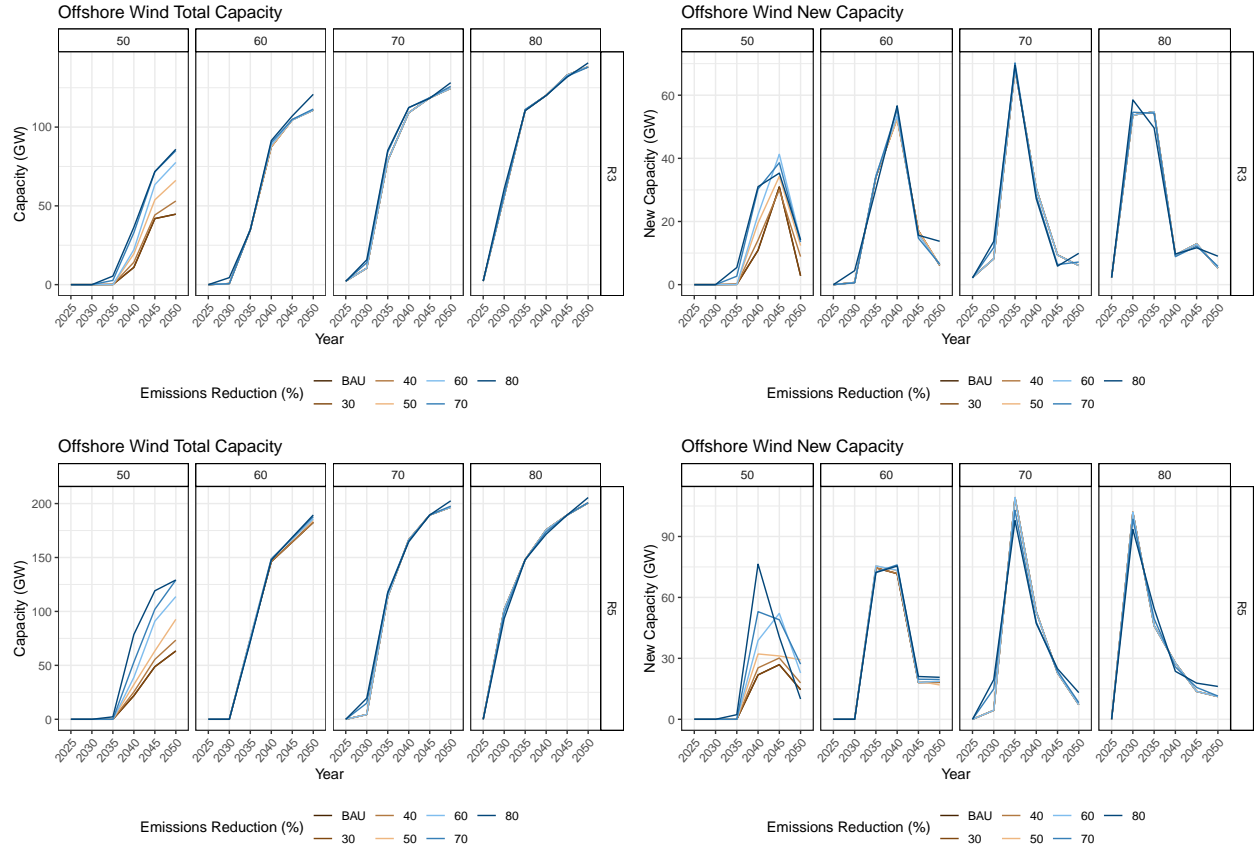
Emissions Reduction (%)	Cost Reduction (%)				
	40	50	60	70	80
BAU	42.3	3845.4	8962.0	9848.8	10204.0
30	43.4	3841.7	8960.8	9848.5	10204.0
40	36.0	4139.4	8960.8	9848.5	10204.0
50	75.3	4758.1	8977.9	9848.5	10204.0
60	221.0	5562.3	8992.0	9848.5	10204.0
70	250.4	6315.4	9034.2	9880.0	10205.3
80	409.6	6502.2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

5.4 Regions

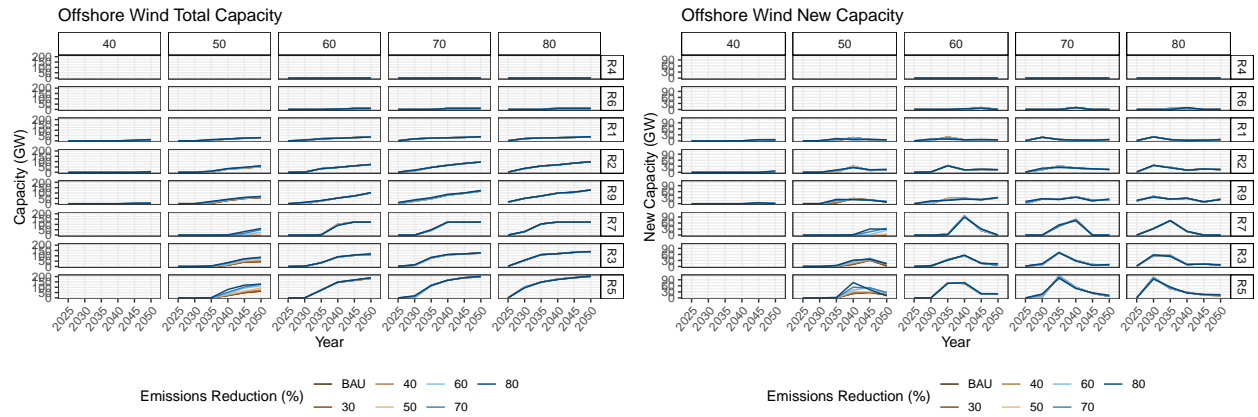
Cumulative and new addition offshore wind capacity by region. Regions are listed from least to highest electricity output.







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



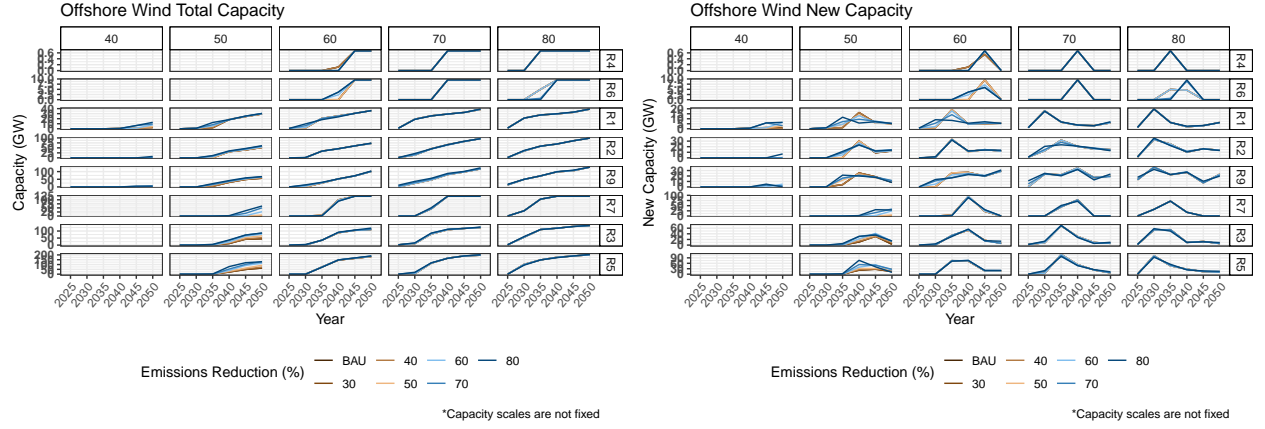


Table 4: Average Installed Capacity (GW)

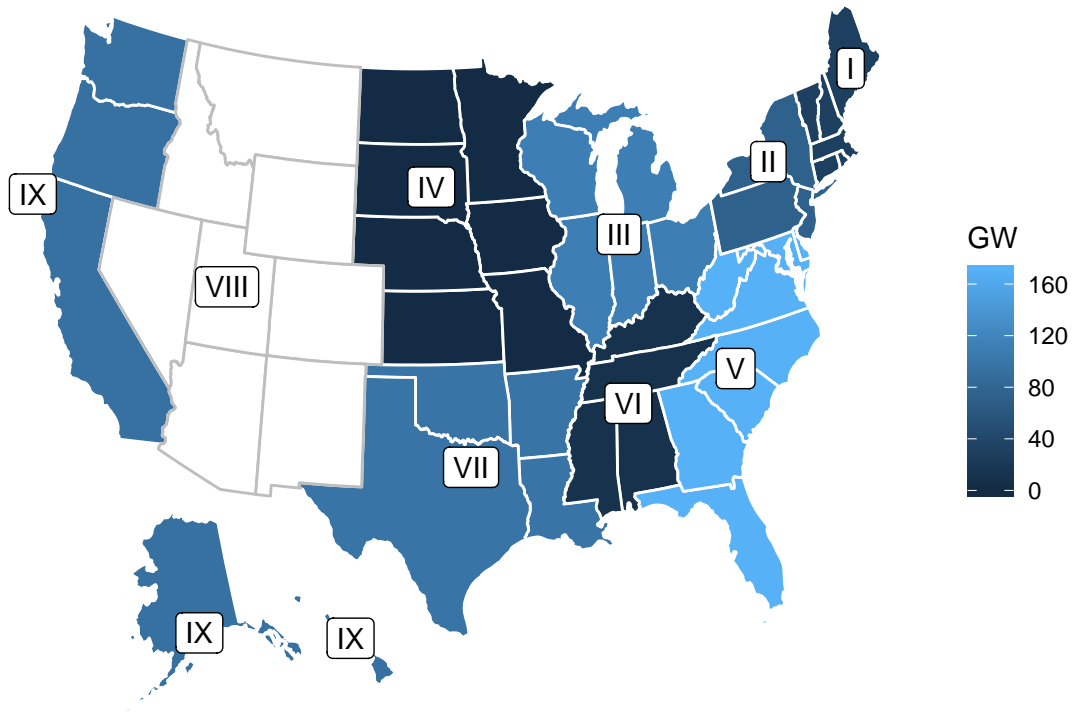
Region	2050 Total
R4	0.67000
R6	9.56000
R1	29.88514
R2	73.21452
R9	93.38871
R7	96.97286
R3	110.37893
R5	169.72857

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

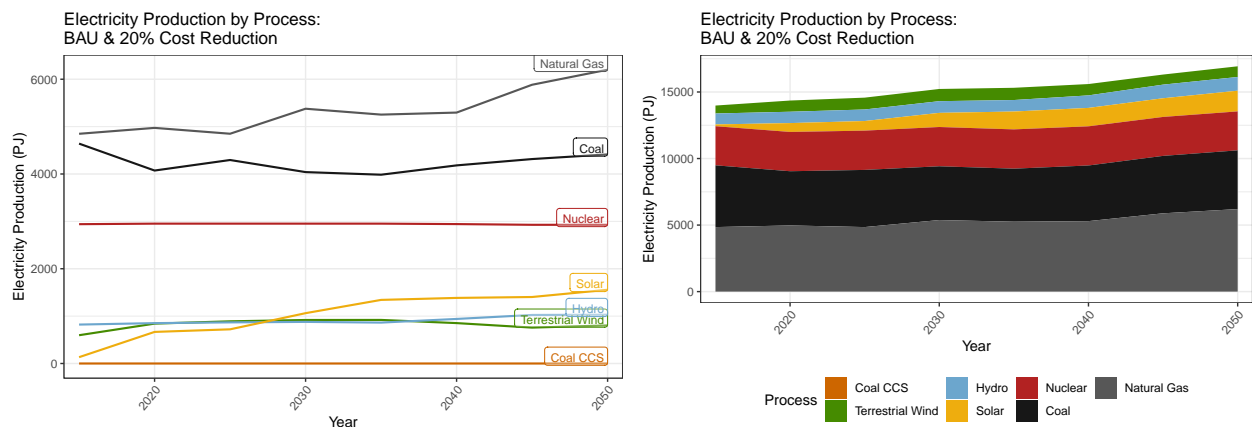
Average Offshore Wind Capacity



6 Grid Mix

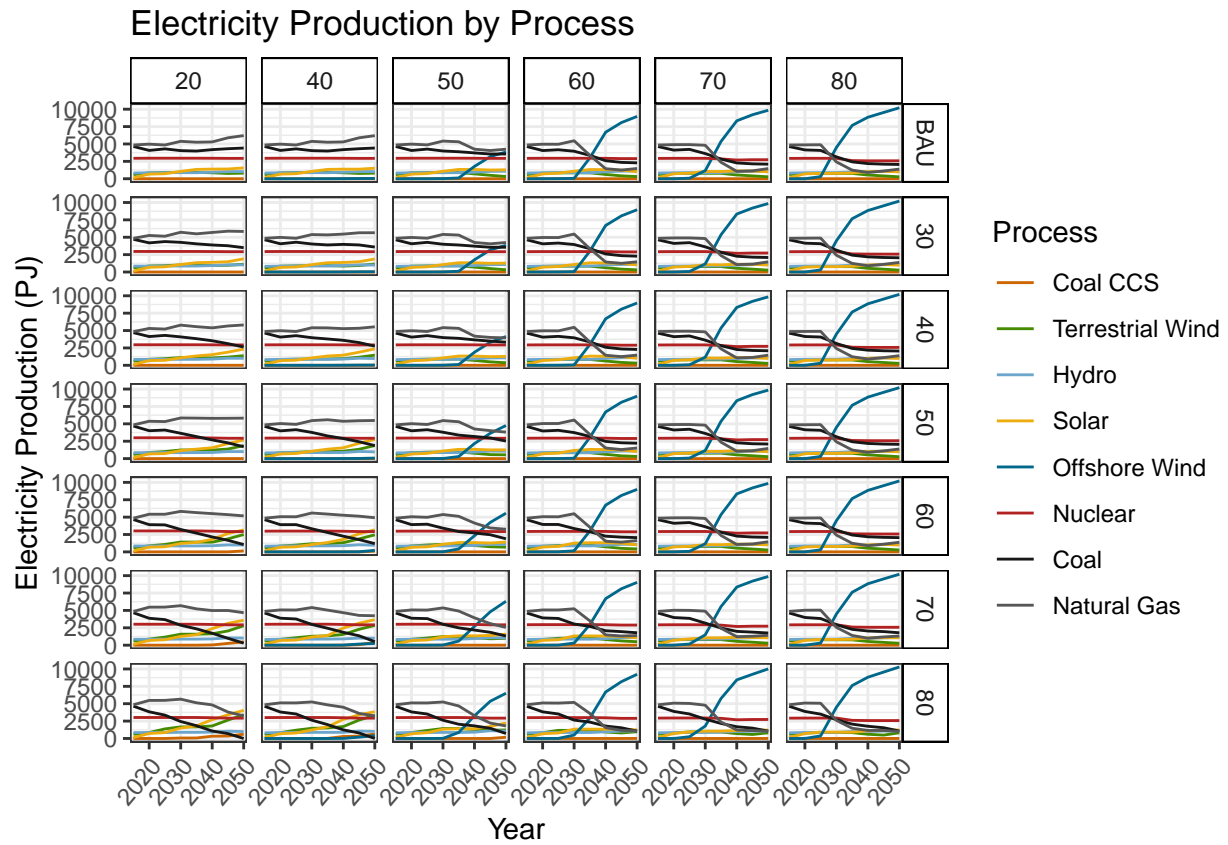
6.1 Baseline Production

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



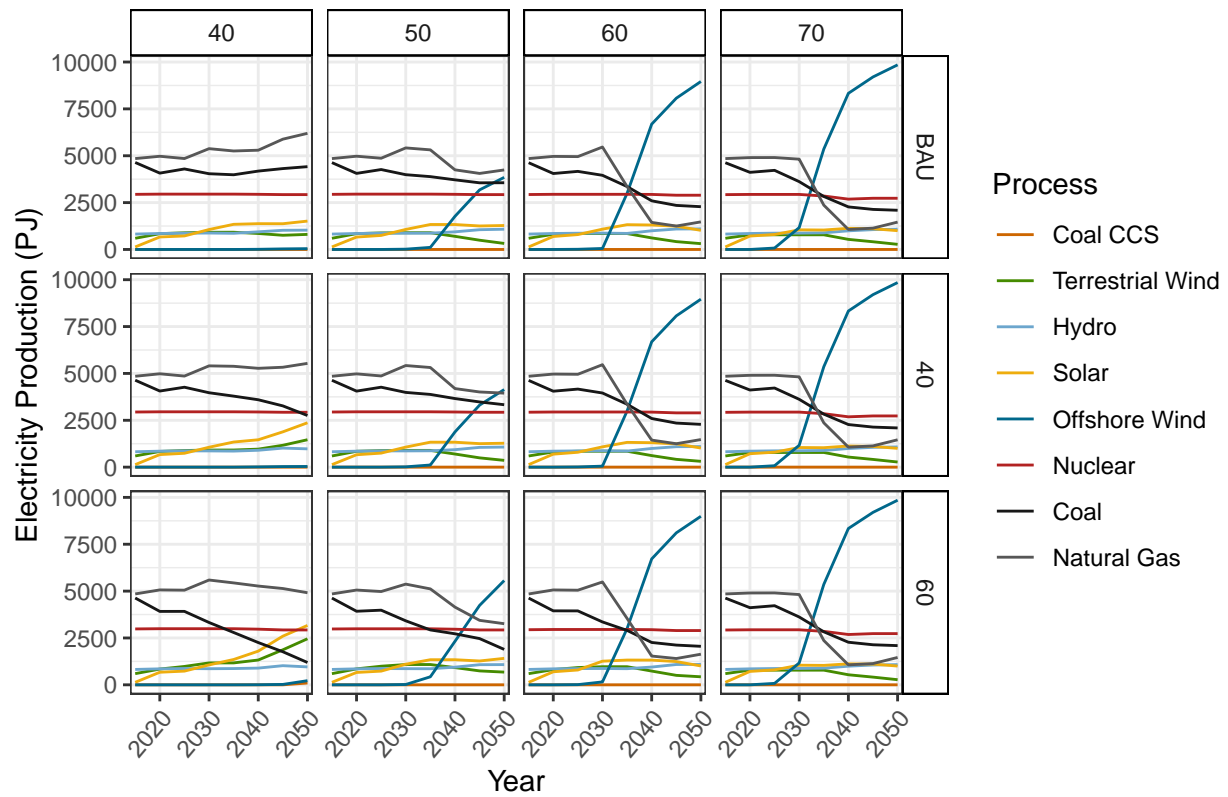
6.2 All Scenarios

Complete Set



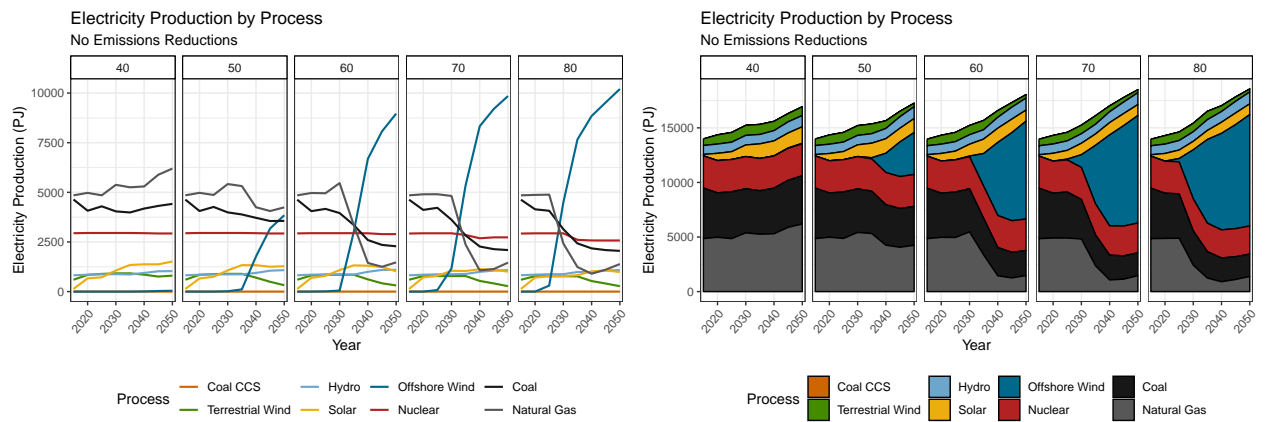
Parsed Set

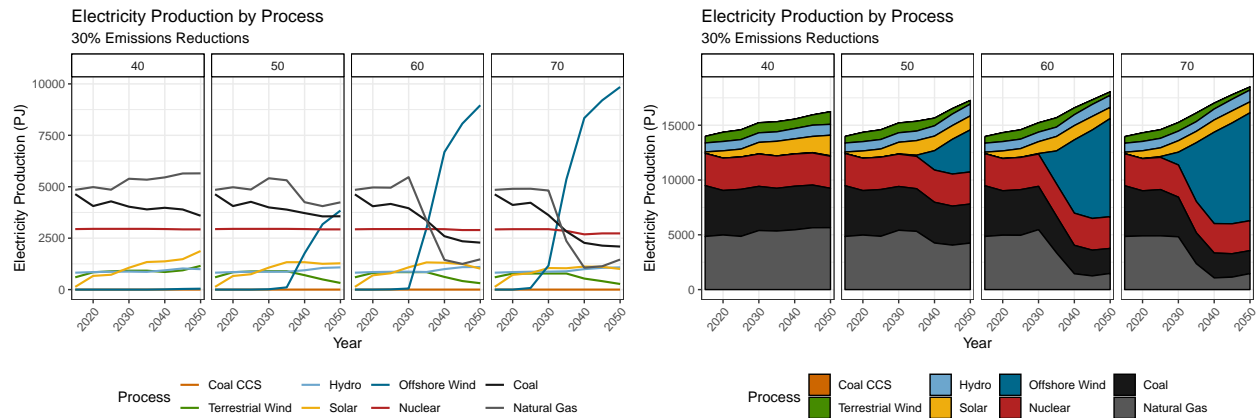
Electricity Production by Process



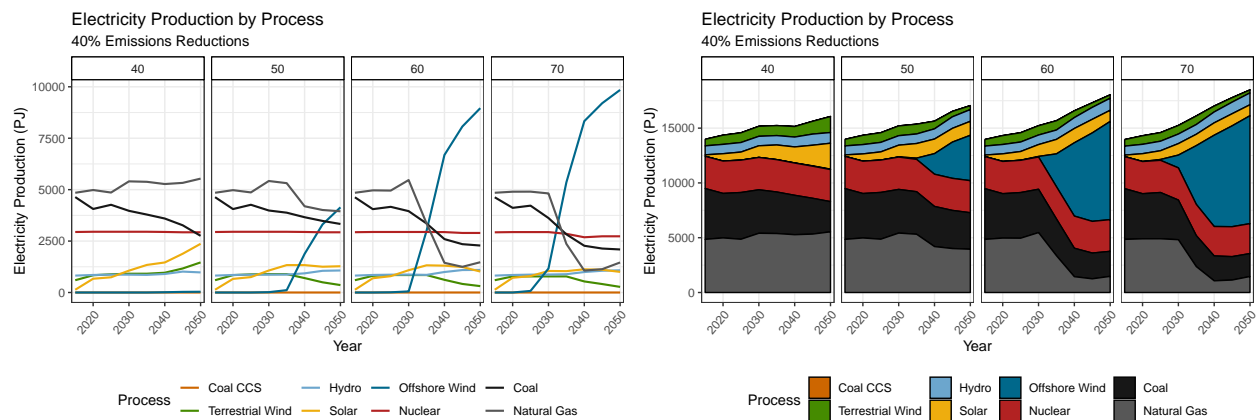
6.3 Emissions Cap

BAU emissions

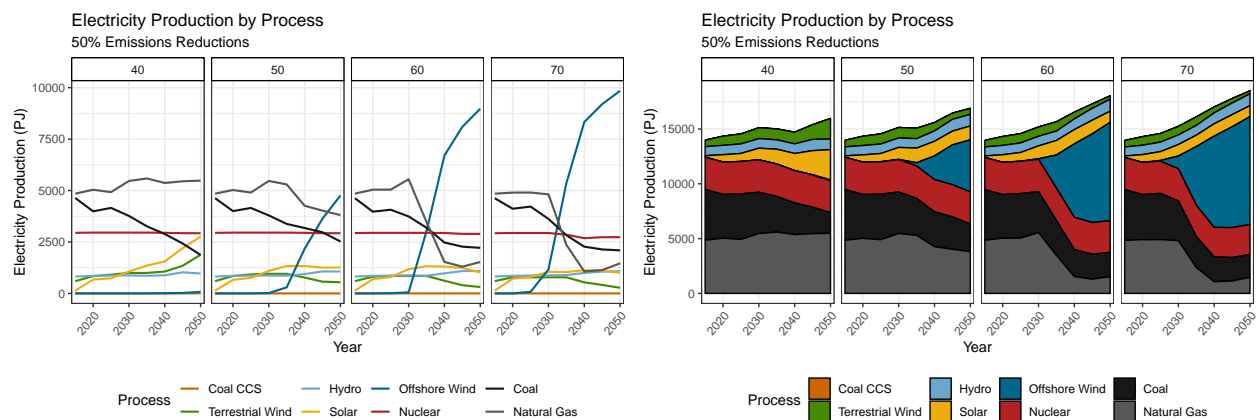




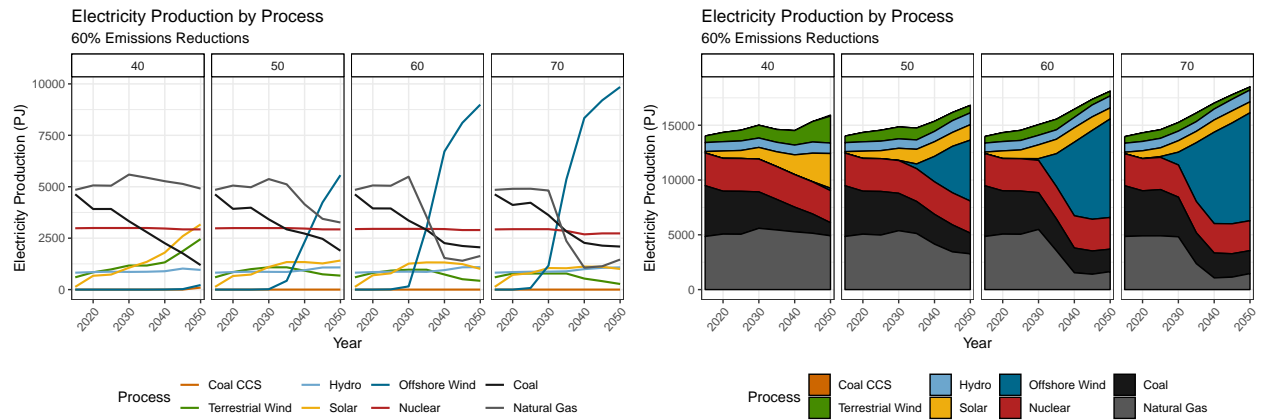
40% emissions reduction



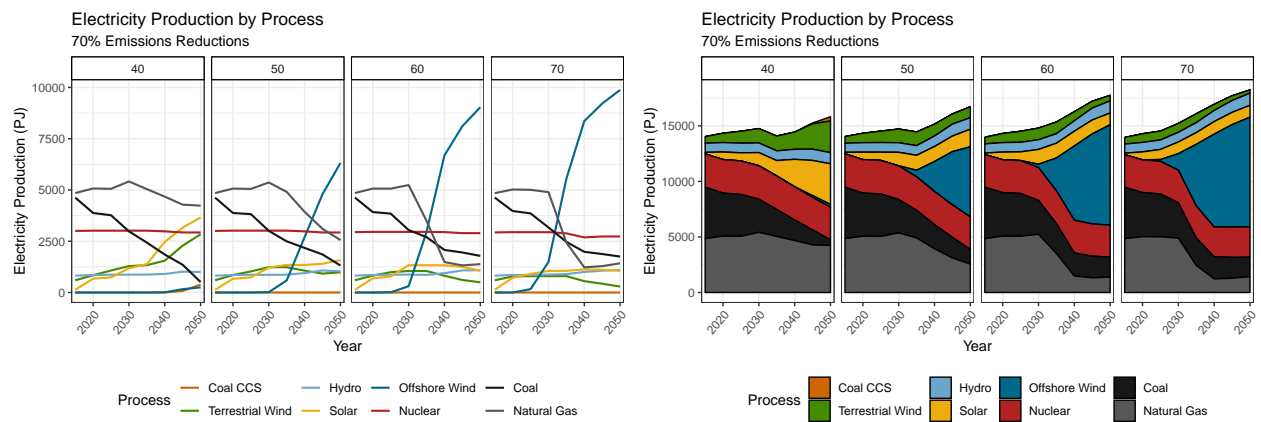
50% emissions reduction



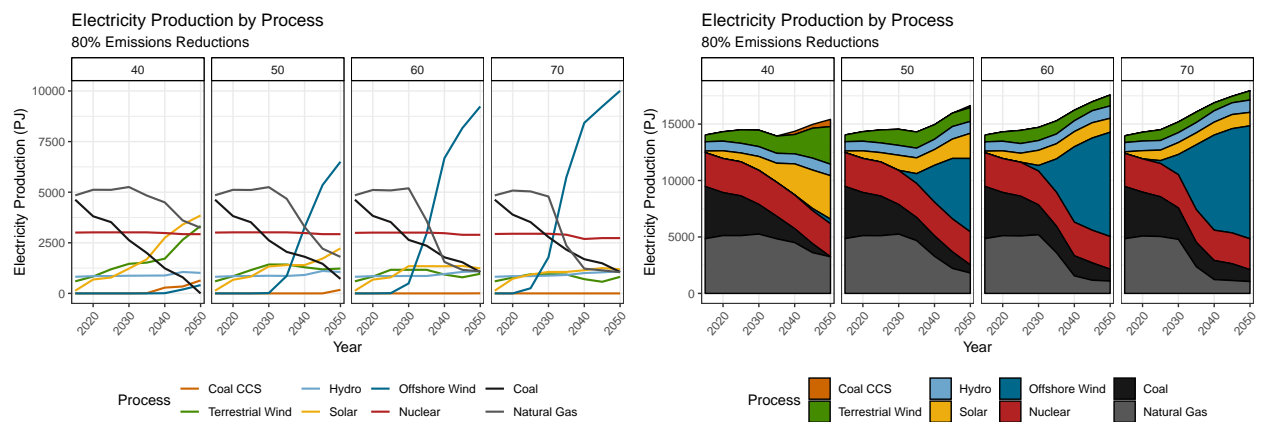
60% emissions reduction



70% emissions reduction

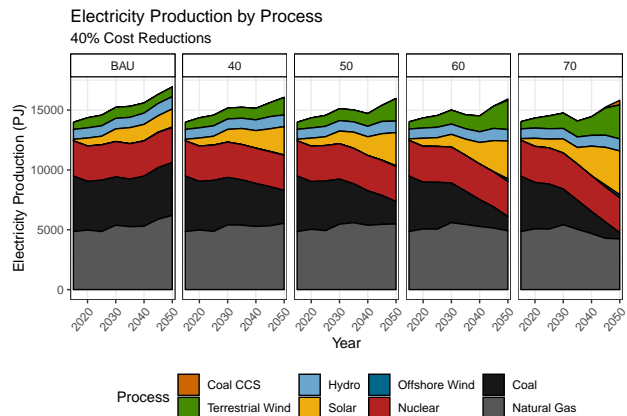
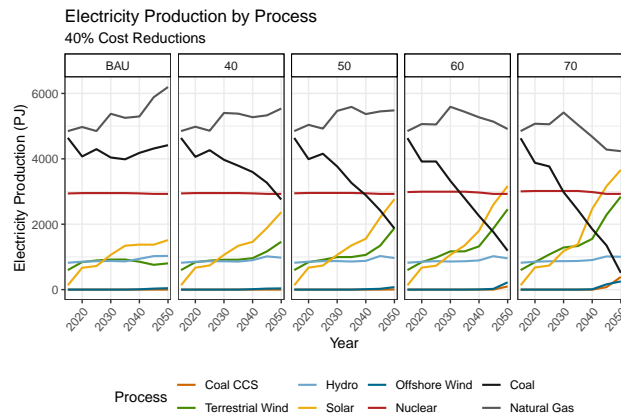


80% emissions reduction

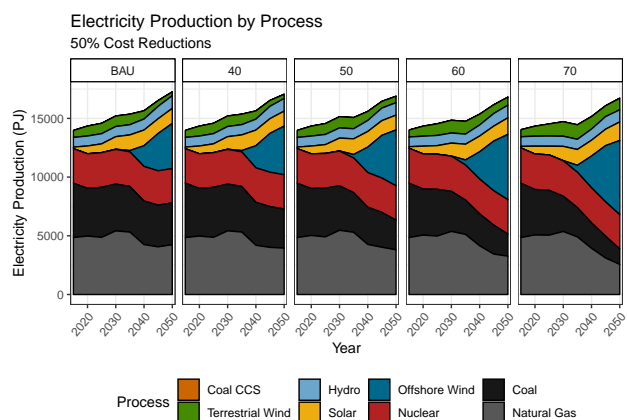
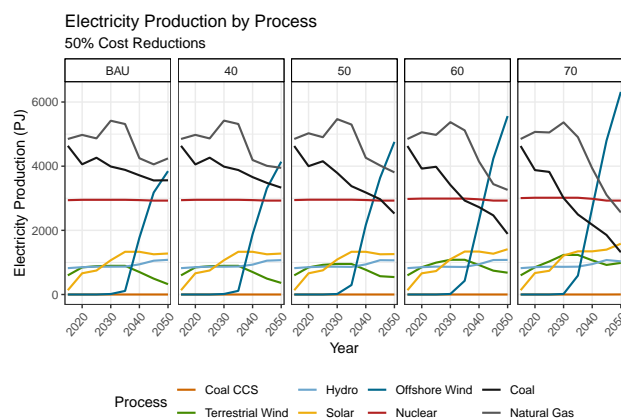


6.4 Cost Reductions

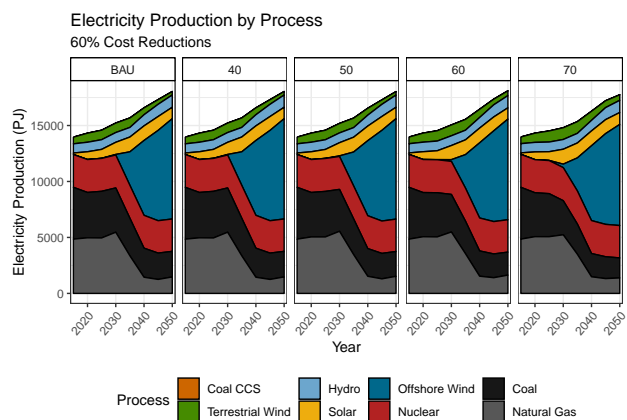
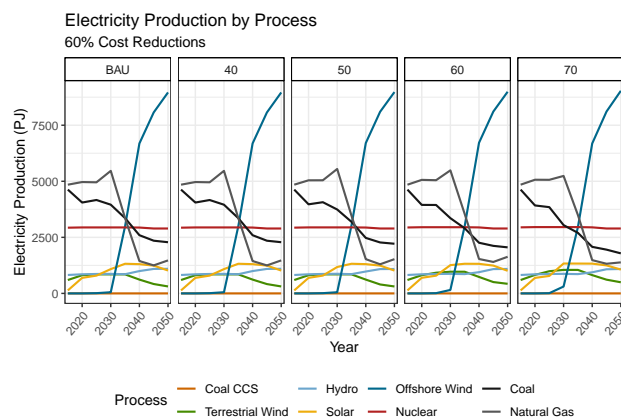
40% cost reduction



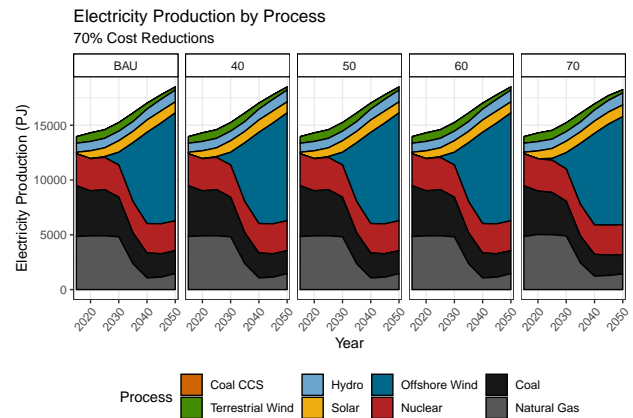
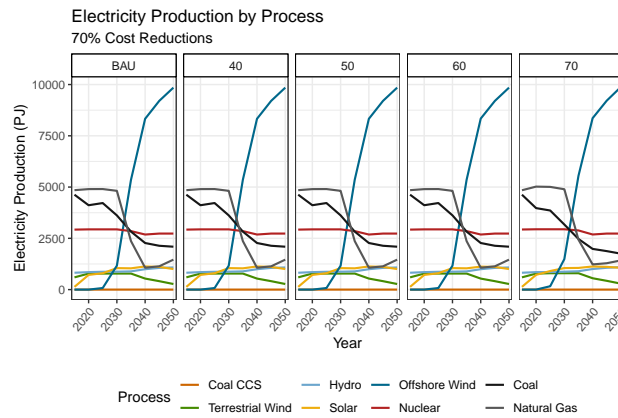
50% cost reduction



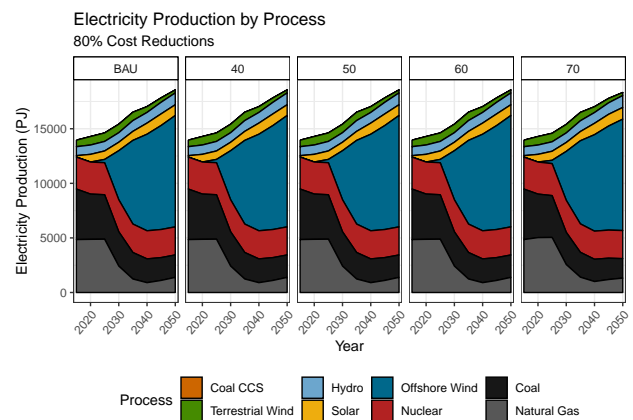
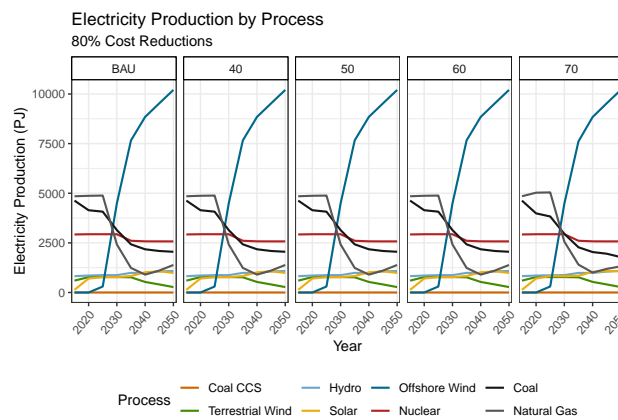
60% cost reduction



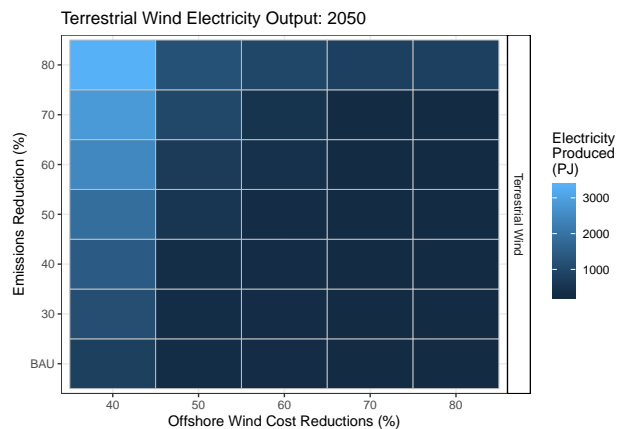
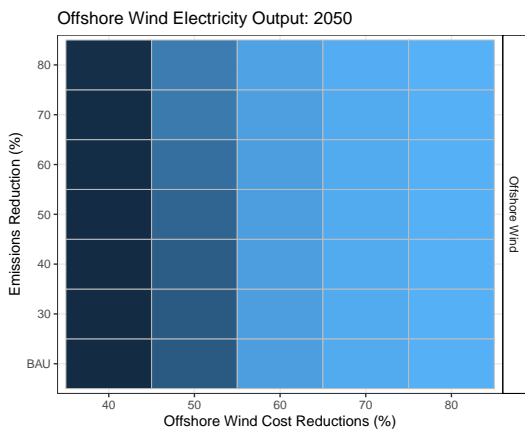
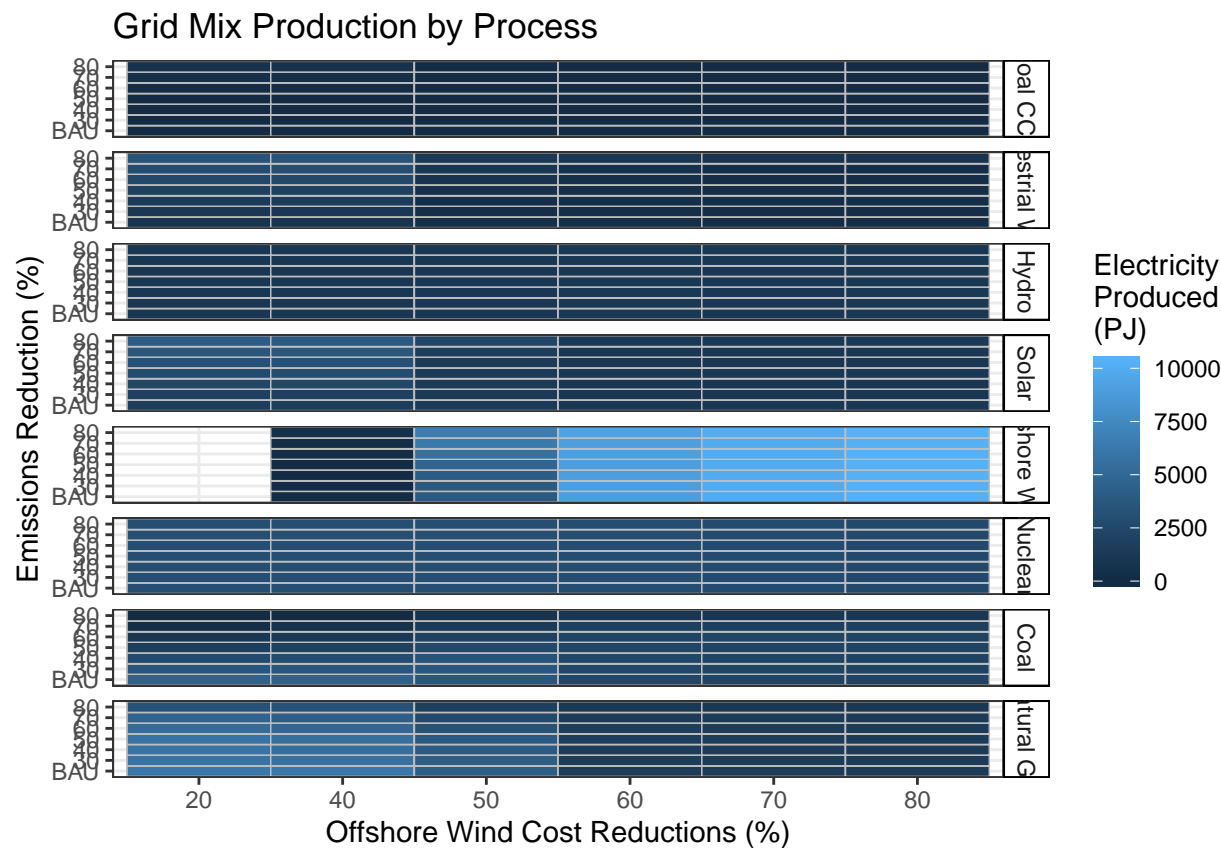
70% cost reduction

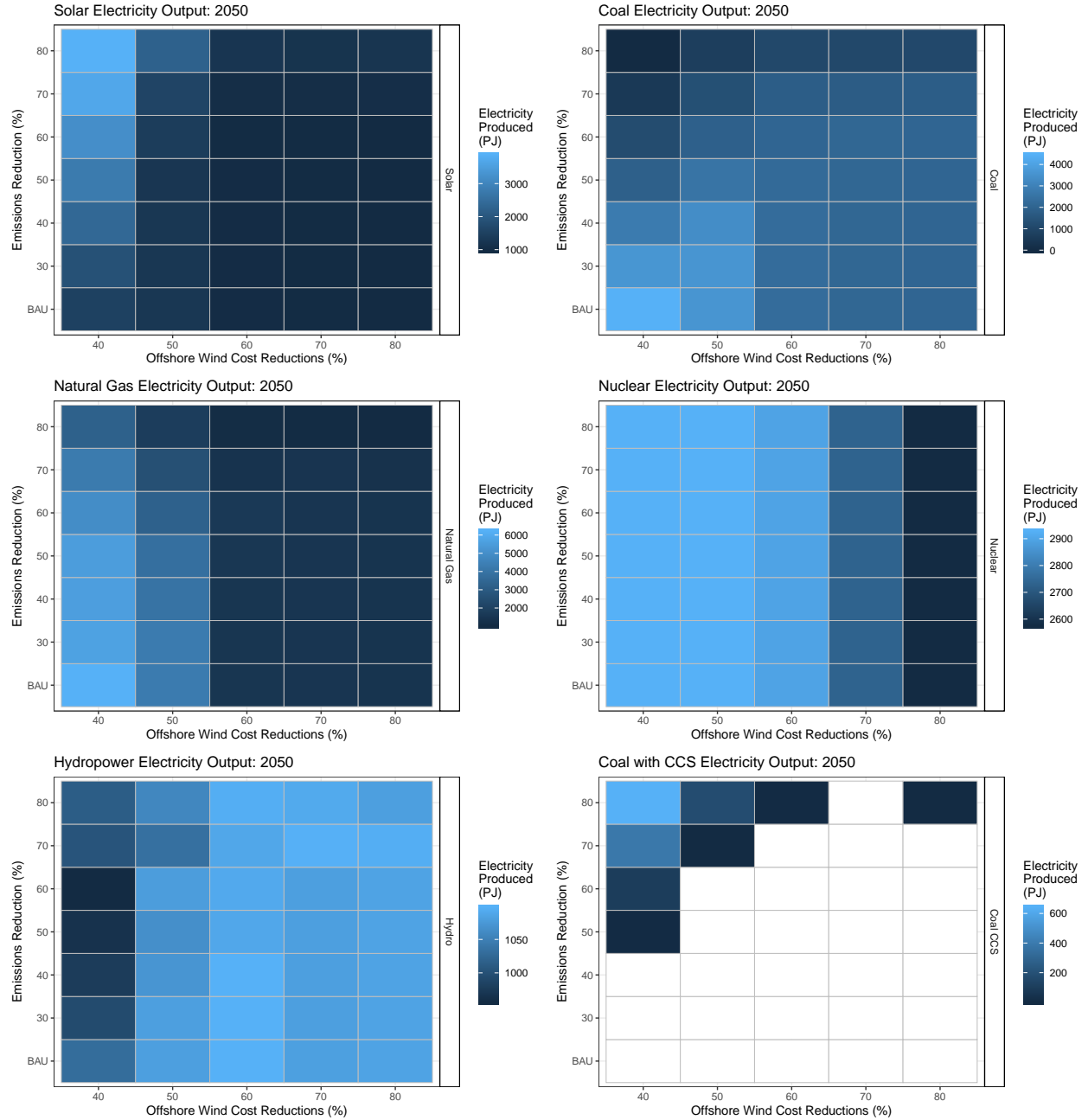


80% cost reduction



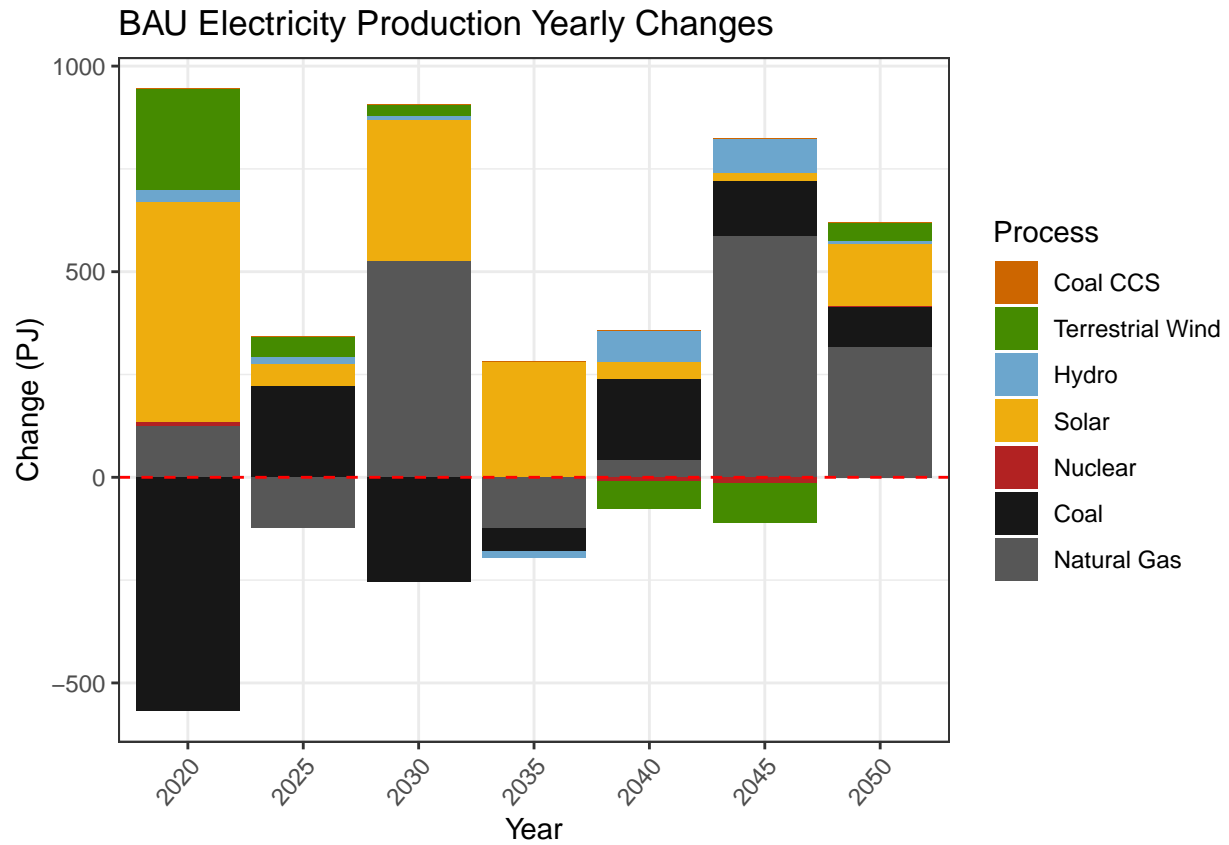
6.5 Heatmaps





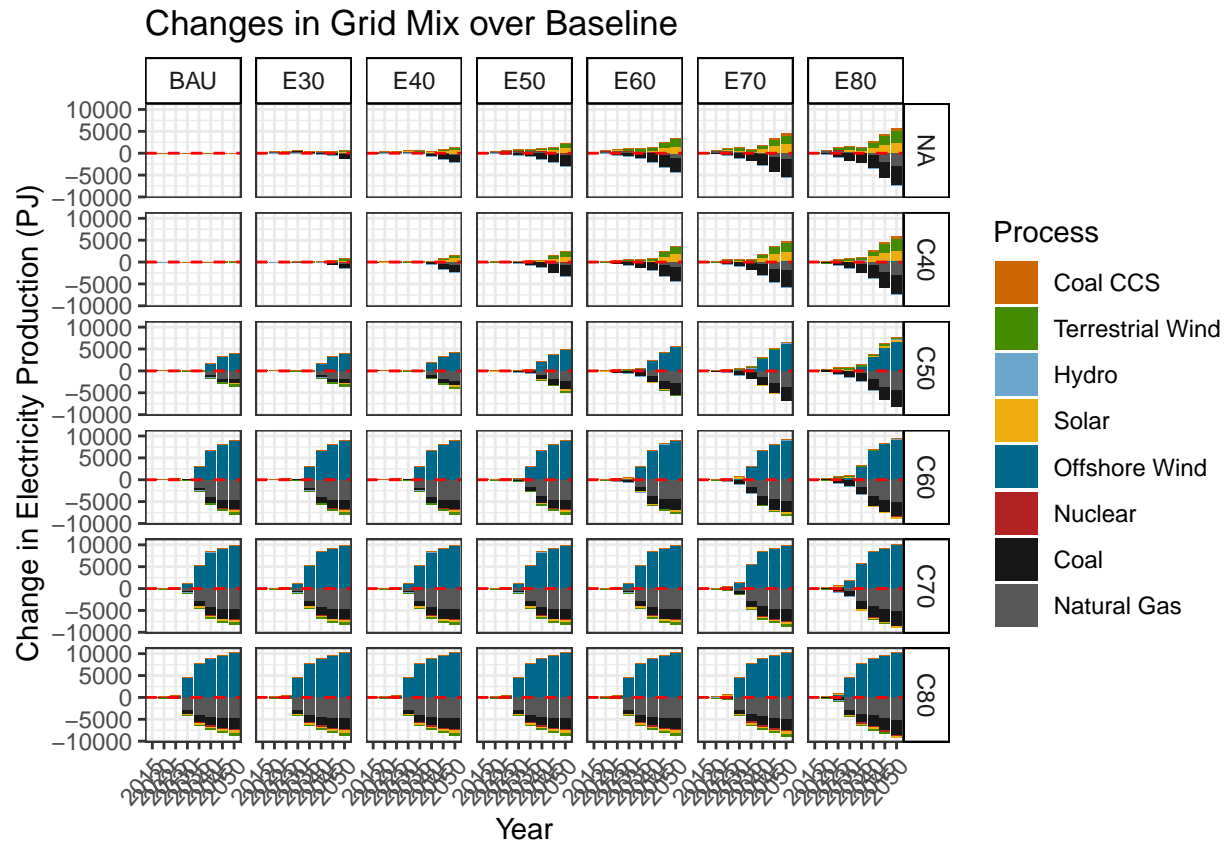
6.6 Retirements and Additions

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.

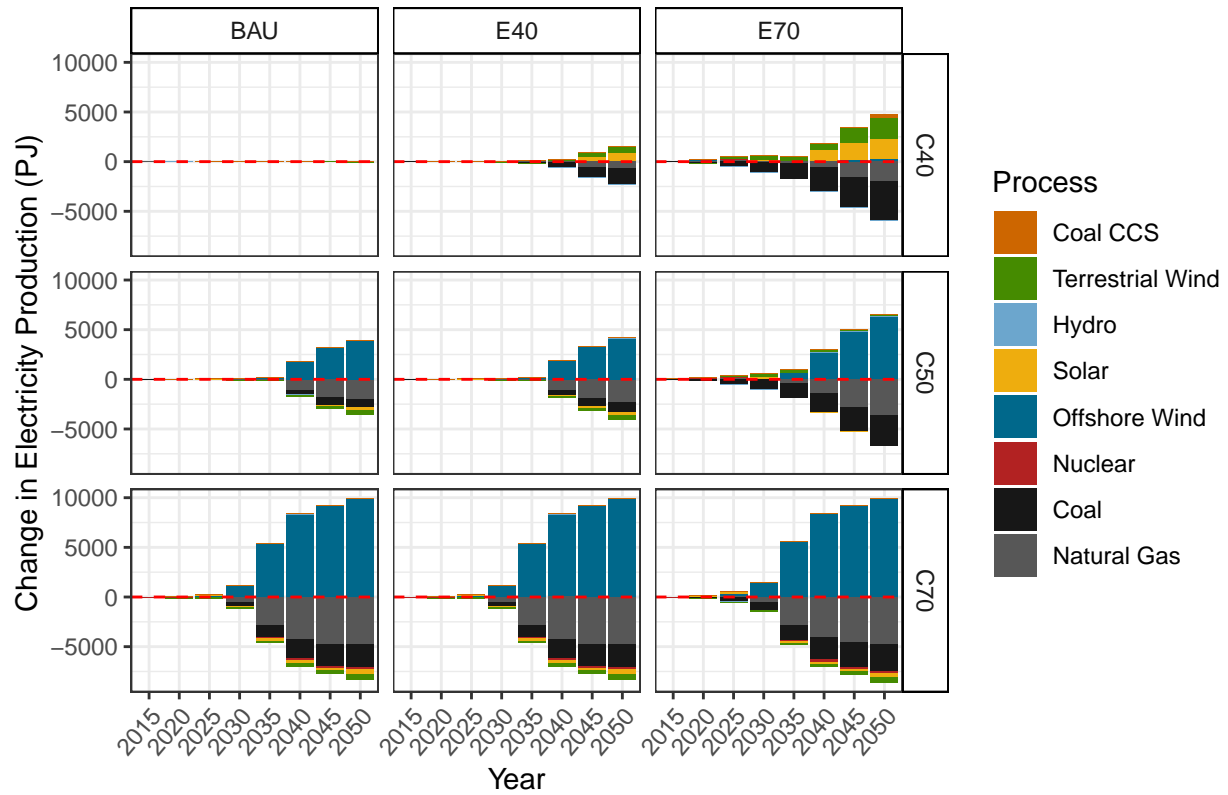


6.7 Changes Over Baseline

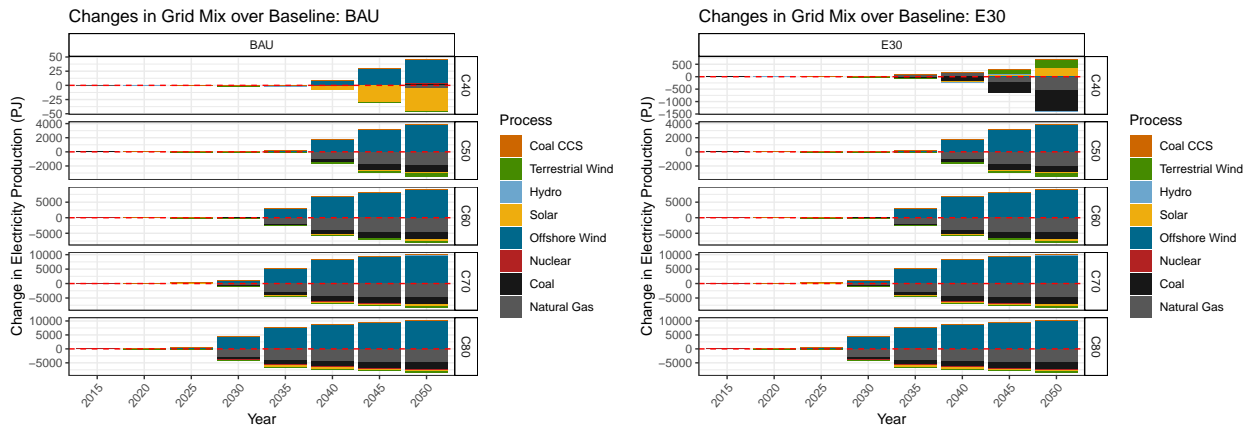
Summary Graph

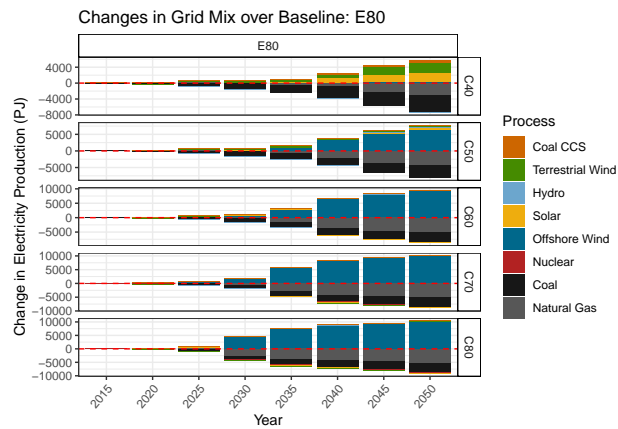
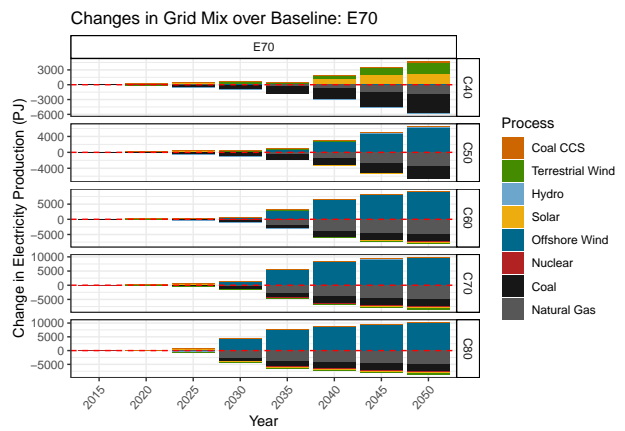
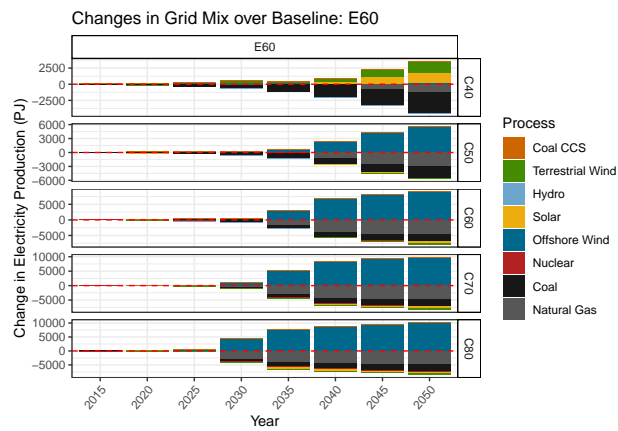
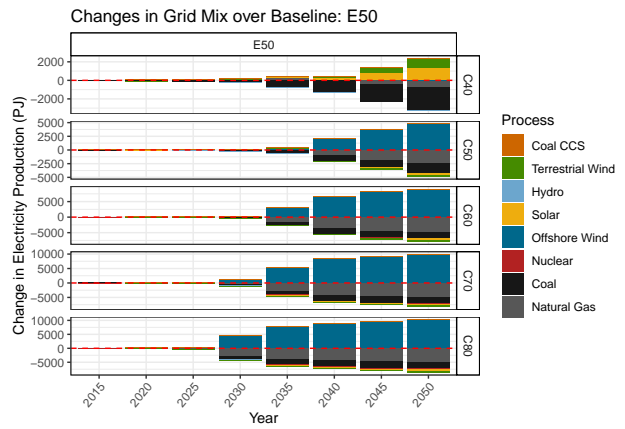
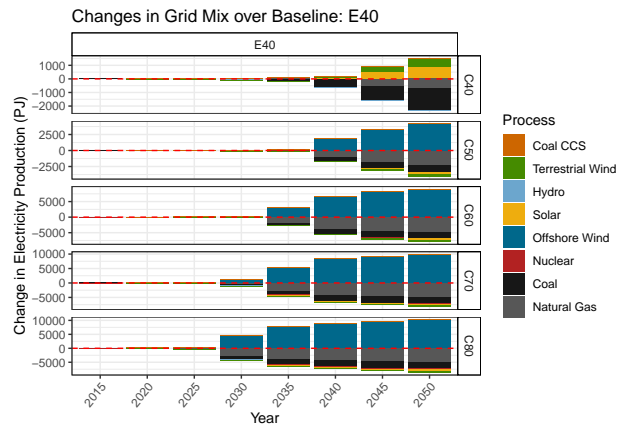


Changes in Grid Mix over Baseline

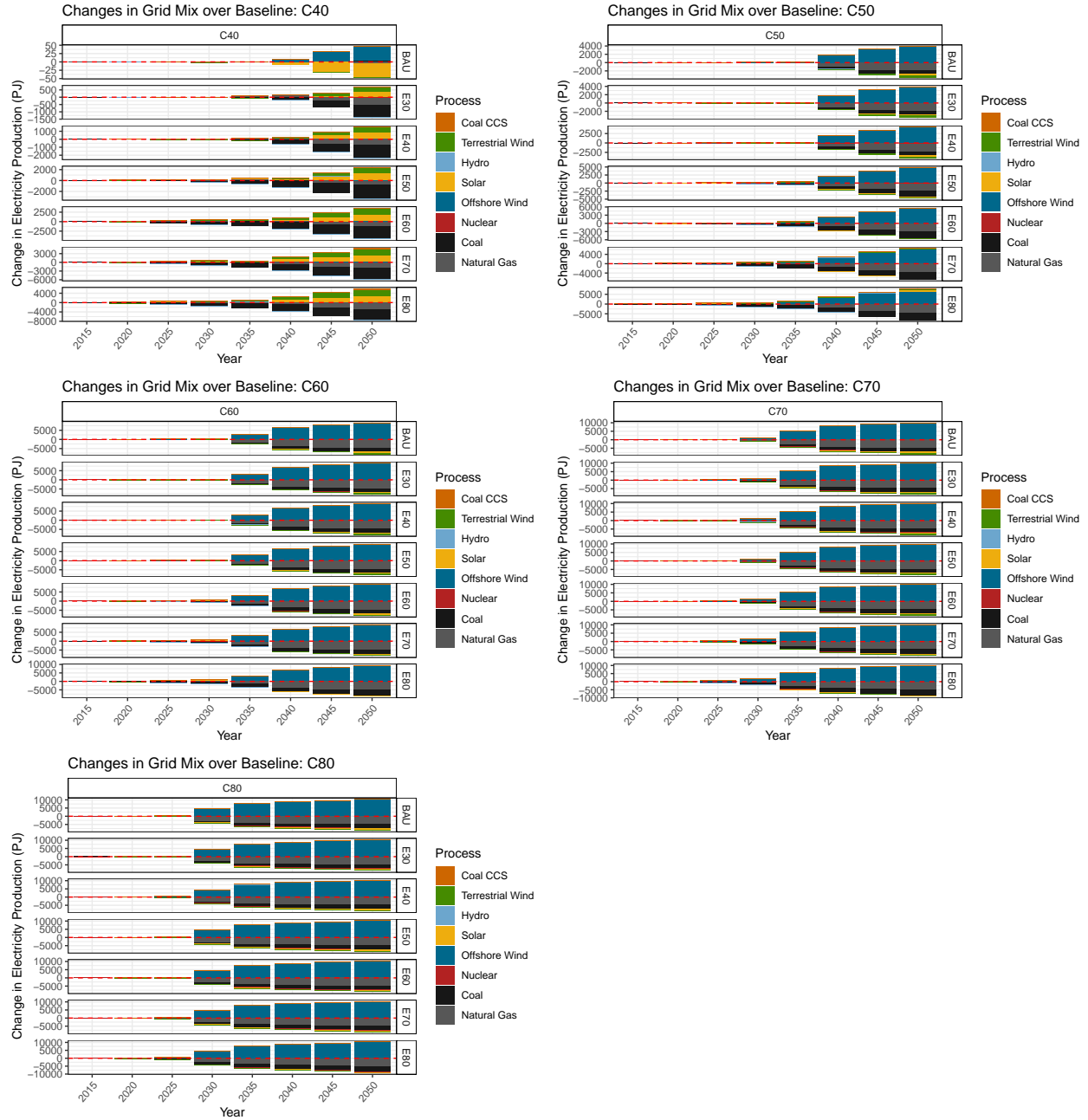


By Emissions Reduction %





By Cost Reduction %

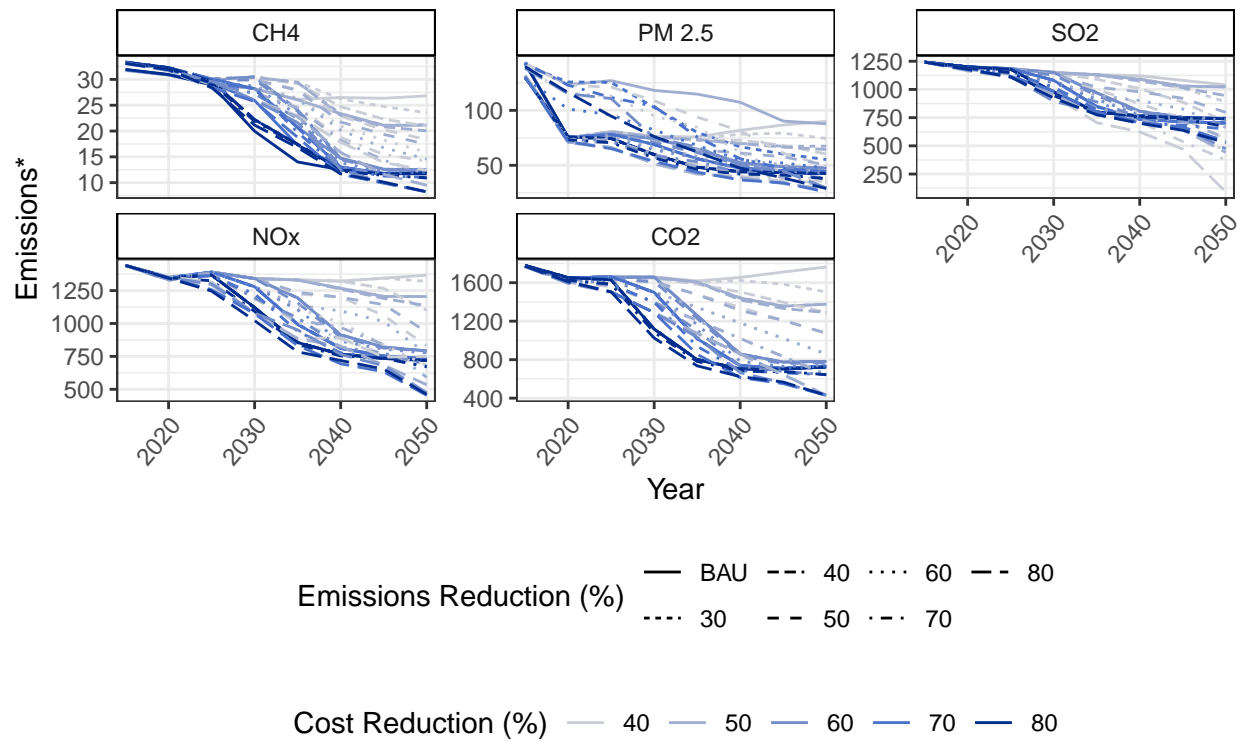


7 Emissions

7.1 Emissions considered in this study include:

CO_2 CH_4 SO_2 NO_x *PM 2.5

Electric Sector Emissions Output



*Units are Mt for CO2