Initialize

```
from amplpy import AMPL, ampl_notebook

ampl = ampl_notebook(
    modules=["highs", "gurobi"],  # modules to install
    license_uuid="1792fa9b-9f52-4d9d-8e9f-6742eb1b2c5a",  # license to use
)  # instantiate AMPL object and register magics

import pandas as pd
import numpy as np
import matplotlib.pyplot as plt
#https://amplpy.ampl.com/en/latest/quick-start.html#load-model-and-data-from-files
```

```
Licensed to Bundle #6427.6818 expiring 20240531: CEE 4880: Applied
Modeling and Simulation for Renewable Energy Systems, Jacob Mays,
Cornell University.
```

```
import random
random.seed(10)
```

Base model

```
%%writefile final_proj_base.mod

param nPeriods >= 1 default 8760;

# Sets
set T = {1..nPeriods} ordered; #time
set G; #generator
set S; #storage
set N; #nuclear

# General parameters
#param length{T};
param demand{T};
param power_viol_penalty >= 0 default 10000;

# Generator parameters
param operating_cost{G};
param social_cost{G};
param invest_cost_g{G};
param availability{T,G} >=0, <=1, default 1;

# Storage parameters
```

```
param invest_cost_s{S};
param storage_init_charge{S}>=0, default 0;
param storage_duration{S}>= 0, default 4;
param discharge_coef{S}>=0, <=1, default .93;
param charge_coef{S}>=0, <=1, default .93;

#Nuclear parameters
param fixed_cost_n{N}; #existing nuclear fixed cost
param operating_cost_n{N}; #existing nuclear op cost
param capacity_n_existing{N}; #existing nuclear capacity

# Variables
var capacity_g{g in G} >= 0;
var capacity_s{s in S} >=0;
var capacity_n{n in N} >= 0; #how much existing nuclear to activate
var output_gt{g in G, t in T} >= 0;
var output_nt{n in N, t in T} >=0; #existing nuclear output per t
var discharge_st{s in S, t in T} >=0;
var charge_st{s in S, t in T} >=0;
var SOC_st{s in S, t in T} >=0;
var slack_t{t in T}>=0;
var surplus_t{t in T}>=0;

# Objective function
minimize total_cost:
    (sum{g in G, t in T} ((operating_cost[g]
+social_cost[g])*output_gt[g,t]))+
    (sum{g in G} (invest_cost_g[g]*capacity_g[g]))+
    (sum{n in N}(fixed_cost_n[n]*capacity_n[n]))+
    (sum{n in N, t in T}(operating_cost_n[n]*output_nt[n,t]))+
    (sum{t in T} power_viol_penalty*(slack_t[t]+surplus_t[t]))+
    (sum{s in S} (invest_cost_s[s]*capacity_s[s]));

# Constraints

s.t. existing_nuclear_capacity{n in N}:
capacity_n[n]<=capacity_n_existing[n];

# generator availability
s.t. power_output{g in G, t in T}:
output_gt[g,t]<=availability[t,g]*capacity_g[g];

s.t. nuclear_output{n in N, t in T}:
output_nt[n,t]<=capacity_n[n];

# demand / system balance
s.t. meet_demand{t in T}:
#sum{g in G}(output_gt[g,t])+(sum{s in S}(discharge_st[s,t]-
charge_st[s,t]))+slack_t-surplus_t[t]=demand_t[t];
(sum{g in G} output_gt[g,t]) +(sum{s in S} (discharge_st[s,t]-
```

```
charge_st[s,t]))+(sum{n in N} output_nt[n,t])+slack_t[t]-surplus_t[t]
= demand[t];

# max storage charge
s.t. max_charge{s in S, t in T}:
charge_st[s,t]<=capacity_s[s];

# max storage discharge
s.t. max_discharge{s in S, t in T}:
discharge_st[s,t]<=capacity_s[s];

# storage SOC consistency
s.t. battery_state_of_charge_first_instance{s in S, t in {first(T)}}:
SOC_st[s,t]-storage_init_charge[s]+discharge_st[s,t]/discharge_coef[s]
-charge_coef[s]*charge_st[s,t]=0;

s.t. battery_state_of_charge{s in S, t in T diff{first(T)}}:
SOC_st[s,t]-SOC_st[s,t-1]+discharge_st[s,t]/discharge_coef[s]-
charge_coef[s]*charge_st[s,t]=0;

s.t. max_storage_capacity{s in S, t in T}:
SOC_st[s,t]<=storage_duration[s]*capacity_s[s];

# exsiting capacities
s.t. current_capacity_solar{g in G}:
capacity_g['SOLAR']>=4400;

s.t. current_capacity_wind{g in G}:
capacity_g['WIND']>=2500;
```

```
Overwriting final_proj_base.mod
```

```
#cost of generator; data from NYISO-11-zone.csv, nuclear from
gen_df = pd.DataFrame([("GAS",38.72,0.449*100,1237000), #898 pounds
CO2e/MWh and $100/ton CO2e
                          ("WIND",0,0,1292000),
                          ("SOLAR",0,0,1290000),
                          ("NUCLEAR",22.73,0,0), # investment cost =
0 because they are all existing
                          ("HYDRO",12.44,0,0)], # same as above
                           columns=["G", "operating_cost",
"social_cost","invest_cost_g"],
                         ).set_index("G")
                           #operating cost($/mwh), social cost
($/mwh), capacity cost($/mw)
#old nulcear information
cost_N_df = pd.DataFrame([("OLD_NUCLEAR",10,0,150000),
                          ],
                           columns=["N", "operating_cost_n",
"capacity_n_existing","fixed_cost_n"],
```

```
                          ).set_index("N")

#storage information
storage_df = pd.DataFrame([("FOUR", 0.93,0.93,4,0,400000),],
                            columns=["S", "discharge_coef",
"charge_coef","storage_duration","storage_init_charge","invest_cost_s"
],
                        ).set_index("S")

#availability
avail_df = pd.read_csv('./solar_wind_avail_2.csv').dropna()
avail_df.index = avail_df.index + 1

#demand
demand_df = pd.read_csv('./fixed_demand_2.csv').dropna()
demand_df.index = demand_df.index + 1

noise = np.random.normal(loc=0, scale=0.1, size=len(avail_df))
avail_df['HYDRO'] += noise
avail_df['HYDRO'] = np.clip(avail_df['HYDRO'], 0, 1)

def base_case(demand_df,avail_df):
    summary_df = pd.DataFrame(columns=['GAS',  'HYDRO','NUCLEAR',
'SOLAR', 'WIND','STORAGE', 'TOTAL_COST'])

    ampl = AMPL()
    solver = 'gurobi'
    ampl.set_option("solver", solver)
    ampl.read('final_proj_base.mod')

    # Define sets and parameters
    ampl.set_data(gen_df, "G")
    ampl.set_data(cost_N_df, "N")
    ampl.set_data(storage_df, "S")
    ampl.param['nPeriods'] = len(demand_df)
    ampl.param['power_viol_penalty'] = 10000
    ampl.param['demand'] = demand_df
    ampl.param['availability'] = avail_df
    capacity_g = ampl.get_variable("capacity_g")
    capacity_g['NUCLEAR'].fix(3400) #3.4 GW of nuclear
    capacity_g['HYDRO'].fix(6085) #6.085 GW of hydro

    ampl.solve()

    # Get resource mix
    resource_mix_list =
np.array(ampl.get_variable("capacity_g").get_values().to_pandas()).fla
tten()

    # Get storage capacity
```

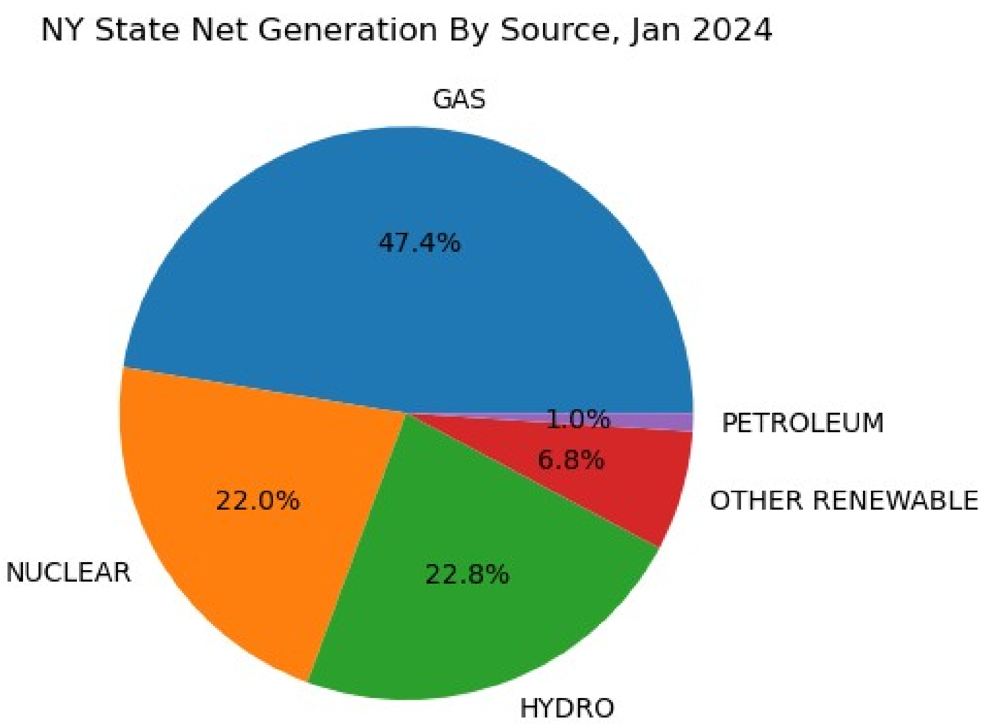
```
    storage_mix_list =
np.array(ampl.get_variable("capacity_s").get_values().to_pandas()).fla
tten()

    # Get total cost
    total_cost_list =
np.array(ampl.get_objective("total_cost").get_values().to_pandas()).fl
atten()

    # Create DataFrame for current iteration
    iteration_df = pd.DataFrame({
        'GAS': resource_mix_list[0],
        'HYDRO': resource_mix_list[1],
        'NUCLEAR': resource_mix_list[2],
        'SOLAR': resource_mix_list[3],
        'WIND': resource_mix_list[4],
        'STORAGE': storage_mix_list[0],
        'TOTAL_COST': total_cost_list[0]
    }, index=[0])

    summary_df = pd.concat([summary_df, iteration_df],
ignore_index=True)
    sum_output = ampl.get_data("{g in G} sum {t in T}
output_gt[g,t]").to_pandas()
    print(sum_output)
    return summary_df

 base_case_df = base_case(demand_df,avail_df)
```

```
Gurobi 11.0.1:Gurobi 11.0.1: optimal solution; objective
4.299183598e+10
51229 simplex iterations
42 barrier iterations

"option abs_boundtol 4.440892098500626e-16;"
or "option rel_boundtol 1.1104033160509338e-16;"
will change deduced dual values.

         sum{t in T} output_gt[g,t]
GAS                     9.159619e+07
HYDRO                   2.416322e+07
NUCLEAR                 2.978400e+07
SOLAR                   5.237409e+06
WIND                    9.921819e+06
```

```
avail_df.describe()
```

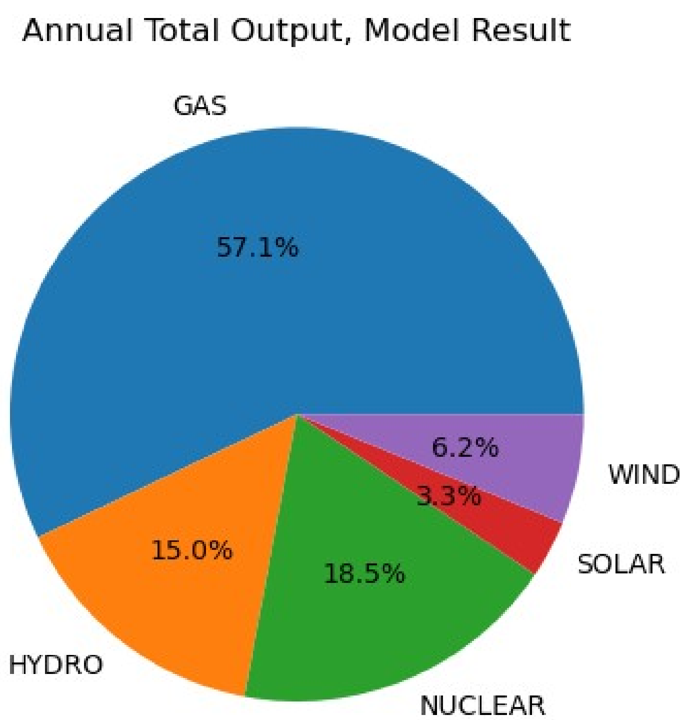
```
              WIND        SOLAR        HYDRO
count  8760.000000  8760.000000  8760.000000
mean      0.453051     0.135881     0.453051
std       0.269249     0.191221     0.269249
```

```
min        0.001250     0.000000     0.001250
25%        0.232250     0.000000     0.232250
50%        0.405438     0.002545     0.405438
75%        0.662875     0.260932     0.662875
max        0.994875     0.758545     0.994875

base_case_df

            GAS    HYDRO  NUCLEAR   SOLAR    WIND      STORAGE
TOTAL_COST
0  18836.602909  6085.0   3400.0  4400.0  2500.0  3452.667193
4.299184e+10

energy_sources = ['GAS', 'NUCLEAR', 'HYDRO', 'OTHER
RENEWABLE','PETROLEUM']
energy_values = [5311, 2461, 2554, 759,114]

plt.pie(energy_values, labels=energy_sources, autopct='%1.1f%%')
plt.title('NY State Net Generation By Source, Jan 2024')
plt.show()
```




```
energy_sources = ['GAS', 'HYDRO', 'NUCLEAR', 'SOLAR', 'WIND']
energy_values = [9.180014e+07, 2.414765e+07, 2.978400e+07,
5.237409e+06, 9.921819e+06]

plt.pie(energy_values, labels=energy_sources, autopct='%1.1f%%')
```

```
plt.title('Annual Total Output, Model Result')
plt.show()
```



Code in decarbonization scenario (`decarb_case`)

Added a parameter called `decarb_percent` and a constraint enforcing it.

```
%%writefile final_proj_decarb.mod

param nPeriods >= 1 default 8760;

# Sets
set T = {1..nPeriods} ordered; #time
#set Y; #years
set G; #generator
set S; #storage
set N; #nuclear

# General parameters
#param length{T};
param demand{T};
param power_viol_penalty >= 0 default 10000;
param decarb_percent >=0, <=1, default 1.0;
```

```
param num_years >=0, default 1;

# Generator parameters
param operating_cost{G};
param social_cost{G};
param invest_cost_g{G};
param availability{T,G} >=0, <=1, default 1;

# Storage parameters
param invest_cost_s{S};
param storage_init_charge{S}>=0, default 0;
param storage_duration{S}>= 0, default 4;
param discharge_coef{S}>=0, <=1, default .93;
param charge_coef{S}>=0, <=1, default .93;

#Nuclear parameters
param fixed_cost_n{N}; #existing nuclear fixed cost
param operating_cost_n{N}; #existing nuclear op cost
param capacity_n_existing{N}; #existing nuclear capacity

# Variables
var capacity_g{g in G} >= 0;
var capacity_s{s in S} >=0;
var capacity_n{n in N} >= 0; #how much existing nuclear to activate
var output_gt{g in G, t in T} >= 0;
var output_nt{n in N, t in T} >=0; #existing nuclear output per t
var discharge_st{s in S, t in T} >=0;
var charge_st{s in S, t in T} >=0;
var SOC_st{s in S, t in T} >=0;
var slack_t{t in T}>=0;
var surplus_t{t in T}>=0;

# Objective function
minimize total_cost:
    (sum{g in G, t in T} ((operating_cost[g]
+social_cost[g])*output_gt[g,t]))+
    (sum{g in G} (invest_cost_g[g]*capacity_g[g]))+
    (sum{n in N}(fixed_cost_n[n]*capacity_n[n]))+
    (sum{n in N, t in T}(operating_cost_n[n]*output_nt[n,t]))+
    (sum{t in T} power_viol_penalty*(slack_t[t]+surplus_t[t]))+
    (sum{s in S} (invest_cost_s[s]*capacity_s[s]));

# Constraints

# existing nuclear
s.t. existing_nuclear_capacity{n in N}:
capacity_n[n]<=capacity_n_existing[n];

# generator availability
s.t. power_output{g in G, t in T}:
```

```
output_gt[g,t]<=availability[t,g]*capacity_g[g];

s.t. nuclear_output{n in N, t in T}:
output_nt[n,t]<=capacity_n[n];

# demand / system balance
s.t. meet_demand{t in T}:
#sum{g in G}(output_gt[g,t])+(sum{s in S}(discharge_st[s,t]-
charge_st[s,t]))+slack_t-surplus_t[t]=demand_t[t];
(sum{g in G} output_gt[g,t]) +(sum{s in S} (discharge_st[s,t]-
charge_st[s,t]))+(sum{n in N} output_nt[n,t])+slack_t[t]-surplus_t[t]
= demand[t];

# max storage charge
s.t. max_charge{s in S, t in T}:
charge_st[s,t]<=capacity_s[s];

# max storage discharge
s.t. max_discharge{s in S, t in T}:
discharge_st[s,t]<=capacity_s[s];

# storage SOC consistency
s.t. battery_state_of_charge_first_instance{s in S, t in {first(T)}}:
SOC_st[s,t]-storage_init_charge[s]+discharge_st[s,t]/discharge_coef[s]
-charge_coef[s]*charge_st[s,t]=0;

s.t. battery_state_of_charge{s in S, t in T diff{first(T)}}:
SOC_st[s,t]-SOC_st[s,t-1]+discharge_st[s,t]/discharge_coef[s]-
charge_coef[s]*charge_st[s,t]=0;

s.t. max_storage_capacity{s in S, t in T}:
SOC_st[s,t]<=storage_duration[s]*capacity_s[s];

# exsiting capacities
s.t. current_capacity_solar{g in G}:
capacity_g['SOLAR']>=4400;

s.t. current_capacity_wind{g in G}:
capacity_g['WIND']>=2500;

# decarbonization
# s.t. decarb{g in G}:
# decarb_percent <= sum{t in T}((output_gt['SOLAR',t]
+output_gt['WIND',t])/(sum{t in T} output_gt[g,t]));

s.t. decarb:
    decarb_percent <= (capacity_g['WIND']+capacity_g['SOLAR']
+capacity_g['HYDRO']+capacity_g['NUCLEAR'])/(sum{g in G}
capacity_g[g])
```

```
Overwriting final_proj_decarb.mod
```

```
def decarb_case(demand_df,avail_df,goal):
    #summary_df = pd.DataFrame(columns=['GAS', 'NUCLEAR', 'SOLAR',
'WIND', 'STORAGE', 'TOTAL_COST'])

    ampl = AMPL()
    solver = 'gurobi'
    ampl.set_option("solver", solver)
    ampl.read('final_proj_decarb.mod')

    # Define sets and parameters
    ampl.set_data(gen_df, "G")
    ampl.set_data(cost_N_df, "N")
    ampl.set_data(storage_df, "S")
    ampl.param['nPeriods'] = len(demand_df)
    ampl.param['power_viol_penalty'] = 10000
    ampl.param['demand'] = demand_df
    ampl.param['availability'] = avail_df
    ampl.param['decarb_percent'] = goal / 100
    capacity_g = ampl.get_variable("capacity_g")
    capacity_g['NUCLEAR'].fix(3400) #3.4 GW of nuclear
    capacity_g['HYDRO'].fix(6085) #6.085 GW of hydro
    ampl.solve()

    # Get resource mix
    resource_mix_list =
np.array(ampl.get_variable("capacity_g").get_values().to_pandas()).fla
tten()

    # Get storage capacity
    storage_mix_list =
np.array(ampl.get_variable("capacity_s").get_values().to_pandas()).fla
tten()

    # Get total cost
    total_cost_list =
np.array(ampl.get_objective("total_cost").get_values().to_pandas()).fl
atten()

    # Create DataFrame for current iteration
    summary_df = pd.DataFrame({
        'GAS': resource_mix_list[0],
        'HYDRO': resource_mix_list[1],
        'NUCLEAR': resource_mix_list[2],
        'SOLAR': resource_mix_list[3],
        'WIND': resource_mix_list[4],
        'STORAGE': storage_mix_list[0],
        'TOTAL_COST': total_cost_list[0]
    }, index=[0])

    sum_output = ampl.get_data("{g in G} sum {t in T}
```

```
output_gt[g,t]").to_pandas()

    return summary_df, sum_output
```

Code in growing demand

Assuming the current demand data is for 2020, I simply multiply 2020's demand by a growth rate every year and add a random noise.

$$\text{Demand}_{2040,t} = \text{Demand}_{2020,t} * 1.0078^{20} + \epsilon, \forall t$$

where $\epsilon \sim N\left(0, \frac{325}{20} = 16.25\right)$

and

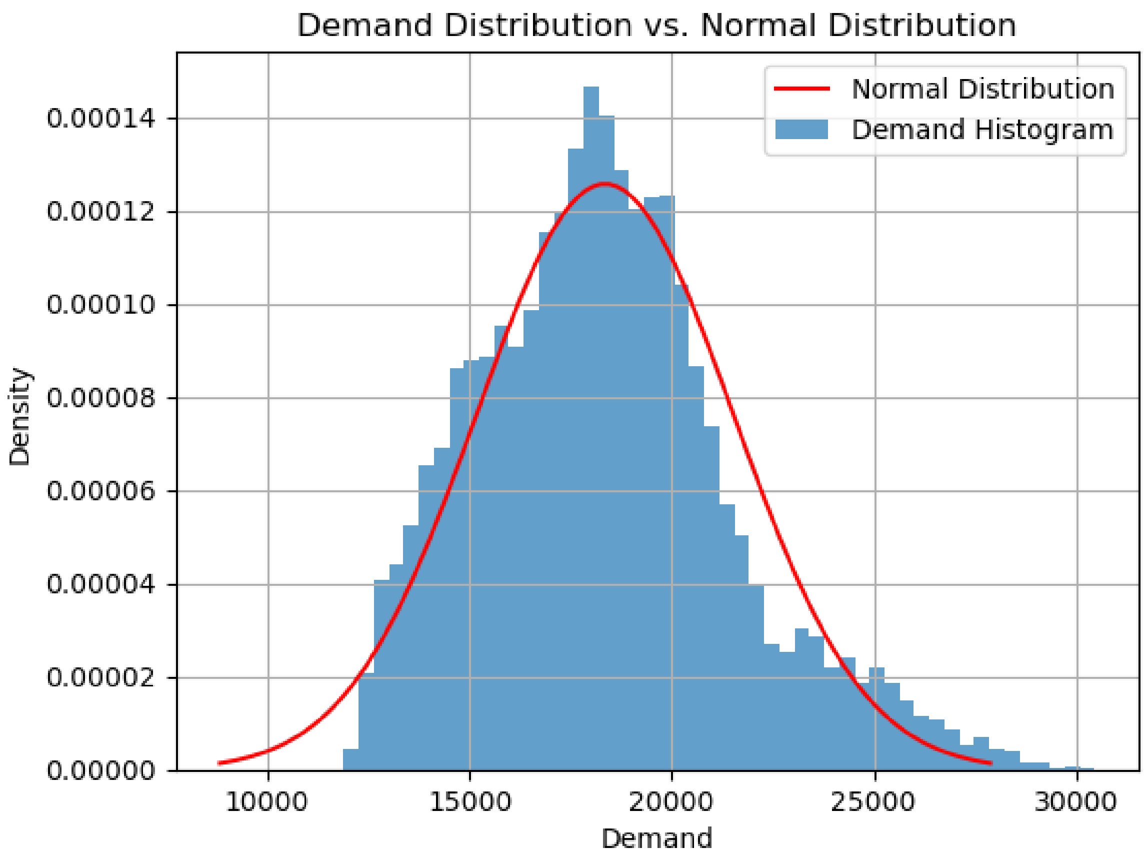
Code in noisy avaiability

$$\text{Avail}_{2040,g,t} = \text{Avail}_{2020,g,t} + \epsilon \, \forall t, g$$

where $\epsilon \sim N(0, 0.05)$ and $0 \leq \text{Avail}_g \leq 1 \, \forall g$

```
import warnings
from scipy.stats import shapiro, norm, kstest

warnings.filterwarnings("ignore")
demand_data = demand_df.to_numpy()
plt.hist(demand_data, bins=50, density=True, alpha=0.7, label='Demand Histogram')

# Plot normal distribution curve with mean and standard deviation from demand data
mu, sigma = np.mean(demand_data), np.std(demand_data)
x = np.linspace(mu - 3*sigma, mu + 3*sigma, 100)
plt.plot(x, norm.pdf(x, mu, sigma), 'r-', label='Normal Distribution')

# Set labels and title
plt.xlabel('Demand')
plt.ylabel('Density')
plt.title('Demand Distribution vs. Normal Distribution')

# Add legend
plt.legend()

# Show the plot
```

```
plt.grid(True)
plt.show()
```




```
def add_noise(data, mean=0, std=0.05):
    noise = np.random.normal(mean, std, data.shape)
    noisy_data = data + noise
    noisy_data[noisy_data < 0] = 0
    noisy_data[noisy_data > 1] = 1
    return noisy_data

avail_2040 = add_noise(avail_df)
demand_2040=demand_df*1.0078**20+np.random.normal(0, 16.25)

demand_2030 = demand_df*1.0078**10 + np.random.normal(0, 325/20)
avail_2030 = add_noise(avail_df)
```

Viz functions defined

```
def graph_pie_installed_capacity(base_90_percent_summary,title):
    energy_sources = base_90_percent_summary.columns[:-1]
    energy_values = base_90_percent_summary.iloc[0][:-1].values
```

```
    plt.pie(energy_values, labels=base_90_percent_summary.columns[:-
1], autopct='%1.1f%%', startangle=140)
    plt.title(title)
    plt.legend(loc='upper right', bbox_to_anchor=(1.1, 1))
    plt.show()
    base_90_percent_summary

def graph_pie_sum_output(base_90_percent_sum_output,title):
    energy_sources = base_90_percent_sum_output.index.tolist()
    energy_values = base_90_percent_sum_output['sum{t in T}
output_gt[g,t]']

    plt.pie(energy_values, labels=energy_sources, autopct='%1.1f%
%',startangle=140)
    plt.title(title)
    plt.axis('equal')  # Equal aspect ratio ensures that pie is drawn
as a circle.
    plt.legend(loc='upper right', bbox_to_anchor=(1.1, 1))
    plt.show()

    base_90_percent_sum_output

def graph_pie_sum_output_far(base_90_percent_sum_output,title,dist):
    energy_sources = base_90_percent_sum_output.index.tolist()
    energy_values = base_90_percent_sum_output['sum{t in T}
output_gt[g,t]']

    plt.pie(energy_values, labels=energy_sources, autopct='%1.1f%
%',startangle=140,pctdistance=dist)
    plt.title(title)
    plt.axis('equal')  # Equal aspect ratio ensures that pie is drawn
as a circle.
    plt.legend(loc='upper right', bbox_to_anchor=(1.1, 1))
    plt.show()

    base_90_percent_sum_output

def graph_stacked_bar(df,xlabel, title):
    energy_sources =
df.drop(columns='TOTAL_COST').columns.tolist()#[ 'GAS', 'HYDRO',
'NUCLEAR', 'SOLAR', 'WIND', 'STORAGE']
    r = np.arange(len(df))
    bottom_series = np.zeros(len(df))

    for i, source in enumerate(energy_sources):
        values = df[source].tolist()
        bars = plt.bar(r, values, bottom=bottom_series, width=0.5,
label=source)
        bottom_series += values
```

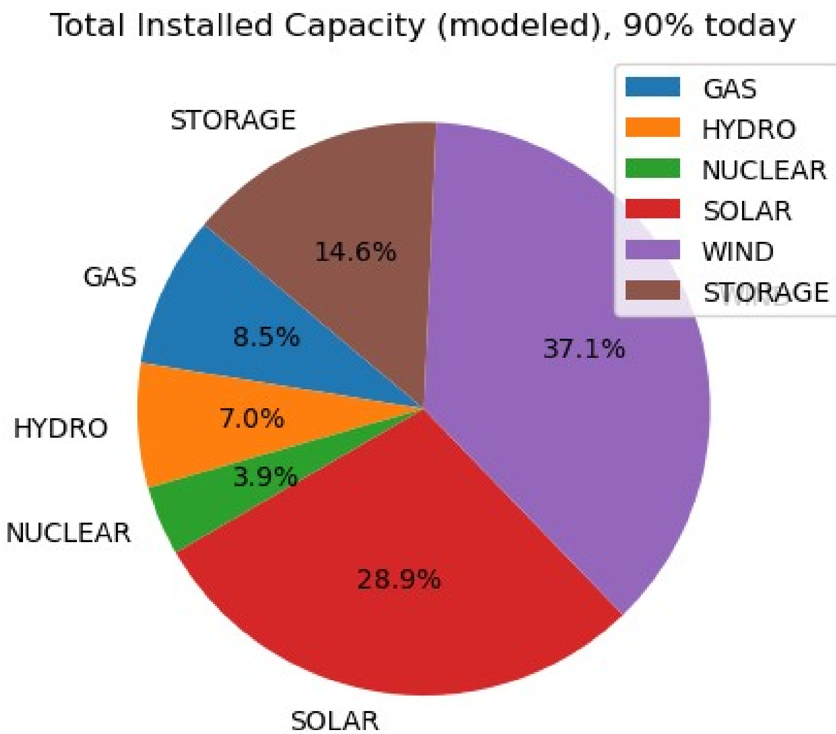
```
        # Add absolute value for storage
        if source == 'STORAGE':
            for bar, value in zip(bars, values):
                height = bar.get_height()
                plt.text(bar.get_x() + bar.get_width() / 2.0,
bar.get_y() + height / 2.0,
                         '{0:.0f} MW'.format(value), ha='center',
va='center',fontsize=8)

        # Add percentage text on each bar
        if source != 'STORAGE':
            for bar, value in zip(bars, values):
                height = bar.get_height()
                total = df[energy_sources[:-1]].sum(axis=1).iloc[i]  #
calculate the total for each row excluding 'STORAGE'
                plt.text(bar.get_x() + bar.get_width() / 2.0,
bar.get_y() + height / 2.0,
                         '{0:.0%}'.format(value/total), ha='center',
va='center',fontsize=8)

    plt.xlabel(xlabel)
    handles, labels = plt.gca().get_legend_handles_labels()
    labels.append('Total Cost')
    handles.append(plt.Line2D([], [], color='black', marker='x'))
    plt.legend(handles, labels, loc='upper left',
bbox_to_anchor=(1.1,1), ncol=1)
    plt.ylabel('Optimal Installed Capacity (MW)')
    ax2 = plt.gca().twinx()
    ax2.set_ylabel('10 billion $')
    ax2.plot(r, df['TOTAL_COST'].tolist(),color='black',marker='x')#,
label='Total Cost'
    plt.xticks(r, invest_costs)
    plt.title(title,y=1.05)

    plt.show()
```

Try `decarb_percent` = 0.9 with today's demand

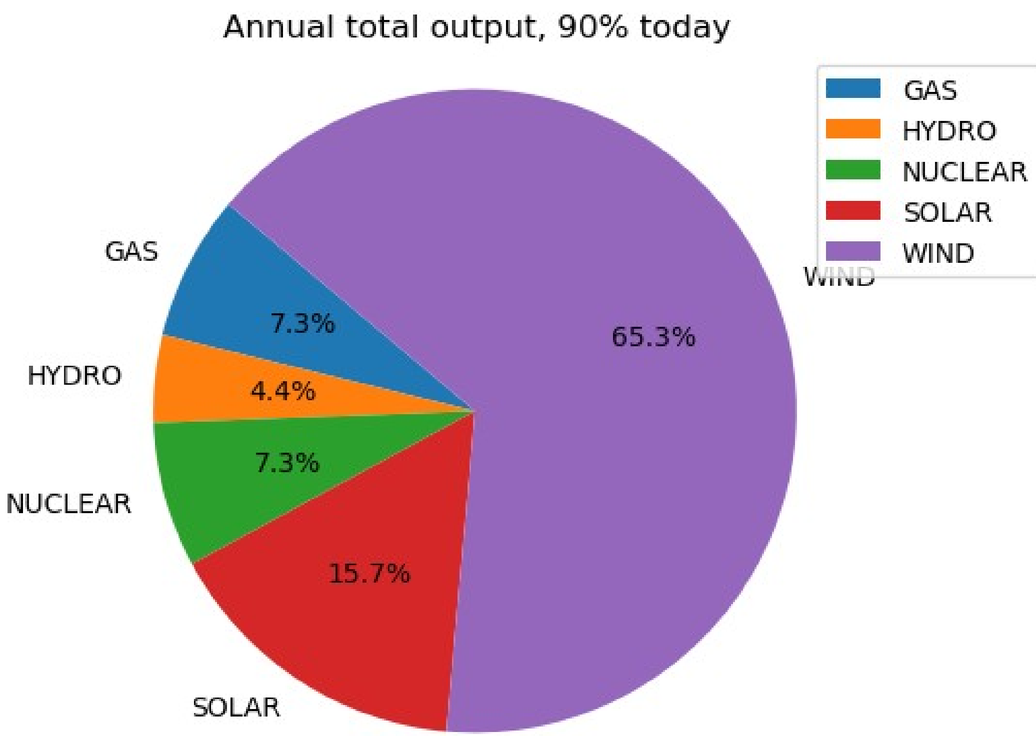
```
base_90_percent_summary, base_90_percent_sum_output =
decarb_case(demand_df,avail_df,90)
```

```
Gurobi 11.0.1:Gurobi 11.0.1: optimal solution; objective
9.74029941e+10
48470 simplex iterations
1 branching node
absmipgap=0.00190735, relmipgap=1.9582e-14
```

```
graph_pie_installed_capacity(base_90_percent_summary,'Total Installed
Capacity (modeled), 90% today')
```




```
graph_pie_sum_output(base_90_percent_sum_output,'Annual total output,
90% today')
```




```
base_90_percent #o
```

Iterate over decarb scenario

Function version

Iterate `decarb_percent` over 0, 0.2, 0.4, 0.6, 0.8, 1.0, using `demand_2040` and `avail_2040`:

```
def different_decarb_goals():
    # Define an empty DataFrame to store results
    summary_df = pd.DataFrame(columns=['GAS', 'NUCLEAR', 'SOLAR',
'WIND', 'STORAGE', 'TOTAL_COST'])

    # Iterate over a decarb goal of 0, 0.1, ..., 1.0
    for decarb_ratio in range(0, 110, 10):
        # Initialize AMPL instance
        ampl = AMPL()
        solver = 'gurobi'
        ampl.set_option("solver", solver)
        ampl.read('final_proj_decarb.mod')

        # Define sets and parameters
```

```
        ampl.set_data(gen_df, "G")
        ampl.set_data(cost_N_df, "N")
        ampl.set_data(storage_df, "S")
        ampl.param['nPeriods'] = len(demand_2040)
        ampl.param['power_viol_penalty'] = 10000
        ampl.param['demand'] = demand_2040
        ampl.param['availability'] = avail_2040
        ampl.param['decarb_percent'] = decarb_ratio / 100
        capacity_g = ampl.get_variable("capacity_g")
        capacity_g['NUCLEAR'].fix(3400) #3.4 GW of nuclear
        capacity_g['HYDRO'].fix(6085) #6.085 GW of hydro
        # if decarb_ratio == 100:
        #     capacity_g = ampl.get_variable("capacity_g")
        #     capacity_g['NUCLEAR'].unfix()
        #     capacity_g['HYDRO'].unfix()
        ampl.solve()

        # Get resource mix
        resource_mix_list =
np.array(ampl.get_variable("capacity_g").get_values().to_pandas()).fla
tten()

        # Get storage capacity
        storage_mix_list =
np.array(ampl.get_variable("capacity_s").get_values().to_pandas()).fla
tten()

        # Get total cost
        total_cost_list =
np.array(ampl.get_objective("total_cost").get_values().to_pandas()).fl
atten()

        # Create DataFrame for current iteration
        iteration_df = pd.DataFrame({
            'GAS': resource_mix_list[0],
            'NUCLEAR': resource_mix_list[1],
            'SOLAR': resource_mix_list[2],
            'WIND': resource_mix_list[3],
            'STORAGE': storage_mix_list[0],
            'TOTAL_COST': total_cost_list[0]
        }, index=[0])

        # Concatenate iteration DataFrame to summary DataFrame
        summary_df = pd.concat([summary_df, iteration_df],
ignore_index=True)

    return summary_df
```

Non-function version

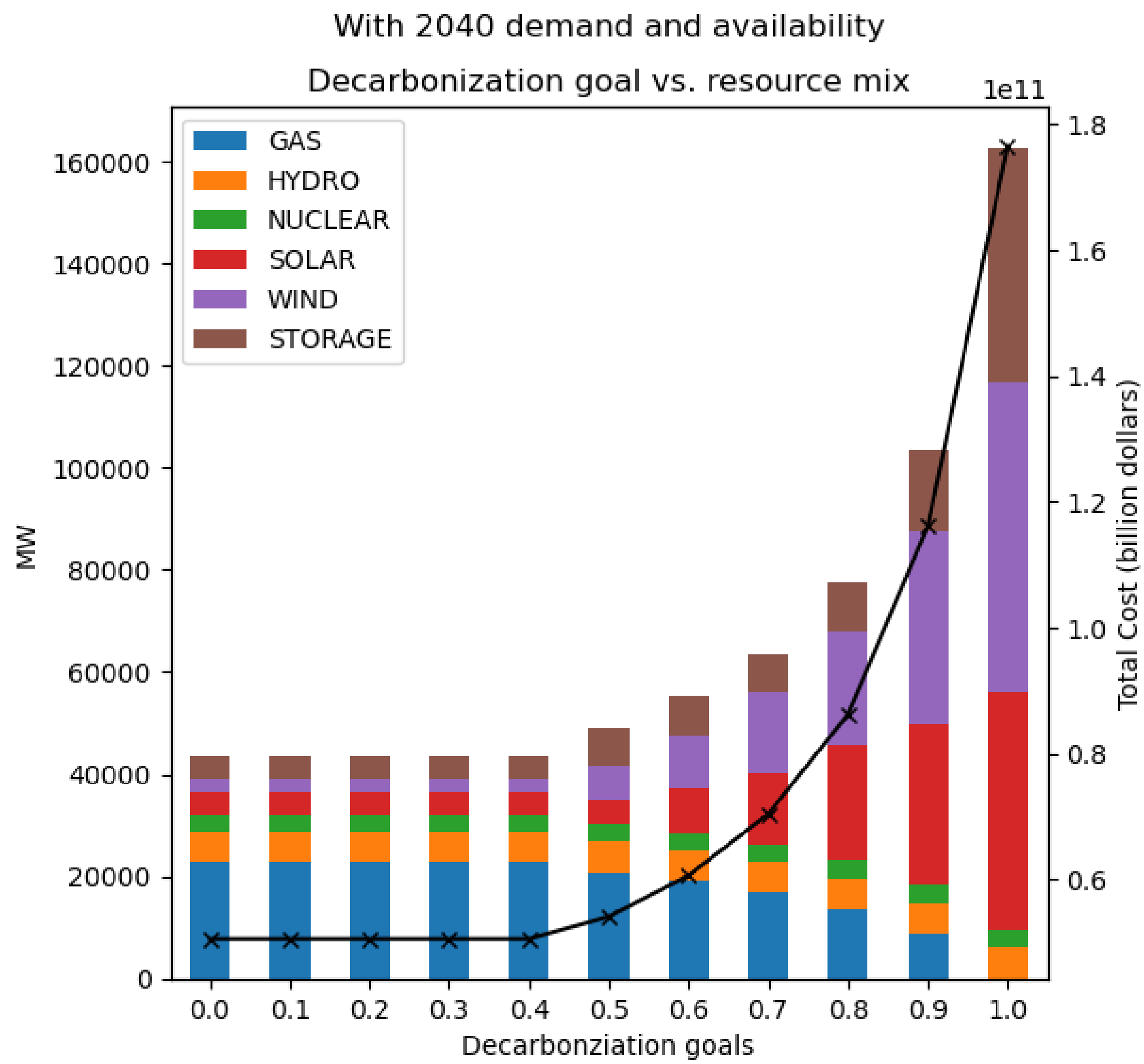
```
summary_df = pd.DataFrame(columns=['GAS', 'HYDRO','NUCLEAR', 'SOLAR',
'WIND', 'STORAGE', 'TOTAL_COST'])

# Iterate over a decarb goal of 0, 0.1, ..., 1.0
for decarb_ratio in range(0, 110, 10):
    # Initialize AMPL instance
    ampl = AMPL()
    solver = 'gurobi'
    ampl.set_option("solver", solver)
    ampl.read('final_proj_decarb.mod')

    # Define sets and parameters
    ampl.set_data(gen_df, "G")
    ampl.set_data(cost_N_df, "N")
    ampl.set_data(storage_df, "S")
    ampl.param['nPeriods'] = len(demand_2040)
    ampl.param['power_viol_penalty'] = 10000
    ampl.param['demand'] = demand_2040
    ampl.param['availability'] = avail_2040
    ampl.param['decarb_percent'] = decarb_ratio / 100
    capacity_g = ampl.get_variable("capacity_g")
    capacity_g['NUCLEAR'].fix(3400) #3.4 GW of nuclear
    capacity_g['HYDRO'].fix(6085) #6.085 GW of hydro
    # if decarb_ratio == 100:
    #     capacity_g = ampl.get_variable("capacity_g")
    #     capacity_g['NUCLEAR'].unfix()
    #     capacity_g['HYDRO'].unfix()
    ampl.solve()

    # Get resource mix
    resource_mix_list =
np.array(ampl.get_variable("capacity_g").get_values().to_pandas()).fla
tten()

    # Get storage capacity
    storage_mix_list =
np.array(ampl.get_variable("capacity_s").get_values().to_pandas()).fla
tten()

    # Get total cost
    total_cost_list =
np.array(ampl.get_objective("total_cost").get_values().to_pandas()).fl
atten()

    # Create DataFrame for current iteration
    iteration_df = pd.DataFrame({
        'GAS': resource_mix_list[0],
        'HYDRO': resource_mix_list[1],
```

```
        'NUCLEAR': resource_mix_list[2],
        'SOLAR': resource_mix_list[3],
        'WIND': resource_mix_list[4],
        'STORAGE': storage_mix_list[0],
        'TOTAL_COST': total_cost_list[0]
    }, index=[0])

    # Concatenate iteration DataFrame to summary DataFrame
    summary_df = pd.concat([summary_df, iteration_df],
ignore_index=True)
```

```
Gurobi 11.0.1:Gurobi 11.0.1: optimal solution; objective
5.063584754e+10
55731 simplex iterations
1 branching node
Gurobi 11.0.1:   NLP heuristic elapsed time = 5.02s
Gurobi 11.0.1: optimal solution; objective 5.063584754e+10
55125 simplex iterations
1 branching node
Gurobi 11.0.1:   NLP heuristic elapsed time = 5.02s
Gurobi 11.0.1: optimal solution; objective 5.063584754e+10
55125 simplex iterations
1 branching node
Gurobi 11.0.1:Gurobi 11.0.1: optimal solution; objective
5.063584754e+10
55125 simplex iterations
1 branching node
Gurobi 11.0.1:   NLP heuristic elapsed time = 5.00s
Gurobi 11.0.1: optimal solution; objective 5.063584754e+10
55125 simplex iterations
1 branching node
Gurobi 11.0.1:Gurobi 11.0.1: optimal solution; objective
5.417157448e+10
53413 simplex iterations
1 branching node
absmipgap=0.0562439, relmipgap=1.03825e-12
Gurobi 11.0.1:Gurobi 11.0.1: optimal solution; objective
6.06731624e+10
49071 simplex iterations
1 branching node
absmipgap=0.0235901, relmipgap=3.88806e-13
Gurobi 11.0.1:   NLP heuristic elapsed time = 5.03s
Gurobi 11.0.1: optimal solution; objective 7.042552702e+10
60413 simplex iterations
1 branching node
absmipgap=0.0290375, relmipgap=4.12315e-13
Gurobi 11.0.1:   NLP heuristic elapsed time = 5.03s
Gurobi 11.0.1: optimal solution; objective 8.628249538e+10
60157 simplex iterations
1 branching node
```

```
Gurobi 11.0.1:   NLP heuristic elapsed time = 5.04s
Gurobi 11.0.1: optimal solution; objective 1.161621951e+11
56744 simplex iterations
1 branching node
absmipgap=0.0155792, relmipgap=1.34116e-13
Gurobi 11.0.1:Gurobi 11.0.1: optimal solution; objective
1.765023865e+11
34623 simplex iterations
1 branching node
```

```
summary_df = different_decarb_goals()

summary_df.to_csv('./2040_decarb_goal_NEW.csv')

ax = summary_df[['GAS', 'HYDRO','NUCLEAR', 'SOLAR', 'WIND',
'STORAGE']].plot(kind='bar', stacked=True, figsize=(6, 6))
summary_df['TOTAL_COST'].plot(kind='line', marker='x', color='k',
secondary_y=True,ax=ax)

ax.set_xlabel('Decarbonziation goals')
ax.set_ylabel('MW')
ax.right_ax.set_ylabel('Total Cost (billion dollars)')

plt.title('Decarbonization goal vs. resource mix')
plt.text(0.5, 1.08, 'With 2040 demand and availability',
horizontalalignment='center', fontsize=12,
transform=plt.gca().transAxes)
decarb_goals = [str(i/10) for i in range(11)]
plt.xticks(range(11), decarb_goals)
plt.show()
```



Sensitivity analysis

1. 70 by 2030

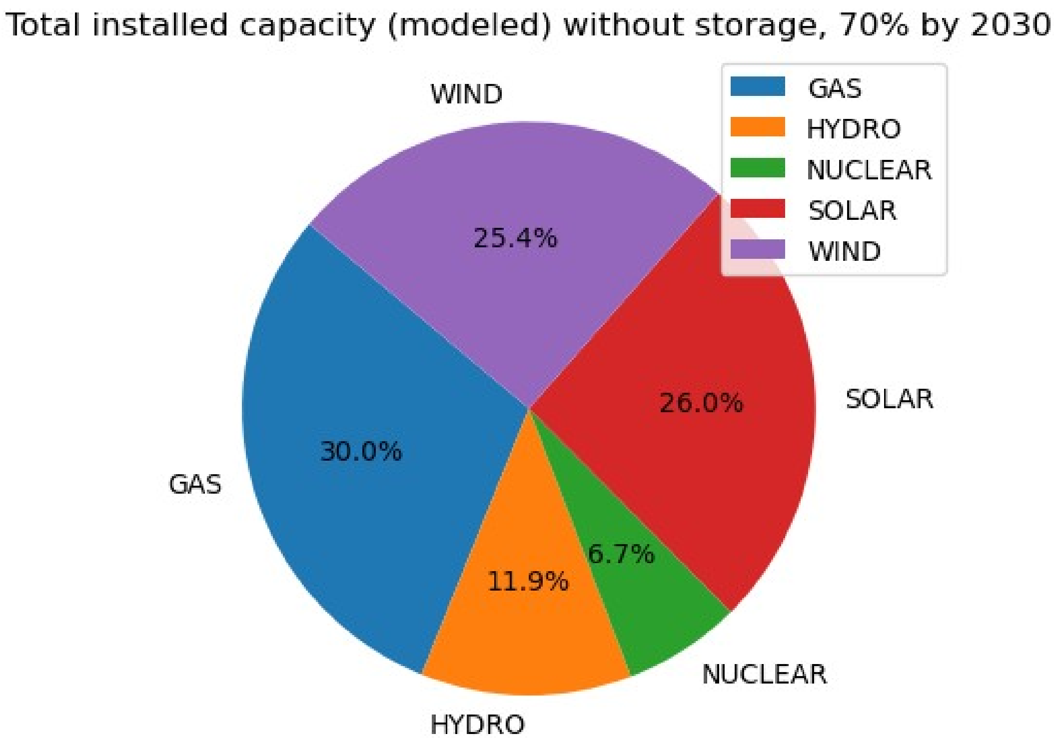
```
decarb_70_by_2030_summary, decarb_70_by_2030_sum_output =
decarb_case(demand_2030,avail_2030,70)
```

```
Gurobi 11.0.1:Gurobi 11.0.1: optimal solution; objective
6.403520567e+10
60741 simplex iterations
1 branching node
absmipgap=0.028862, relmipgap=4.50721e-13
```

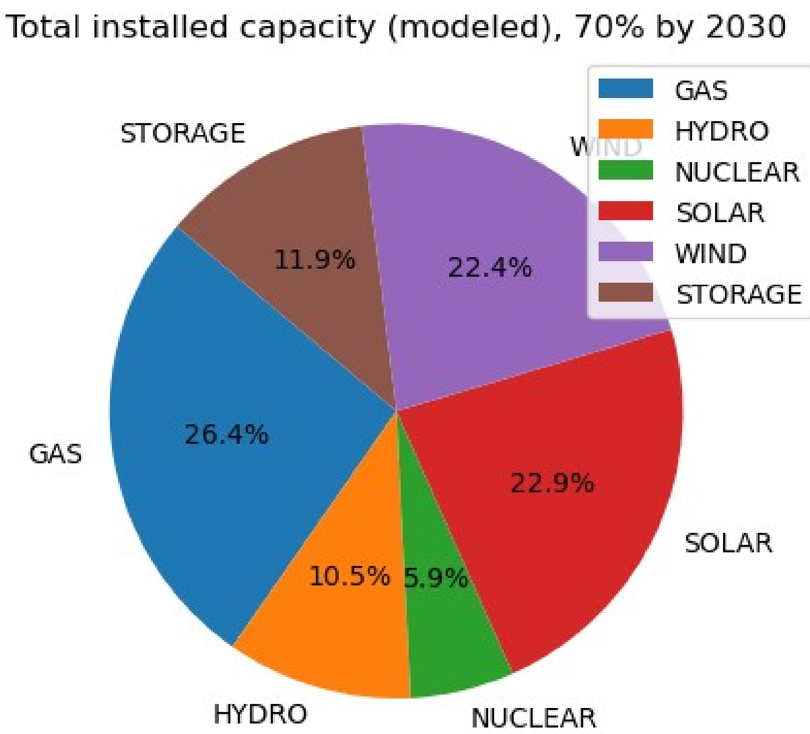
```
decarb_70_by_2030_summary
```

```
              GAS   HYDRO  NUCLEAR        SOLAR         WIND  
STORAGE
0  15324.792095  6085.0   3400.0  13303.999361  12968.848861  
6929.039201  \

     TOTAL_COST
0  6.403521e+10
```

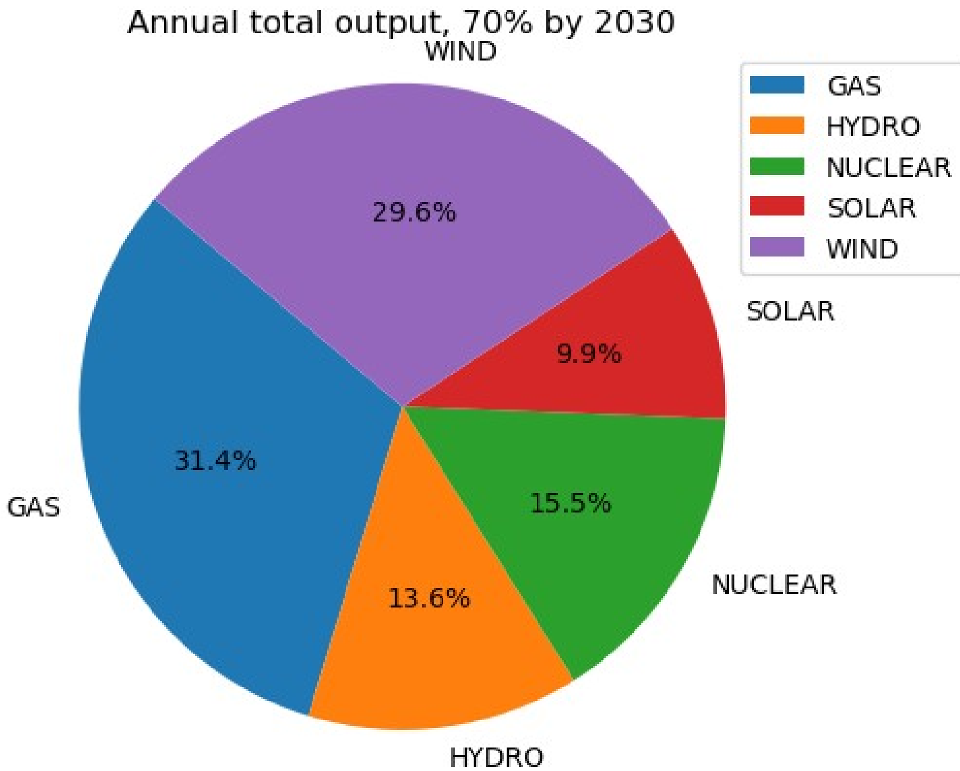
```
graph_pie_installed_capacity(decarb_70_by_2030_summary.drop(columns=['
STORAGE']), 'Total installed capacity (modeled) without storage, 70%
by 2030')
```




```
graph_pie_installed_capacity(decarb_70_by_2030_summary, 'Total
installed capacity (modeled), 70% by 2030')
```




```
graph_pie_sum_output(decarb_70_by_2030_sum_output,'Annual total
output, 70% by 2030')
```

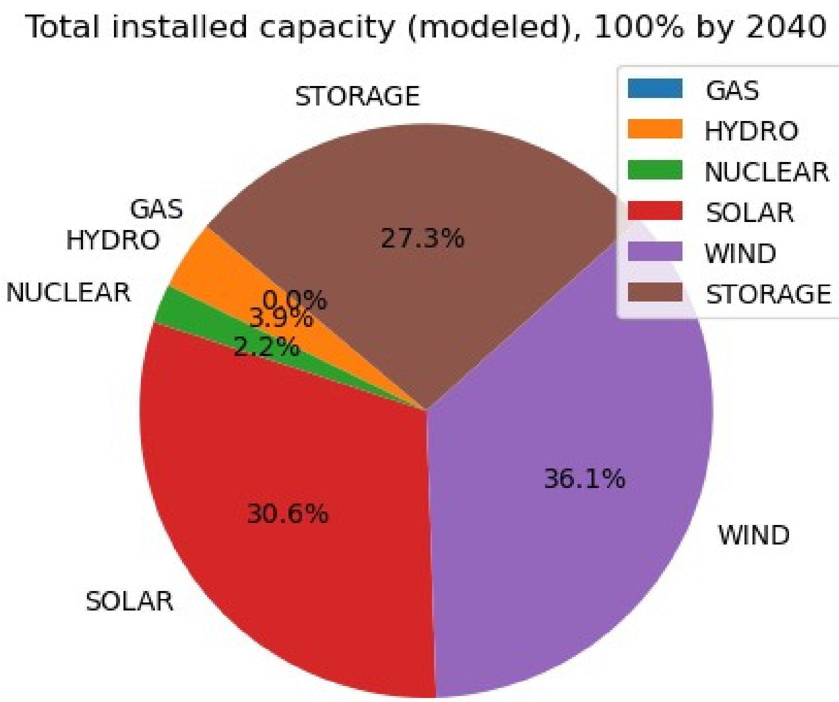


2. 100 by 2040

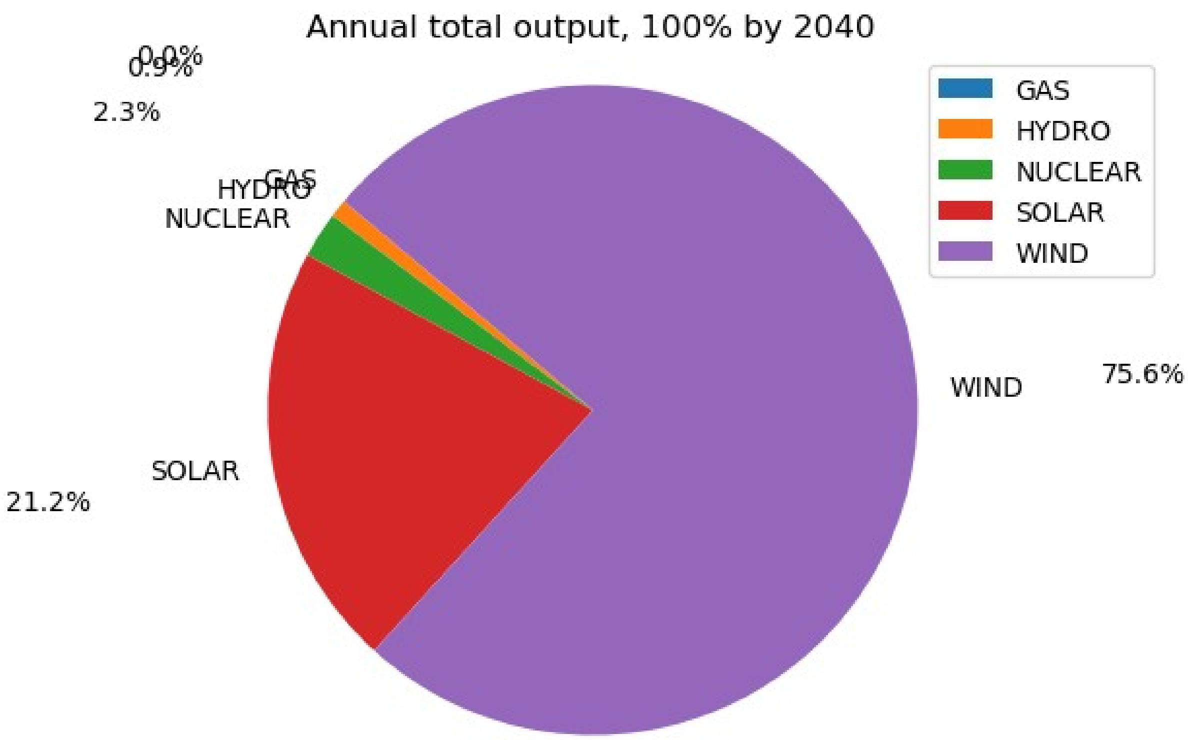
```
decarb_100_by_2040_summary, decarb_100_by_2040_sum_output =
decarb_case(demand_2040,avail_2040,100)
```

```
Gurobi 11.0.1:Gurobi 11.0.1: optimal solution; objective
1.766522128e+11
33551 simplex iterations
1 branching node
```

```
graph_pie_installed_capacity(decarb_100_by_2040_summary, 'Total
installed capacity (modeled), 100% by 2040')
```




```
graph_pie_sum_output_far(decarb_100_by_2040_sum_output,'Annual total
output, 100% by 2040',1.7)
```



3. Sensitivity: battery price

Uses 2030 demand and avail, and 70% as target

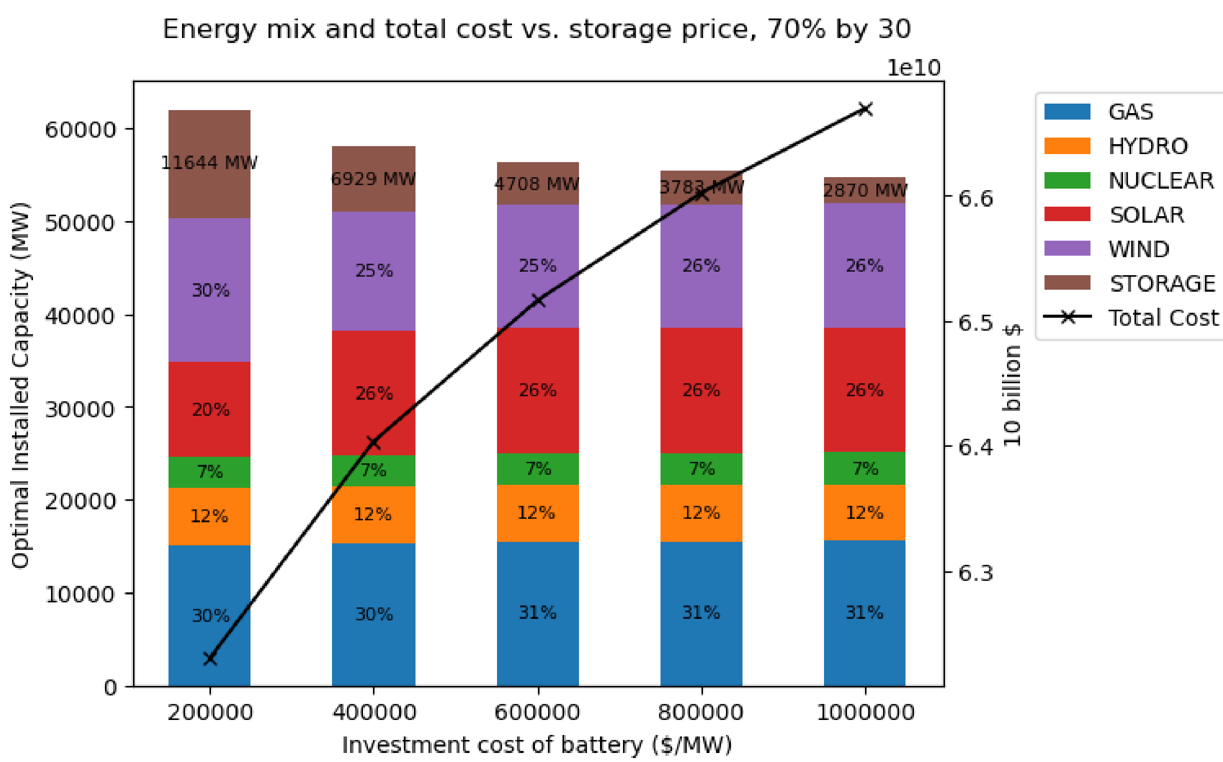
```
common_values = ["FOUR", 0.93, 0.93, 4, 0]

invest_costs = [200000, 400000, 600000, 800000, 1000000]

df_names = [pd.DataFrame([common_values + [cost]],
                         columns=["S", "discharge_coef",
"charge_coef", "storage_duration", "storage_init_charge",
"invest_cost_s"]).set_index("S")
            for cost in invest_costs]

#70 by 2030
summary_df_sa_bat = pd.DataFrame(columns=['GAS', 'HYDRO','NUCLEAR',
'SOLAR', 'WIND', 'STORAGE', 'TOTAL_COST'])

for i in range(len(df_names)):
    ampl = AMPL()
    solver = 'gurobi'
    ampl.set_option("solver", solver)
    ampl.read('final_proj_decarb.mod')

    # Define sets and parameters
    ampl.set_data(gen_df, "G")
```

```
    ampl.set_data(cost_N_df, "N")
    ampl.set_data(df_names[i], "S")
    ampl.param['nPeriods'] = len(demand_2030)
    ampl.param['power_viol_penalty'] = 10000
    ampl.param['demand'] = demand_2030
    ampl.param['availability'] = avail_2030
    ampl.param['decarb_percent'] = 0.7
    capacity_g = ampl.get_variable("capacity_g")
    capacity_g['NUCLEAR'].fix(3400) #3.4 GW of nuclear
    capacity_g['HYDRO'].fix(6085) #6.085 GW of hydro
    ampl.solve()

    # Get resource mix
    resource_mix_list =
np.array(ampl.get_variable("capacity_g").get_values().to_pandas()).fla
tten()

    # Get storage capacity
    storage_mix_list =
np.array(ampl.get_variable("capacity_s").get_values().to_pandas()).fla
tten()

    # Get total cost
    total_cost_list =
np.array(ampl.get_objective("total_cost").get_values().to_pandas()).fl
atten()

    # Create DataFrame for current iteration
    iteration_df = pd.DataFrame({
        'GAS': resource_mix_list[0],
        'HYDRO': resource_mix_list[1],
        'NUCLEAR': resource_mix_list[2],
        'SOLAR': resource_mix_list[3],
        'WIND': resource_mix_list[4],
        'STORAGE': storage_mix_list[0],
        'TOTAL_COST': total_cost_list[0]
    }, index=[0])

    # Concatenate iteration DataFrame to summary DataFrame
    summary_df_sa_bat = pd.concat([summary_df_sa_bat, iteration_df],
ignore_index=True)
```

```
Gurobi 11.0.1:Gurobi 11.0.1: optimal solution; objective
6.230392859e+10
53281 simplex iterations
1 branching node
absmipgap=0.00753021, relmipgap=1.20863e-13
Gurobi 11.0.1:Gurobi 11.0.1: optimal solution; objective
6.403520567e+10
60741 simplex iterations
```

```
1 branching node
absmipgap=0.028862, relmipgap=4.50721e-13
Gurobi 11.0.1:Gurobi 11.0.1: optimal solution; objective
6.516211475e+10
56874 simplex iterations
1 branching node
absmipgap=0.0117874, relmipgap=1.80894e-13
Gurobi 11.0.1:Gurobi 11.0.1: optimal solution; objective
6.602212084e+10
56351 simplex iterations
1 branching node
absmipgap=0.0107574, relmipgap=1.62937e-13
Gurobi 11.0.1:Gurobi 11.0.1: optimal solution; objective
6.669820426e+10
74892 simplex iterations
1 branching node
absmipgap=0.0197601, relmipgap=2.96262e-13
```

```
invest_costs = [200000, 400000, 600000, 800000, 1000000]
graph_stacked_bar(summary_df_sa_bat, "Investment cost of battery
($/MW)","Energy mix and total cost vs. storage price, 70% by 30")
```



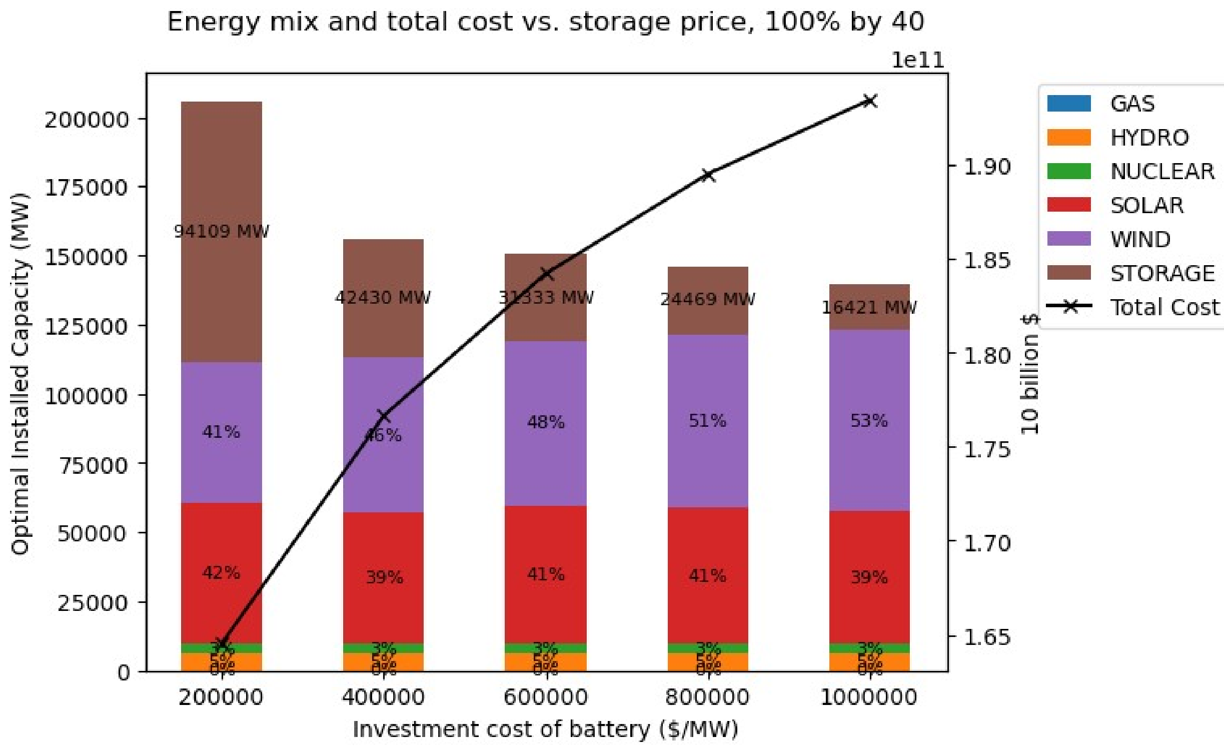

```
summary_df_sa_bat.to_csv('./summary_df_sa_bat_nuclear')

common_values = ["FOUR", 0.93, 0.93, 4, 0]
```

```
invest_costs = [200000, 400000, 600000, 800000, 1000000]

df_names = [pd.DataFrame([common_values + [cost]],
                         columns=["S", "discharge_coef",
"charge_coef", "storage_duration", "storage_init_charge",
"invest_cost_s"]).set_index("S")
            for cost in invest_costs]

summary_df_sa_bat_100_by_2040 = pd.DataFrame(columns=['GAS',
'HYDRO','NUCLEAR', 'SOLAR', 'WIND', 'STORAGE', 'TOTAL_COST'])

for i in range(len(df_names)):
    ampl = AMPL()
    solver = 'gurobi'
    ampl.set_option("solver", solver)
    ampl.read('final_proj_decarb.mod')

    # Define sets and parameters
    ampl.set_data(gen_df, "G")
    ampl.set_data(cost_N_df, "N")
    ampl.set_data(df_names[i], "S")
    ampl.param['nPeriods'] = len(demand_2040)
    ampl.param['power_viol_penalty'] = 10000
    ampl.param['demand'] = demand_2040
    ampl.param['availability'] = avail_2040
    ampl.param['decarb_percent'] = 1.0
    capacity_g = ampl.get_variable("capacity_g")
    capacity_g['NUCLEAR'].fix(3400) #3.4 GW of nuclear
    capacity_g['HYDRO'].fix(6085) #6.085 GW of hydro
    ampl.solve()

    # Get resource mix
    resource_mix_list =
np.array(ampl.get_variable("capacity_g").get_values().to_pandas()).fla
tten()

    # Get storage capacity
    storage_mix_list =
np.array(ampl.get_variable("capacity_s").get_values().to_pandas()).fla
tten()

    # Get total cost
    total_cost_list =
np.array(ampl.get_objective("total_cost").get_values().to_pandas()).fl
atten()

    # Create DataFrame for current iteration
    iteration_df = pd.DataFrame({
        'GAS': resource_mix_list[0],
        'HYDRO': resource_mix_list[1],
```

```
        'NUCLEAR': resource_mix_list[2],
        'SOLAR': resource_mix_list[3],
        'WIND': resource_mix_list[4],
        'STORAGE': storage_mix_list[0],
        'TOTAL_COST': total_cost_list[0]
    }, index=[0])

    # Concatenate iteration DataFrame to summary DataFrame
    summary_df_sa_bat_100_by_2040 =
pd.concat([summary_df_sa_bat_100_by_2040, iteration_df],
ignore_index=True)
```

```
Gurobi 11.0.1:Gurobi 11.0.1: optimal solution; objective
1.645357826e+11
32050 simplex iterations
1 branching node
Gurobi 11.0.1:Gurobi 11.0.1: optimal solution; objective
1.766522128e+11
33551 simplex iterations
1 branching node
Gurobi 11.0.1:Gurobi 11.0.1: optimal solution; objective
1.842153281e+11
36422 simplex iterations
1 branching node
absmipgap=0.0062561, relmipgap=3.39608e-14
Gurobi 11.0.1:   NLP heuristic elapsed time = 5.04s
Gurobi 11.0.1: optimal solution; objective 1.895190278e+11
34898 simplex iterations
1 branching node
Gurobi 11.0.1:Gurobi 11.0.1: optimal solution; objective
1.934666155e+11
35157 simplex iterations
1 branching node
absmipgap=0.00592041, relmipgap=3.06017e-14
```

```
invest_costs = [200000, 400000, 600000, 800000, 1000000]
graph_stacked_bar(summary_df_sa_bat_100_by_2040, "Investment cost of
battery ($/MW)","Energy mix and total cost vs. storage price, 100% by
40")
```



4. Sensitivity: renewable investment cost

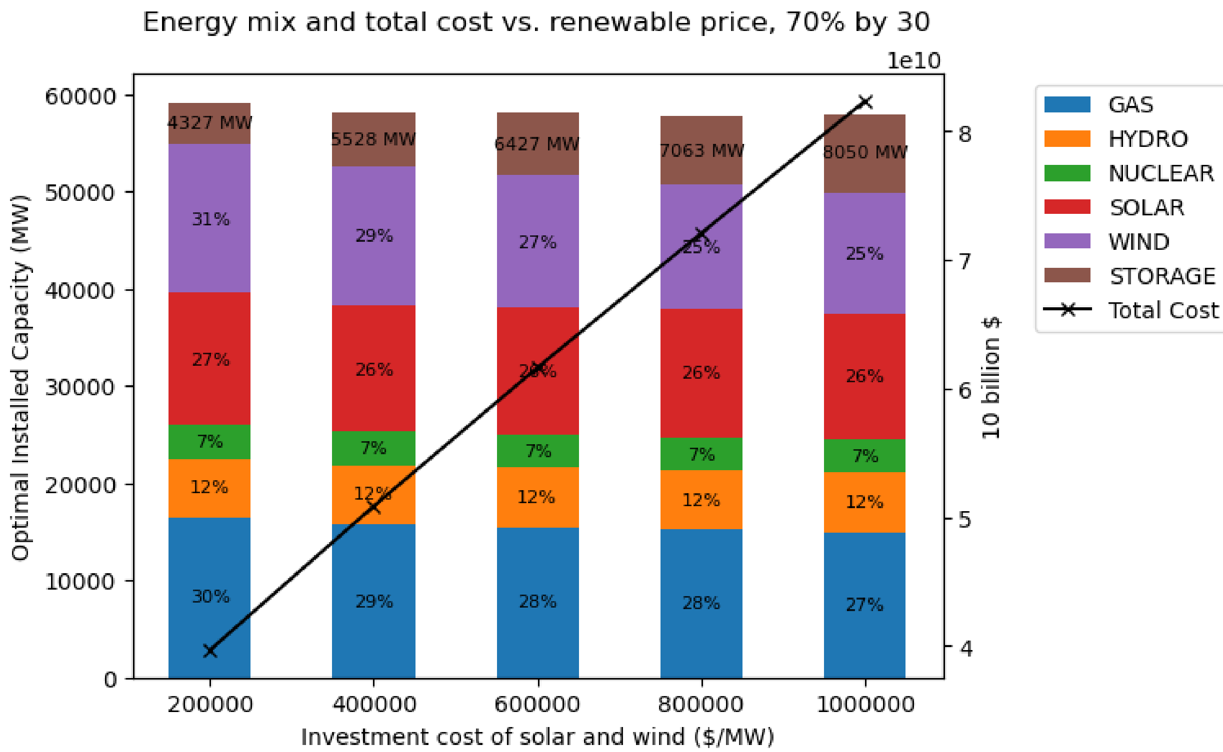
```
common_values = [("GAS",38.72,44.9,1237000),
                 ("WIND",0,0,None),  # None will be replaced by the 
actual value in the loop
                 ("SOLAR",0,0,None),  # None will be replaced by the 
actual value in the loop
                 ("NUCLEAR",22.73,0,0),
                ("HYDRO", 12.44,0,0)]

invest_costs = [400000, 800000, 1200000, 1600000, 2000000]

df_names = []
for cost in invest_costs:
    data = [list(item) for item in common_values]  # Create a copy of 
the common values
    data[1][-1] = cost  # Update the investment cost for wind
    data[2][-1] = cost  # Update the investment cost for solar
    df = pd.DataFrame(data, columns=["G", "operating_cost", 
"social_cost","invest_cost_g"]).set_index("G")
    df_names.append(df)

summary_df_sa_renewable = pd.DataFrame(columns=['GAS','HYDRO', 
'NUCLEAR', 'SOLAR', 'WIND', 'STORAGE', 'TOTAL_COST'])

for i in range(len(df_names)):
    ampl = AMPL()
```

```
    solver = 'gurobi'
    ampl.set_option("solver", solver)
    ampl.read('final_proj_decarb.mod')

    # Define sets and parameters
    ampl.set_data(df_names[i], "G")
    ampl.set_data(cost_N_df, "N")
    ampl.set_data(storage_df, "S")
    ampl.param['nPeriods'] = len(demand_2030)
    ampl.param['power_viol_penalty'] = 10000
    ampl.param['demand'] = demand_2030
    ampl.param['availability'] = avail_2030
    ampl.param['decarb_percent'] = 0.7
    capacity_g = ampl.get_variable("capacity_g")
    capacity_g['NUCLEAR'].fix(3400) #3.4 GW of nuclear
    capacity_g['HYDRO'].fix(6085) #6.085 GW of hydro
    ampl.solve()

    # Get resource mix
    resource_mix_list =
np.array(ampl.get_variable("capacity_g").get_values().to_pandas()).fla
tten()

    # Get storage capacity
    storage_mix_list =
np.array(ampl.get_variable("capacity_s").get_values().to_pandas()).fla
tten()

    # Get total cost
    total_cost_list =
np.array(ampl.get_objective("total_cost").get_values().to_pandas()).fl
atten()

    # Create DataFrame for current iteration
    iteration_df = pd.DataFrame({
        'GAS': resource_mix_list[0],
        'HYDRO': resource_mix_list[1],
        'NUCLEAR': resource_mix_list[2],
        'SOLAR': resource_mix_list[3],
        'WIND': resource_mix_list[4],
        'STORAGE': storage_mix_list[0],
        'TOTAL_COST': total_cost_list[0]
    }, index=[0])

    # Concatenate iteration DataFrame to summary DataFrame
    summary_df_sa_renewable = pd.concat([summary_df_sa_renewable,
iteration_df], ignore_index=True)
```

```
Gurobi 11.0.1:Gurobi 11.0.1: optimal solution; objective
3.967338173e+10
```

```
60826 simplex iterations
1 branching node
absmipgap=0.015274, relmipgap=3.84995e-13
Gurobi 11.0.1:Gurobi 11.0.1: optimal solution; objective
5.085728427e+10
54134 simplex iterations
1 branching node
absmipgap=0.0126953, relmipgap=2.49626e-13
Gurobi 11.0.1:Gurobi 11.0.1: optimal solution; objective
6.162979222e+10
58612 simplex iterations
1 branching node
absmipgap=0.020874, relmipgap=3.387e-13
Gurobi 11.0.1:Gurobi 11.0.1: optimal solution; objective
7.208203728e+10
56075 simplex iterations
1 branching node
absmipgap=0.0227356, relmipgap=3.15413e-13
Gurobi 11.0.1:Gurobi 11.0.1: optimal solution; objective
8.235124054e+10
57469 simplex iterations
1 branching node
absmipgap=0.0393524, relmipgap=4.77861e-13
```

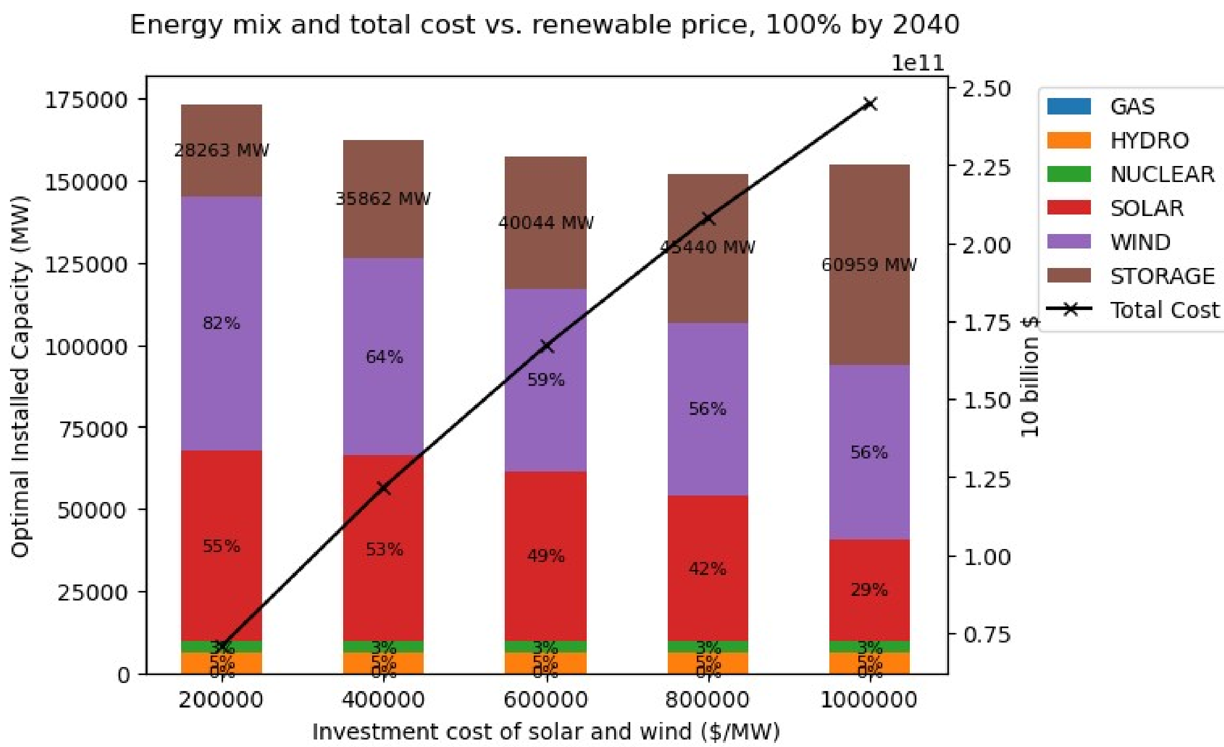
```
graph_stacked_bar(summary_df_sa_renewable,"Investment cost of solar
and wind ($/MW)","Energy mix and total cost vs. renewable price, 70%
by 30")
```




```
summary_df_sa_renewable_100_by_2040 =
pd.DataFrame(columns=['GAS','HYDRO', 'NUCLEAR', 'SOLAR', 'WIND',
'STORAGE', 'TOTAL_COST'])

for i in range(len(df_names)):
    ampl = AMPL()
    solver = 'gurobi'
    ampl.set_option("solver", solver)
    ampl.read('final_proj_decarb.mod')

    # Define sets and parameters
    ampl.set_data(df_names[i], "G")
    ampl.set_data(cost_N_df, "N")
    ampl.set_data(storage_df, "S")
    ampl.param['nPeriods'] = len(demand_2040)
    ampl.param['power_viol_penalty'] = 10000
    ampl.param['demand'] = demand_2040
    ampl.param['availability'] = avail_2040
    ampl.param['decarb_percent'] = 1.0
    capacity_g = ampl.get_variable("capacity_g")
    capacity_g['NUCLEAR'].fix(3400) #3.4 GW of nuclear
    capacity_g['HYDRO'].fix(6085) #6.085 GW of hydro
    ampl.solve()

    # Get resource mix
    resource_mix_list =
```

```
np.array(ampl.get_variable("capacity_g").get_values().to_pandas()).fla
tten()

    # Get storage capacity
    storage_mix_list =
np.array(ampl.get_variable("capacity_s").get_values().to_pandas()).fla
tten()

    # Get total cost
    total_cost_list =
np.array(ampl.get_objective("total_cost").get_values().to_pandas()).fl
atten()

    # Create DataFrame for current iteration
    iteration_df = pd.DataFrame({
        'GAS': resource_mix_list[0],
        'HYDRO': resource_mix_list[1],
        'NUCLEAR': resource_mix_list[2],
        'SOLAR': resource_mix_list[3],
        'WIND': resource_mix_list[4],
        'STORAGE': storage_mix_list[0],
        'TOTAL_COST': total_cost_list[0]
    }, index=[0])

    # Concatenate iteration DataFrame to summary DataFrame
    summary_df_sa_renewable_100_by_2040 =
pd.concat([summary_df_sa_renewable_100_by_2040, iteration_df],
ignore_index=True)

Gurobi 11.0.1:Gurobi 11.0.1: optimal solution; objective
7.083328443e+10
25248 simplex iterations
1 branching node
Gurobi 11.0.1:Gurobi 11.0.1: optimal solution; objective
1.217336758e+11
28466 simplex iterations
1 branching node
absmipgap=0.00393677, relmipgap=3.23392e-14
Gurobi 11.0.1:Gurobi 11.0.1: optimal solution; objective
1.669832646e+11
33757 simplex iterations
1 branching node
Gurobi 11.0.1:Gurobi 11.0.1: optimal solution; objective
2.081232416e+11
32875 simplex iterations
1 branching node
absmipgap=0.0067749, relmipgap=3.25524e-14
Gurobi 11.0.1:Gurobi 11.0.1: optimal solution; objective
2.449179952e+11
```

```
39949 simplex iterations
1 branching node

graph_stacked_bar(summary_df_sa_renewable_100_by_2040,"Investment cost of solar and wind ($/MW)","Energy mix and total cost vs. renewable price, 100% by 2040")
```



5. Catastrophe

```
big_noise = np.random.normal(loc=-0.15, scale=0.25, size=len(avail_df))

avail_2030_catastrophe = avail_2030.copy()
avail_2030_catastrophe['SOLAR']+=big_noise
avail_2030_catastrophe['WIND']+=big_noise
avail_2030_catastrophe['HYDRO']+=big_noise
avail_2030_catastrophe['SOLAR'] = np.clip(avail_2030_catastrophe['SOLAR'], 0, 1)
avail_2030_catastrophe['WIND'] = np.clip(avail_2030_catastrophe['WIND'], 0, 1)
avail_2030_catastrophe['HYDRO'] = np.clip(avail_2030_catastrophe['HYDRO'], 0, 1)
```

The code below iterates over different weather availability variances

```
summary_df = pd.DataFrame(columns=['GAS', 'HYDRO','NUCLEAR', 'SOLAR', 'WIND', 'STORAGE', 'TOTAL_COST'])
```

```
for variance in np.linspace(0.05, 0.25, 5):
        # Initialize AMPL instance
        ampl = AMPL()
        solver = 'gurobi'
        ampl.set_option("solver", solver)
        ampl.read('final_proj_decarb.mod')

        # Define sets and parameters
        ampl.set_data(gen_df, "G")
        ampl.set_data(cost_N_df, "N")
        ampl.set_data(storage_df, "S")
        ampl.param['nPeriods'] = len(demand_2030)
        ampl.param['power_viol_penalty'] = 10000
        ampl.param['demand'] = demand_2030

        # Generate catastrophe scenario
        big_noise = np.random.normal(loc=0, scale=variance,
size=len(avail_df))
        avail_2030_catastrophe = avail_2030.copy()
        avail_2030_catastrophe['SOLAR']+=big_noise
        avail_2030_catastrophe['WIND']+=big_noise
        avail_2030_catastrophe['HYDRO']+=big_noise
        avail_2030_catastrophe['SOLAR'] =
np.clip(avail_2030_catastrophe['SOLAR'], 0, 1)
        avail_2030_catastrophe['WIND'] =
np.clip(avail_2030_catastrophe['WIND'], 0, 1)
        avail_2030_catastrophe['HYDRO'] =
np.clip(avail_2030_catastrophe['HYDRO'], 0, 1)

        ampl.param['availability'] = avail_2030_catastrophe
        ampl.param['decarb_percent'] = 70 / 100
        capacity_g = ampl.get_variable("capacity_g")
        capacity_g['NUCLEAR'].fix(3400) #3.4 GW of nuclear
        capacity_g['HYDRO'].fix(6085) #6.085 GW of hydro

        # help it run faster
        ampl.set_option('gurobi_options', 'mipgap=0.05')

        ampl.solve()

        resource_mix_list =
np.array(ampl.get_variable("capacity_g").get_values().to_pandas()).fla
tten()
        storage_mix_list =
np.array(ampl.get_variable("capacity_s").get_values().to_pandas()).fla
tten()
        total_cost_list =
np.array(ampl.get_objective("total_cost").get_values().to_pandas()).fl
atten()
```

```
        # Create DataFrame for current iteration
        iteration_df = pd.DataFrame({
            'GAS': resource_mix_list[0],
            'HYDRO': resource_mix_list[1],
            'NUCLEAR': resource_mix_list[2],
            'SOLAR': resource_mix_list[3],
            'WIND': resource_mix_list[4],
            'STORAGE': storage_mix_list[0],
            'TOTAL_COST': total_cost_list[0]
        }, index=[0])

        # Concatenate iteration DataFrame to summary DataFrame
        summary_df = pd.concat([summary_df, iteration_df],
ignore_index=True)
```

```
Gurobi 11.0.1:Gurobi 11.0.1: optimal solution; objective
6.346316149e+10
57515 simplex iterations
1 branching node
absmipgap=0.0230331, relmipgap=3.62937e-13
Gurobi 11.0.1:Gurobi 11.0.1: optimal solution; objective
6.359055403e+10
54262 simplex iterations
1 branching node
absmipgap=0.00360107, relmipgap=5.66291e-14
Gurobi 11.0.1:Gurobi 11.0.1: optimal solution; objective
6.280328025e+10
55950 simplex iterations
1 branching node
absmipgap=0.0492935, relmipgap=7.84888e-13
Gurobi 11.0.1:Gurobi 11.0.1: optimal solution; objective
6.246243397e+10
56347 simplex iterations
1 branching node
absmipgap=0.0483856, relmipgap=7.74636e-13
Gurobi 11.0.1:Gurobi 11.0.1: optimal solution; objective
6.336075485e+10
50454 simplex iterations
1 branching node
absmipgap=0.063446, relmipgap=1.00135e-12
```

```
catastrophe_df=summary_df.copy()

summary_df = pd.DataFrame(columns=['GAS', 'HYDRO','NUCLEAR', 'SOLAR',
'WIND', 'STORAGE', 'TOTAL_COST'])

for variance in np.linspace(0.05, 0.25, 5):
        # Initialize AMPL instance
        ampl = AMPL()
```

```
        solver = 'gurobi'
        ampl.set_option("solver", solver)
        ampl.read('final_proj_decarb.mod')

        # Define sets and parameters
        ampl.set_data(gen_df, "G")
        ampl.set_data(cost_N_df, "N")
        ampl.set_data(storage_df, "S")
        ampl.param['nPeriods'] = len(demand_2030)
        ampl.param['power_viol_penalty'] = 10000
        ampl.param['demand'] = demand_2030

        # Generate catastrophe scenario
        big_noise = np.random.normal(loc=0, scale=variance,
size=len(avail_df))
        avail_2030_catastrophe = avail_2030.copy()
        avail_2030_catastrophe['SOLAR']+=big_noise
        avail_2030_catastrophe['WIND']+=big_noise
        avail_2030_catastrophe['HYDRO']+=big_noise
        avail_2030_catastrophe['SOLAR'] =
np.clip(avail_2030_catastrophe['SOLAR'], 0, 1)
        avail_2030_catastrophe['WIND'] =
np.clip(avail_2030_catastrophe['WIND'], 0, 1)
        avail_2030_catastrophe['HYDRO'] =
np.clip(avail_2030_catastrophe['HYDRO'], 0, 1)

        ampl.param['availability'] = avail_2030_catastrophe
        ampl.param['decarb_percent'] = 70 / 100
        capacity_g = ampl.get_variable("capacity_g")
        capacity_g['NUCLEAR'].fix(3400) #3.4 GW of nuclear
        capacity_g['HYDRO'].fix(6085) #6.085 GW of hydro

        # help it run faster
        ampl.set_option('gurobi_options', 'mipgap=0.1')

        ampl.solve()

        resource_mix_list =
np.array(ampl.get_variable("capacity_g").get_values().to_pandas()).fla
tten()
        storage_mix_list =
np.array(ampl.get_variable("capacity_s").get_values().to_pandas()).fla
tten()
        total_cost_list =
np.array(ampl.get_objective("total_cost").get_values().to_pandas()).fl
atten()

        # Create DataFrame for current iteration
        iteration_df = pd.DataFrame({
            'GAS': resource_mix_list[0],
```

```
            'HYDRO': resource_mix_list[1],
            'NUCLEAR': resource_mix_list[2],
            'SOLAR': resource_mix_list[3],
            'WIND': resource_mix_list[4],
            'STORAGE': storage_mix_list[0],
            'TOTAL_COST': total_cost_list[0]
        }, index=[0])

        # Concatenate iteration DataFrame to summary DataFrame
        summary_df = pd.concat([summary_df, iteration_df],
ignore_index=True)
```

```
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 6.390302321e+10
62777 simplex iterations
1 branching node
absmipgap=0.0358505, relmipgap=5.61015e-13
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 6.335686412e+10
55708 simplex iterations
1 branching node
absmipgap=0.0291824, relmipgap=4.60604e-13
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 6.308082293e+10
54469 simplex iterations
1 branching node
absmipgap=0.0184631, relmipgap=2.9269e-13
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 6.38850283e+10
52620 simplex iterations
1 branching node
absmipgap=0.0635681, relmipgap=9.95039e-13
Gurobi 11.0.1:
```

Iterate over 10 times, mean = -0.1

```
# Initialize a list to store the results of each run
summary_dfs = []

# Number of runs
n_runs = 10

for run in range(n_runs):
    summary_df = pd.DataFrame(columns=['GAS', 'HYDRO','NUCLEAR',
'SOLAR', 'WIND', 'STORAGE', 'TOTAL_COST'])

    for variance in np.linspace(0.05, 0.25, 5):
        # Initialize AMPL instance
        ampl = AMPL()
        solver = 'gurobi'
```

```
        ampl.set_option("solver", solver)
        ampl.read('final_proj_decarb.mod')

        # Define sets and parameters
        ampl.set_data(gen_df, "G")
        ampl.set_data(cost_N_df, "N")
        ampl.set_data(storage_df, "S")
        ampl.param['nPeriods'] = len(demand_2030)
        ampl.param['power_viol_penalty'] = 10000
        ampl.param['demand'] = demand_2030

        # Generate catastrophe scenario
        big_noise = np.random.normal(loc=-0.1, scale=variance,
size=len(avail_df))
        avail_2030_catastrophe = avail_2030.copy()
        avail_2030_catastrophe['SOLAR']+=big_noise
        avail_2030_catastrophe['WIND']+=big_noise
        avail_2030_catastrophe['HYDRO']+=big_noise
        avail_2030_catastrophe['SOLAR'] =
np.clip(avail_2030_catastrophe['SOLAR'], 0, 1)
        avail_2030_catastrophe['WIND'] =
np.clip(avail_2030_catastrophe['WIND'], 0, 1)
        avail_2030_catastrophe['HYDRO'] =
np.clip(avail_2030_catastrophe['HYDRO'], 0, 1)

        ampl.param['availability'] = avail_2030_catastrophe
        ampl.param['decarb_percent'] = 70 / 100
        capacity_g = ampl.get_variable("capacity_g")
        capacity_g['NUCLEAR'].fix(3400) #3.4 GW of nuclear
        capacity_g['HYDRO'].fix(6085) #6.085 GW of hydro

        # help it run faster
        ampl.set_option('gurobi_options', 'mipgap=0.1')

        ampl.solve()

        resource_mix_list =
np.array(ampl.get_variable("capacity_g").get_values().to_pandas()).fla
tten()
        storage_mix_list =
np.array(ampl.get_variable("capacity_s").get_values().to_pandas()).fla
tten()
        total_cost_list =
np.array(ampl.get_objective("total_cost").get_values().to_pandas()).fl
atten()

        # Create DataFrame for current iteration
        iteration_df = pd.DataFrame({
            'GAS': resource_mix_list[0],
            'HYDRO': resource_mix_list[1],
```

```
            'NUCLEAR': resource_mix_list[2],
            'SOLAR': resource_mix_list[3],
            'WIND': resource_mix_list[4],
            'STORAGE': storage_mix_list[0],
            'TOTAL_COST': total_cost_list[0]
        }, index=[0])

        # Concatenate iteration DataFrame to summary DataFrame
        summary_df = pd.concat([summary_df, iteration_df],
ignore_index=True)

    # Append the summary DataFrame of this run to the list
    summary_dfs.append(summary_df)

# Concatenate all the summary DataFrames
all_runs_df = pd.concat(summary_dfs)

# Calculate the average for each column
average_df = all_runs_df.groupby(all_runs_df.index).mean()

all_runs_df.to_csv('./catastrophe_10_runs_mean_neg01.csv')
```

```
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 7.265710043e+10
50188 simplex iterations
1 branching node
absmipgap=0.0100555, relmipgap=1.38397e-13
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 7.196941211e+10
52170 simplex iterations
1 branching node
absmipgap=0.0124969, relmipgap=1.73642e-13
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 7.133899088e+10
60217 simplex iterations
1 branching node
absmipgap=0.0472107, relmipgap=6.6178e-13
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 7.076766546e+10
56622 simplex iterations
1 branching node
absmipgap=0.00584412, relmipgap=8.25817e-14
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 6.946483122e+10
49620 simplex iterations
1 branching node
absmipgap=0.0401154, relmipgap=5.77492e-13
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 7.236780336e+10
65057 simplex iterations
```

```
1 branching node
absmipgap=0.00210571, relmipgap=2.90974e-14
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 7.251341233e+10
55664 simplex iterations
1 branching node
absmipgap=0.0102844, relmipgap=1.41828e-13
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 7.142015767e+10
55396 simplex iterations
1 branching node
absmipgap=0.00531006, relmipgap=7.43496e-14
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 7.041785386e+10
48391 simplex iterations
1 branching node
absmipgap=0.0614624, relmipgap=8.72824e-13
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 7.035779237e+10
57106 simplex iterations
1 branching node
absmipgap=0.0539093, relmipgap=7.66217e-13
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 7.277936113e+10
62509 simplex iterations
1 branching node
absmipgap=0.00256348, relmipgap=3.52226e-14
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 7.176316705e+10
51629 simplex iterations
1 branching node
absmipgap=0.0256195, relmipgap=3.57001e-13
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 7.128653255e+10
53926 simplex iterations
1 branching node
absmipgap=0.0179749, relmipgap=2.52149e-13
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 7.032388933e+10
52676 simplex iterations
1 branching node
absmipgap=0.0446167, relmipgap=6.34446e-13
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 6.850276332e+10
50881 simplex iterations
1 branching node
absmipgap=0.0326691, relmipgap=4.76901e-13
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 7.276105593e+10
```

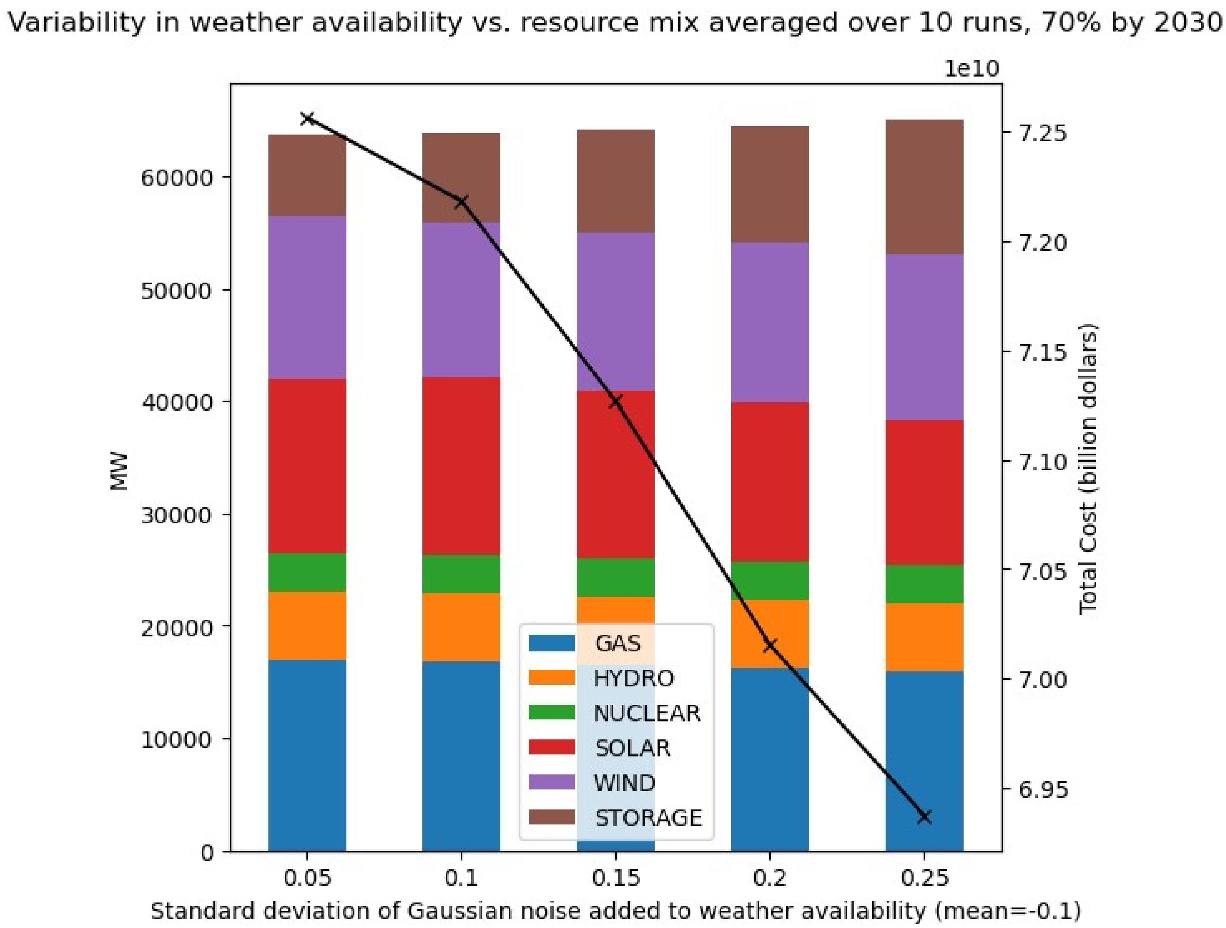
```
55241 simplex iterations
1 branching node
absmipgap=0.00572205, relmipgap=7.86416e-14
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 7.216685313e+10
54913 simplex iterations
1 branching node
absmipgap=0.00938416, relmipgap=1.30034e-13
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 7.116663233e+10
60936 simplex iterations
1 branching node
absmipgap=0.0141144, relmipgap=1.98329e-13
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 7.004030509e+10
50689 simplex iterations
1 branching node
absmipgap=0.0264587, relmipgap=3.77764e-13
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 6.989265554e+10
51334 simplex iterations
1 branching node
absmipgap=0.0533142, relmipgap=7.62801e-13
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 7.251634067e+10
48756 simplex iterations
1 branching node
absmipgap=0.00593567, relmipgap=8.18528e-14
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 7.225044063e+10
47501 simplex iterations
1 branching node
absmipgap=0.012146, relmipgap=1.6811e-13
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 7.230614852e+10
54996 simplex iterations
1 branching node
absmipgap=0.0299683, relmipgap=4.14464e-13
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 7.041578257e+10
54221 simplex iterations
1 branching node
absmipgap=0.00465393, relmipgap=6.60922e-14
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 7.008411609e+10
65934 simplex iterations
1 branching node
absmipgap=0.026001, relmipgap=3.70997e-13
Gurobi 11.0.1:   mip:gap = 0.1
```

```
Gurobi 11.0.1: optimal solution; objective 7.228816663e+10
54006 simplex iterations
1 branching node
absmipgap=0.00289917, relmipgap=4.01057e-14
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 7.22133827e+10
53906 simplex iterations
1 branching node
absmipgap=0.0239258, relmipgap=3.31321e-13
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 7.127417272e+10
46950 simplex iterations
1 branching node
absmipgap=0.00427246, relmipgap=5.9944e-14
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 7.036654428e+10
52318 simplex iterations
1 branching node
absmipgap=0.0304108, relmipgap=4.32176e-13
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 6.89411526e+10
49162 simplex iterations
1 branching node
absmipgap=0.0361023, relmipgap=5.23668e-13
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 7.240010184e+10
54126 simplex iterations
1 branching node
absmipgap=0.00376892, relmipgap=5.20568e-14
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 7.24395108e+10
68548 simplex iterations
1 branching node
absmipgap=0.00662231, relmipgap=9.14185e-14
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 7.059048996e+10
50004 simplex iterations
1 branching node
absmipgap=0.0109406, relmipgap=1.54986e-13
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 7.051259632e+10
56987 simplex iterations
1 branching node
absmipgap=0.00675964, relmipgap=9.58643e-14
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 6.930407149e+10
50933 simplex iterations
1 branching node
absmipgap=0.0314941, relmipgap=4.54434e-13
```

```
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 7.226250037e+10
50561 simplex iterations
1 branching node
absmipgap=0.00331116, relmipgap=4.58212e-14
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 7.198685679e+10
50285 simplex iterations
1 branching node
absmipgap=0.00538635, relmipgap=7.48241e-14
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 7.108907044e+10
71833 simplex iterations
1 branching node
absmipgap=0.0402679, relmipgap=5.66444e-13
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 6.910745924e+10
54071 simplex iterations
1 branching node
absmipgap=0.00935364, relmipgap=1.35349e-13
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 6.83643622e+10
58437 simplex iterations
1 branching node
absmipgap=0.0303726, relmipgap=4.44276e-13
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 7.261495833e+10
52624 simplex iterations
1 branching node
absmipgap=0.0027771, relmipgap=3.82442e-14
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 7.229874965e+10
55938 simplex iterations
1 branching node
absmipgap=0.0256042, relmipgap=3.54145e-13
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 7.147195983e+10
59435 simplex iterations
1 branching node
absmipgap=0.0244598, relmipgap=3.4223e-13
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 7.036850689e+10
52774 simplex iterations
1 branching node
absmipgap=0.0182343, relmipgap=2.59125e-13
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 7.01946656e+10
52225 simplex iterations
1 branching node
```

```
absmipgap=0.00798035, relmipgap=1.13689e-13
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 7.298430686e+10
49747 simplex iterations
1 branching node
absmipgap=0.00361633, relmipgap=4.95495e-14
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 7.221835821e+10
55104 simplex iterations
1 branching node
absmipgap=0.00376892, relmipgap=5.21879e-14
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 7.072943207e+10
50321 simplex iterations
1 branching node
absmipgap=0.025238, relmipgap=3.56825e-13
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 6.920801273e+10
54920 simplex iterations
1 branching node
absmipgap=0.0728912, relmipgap=1.05322e-12
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 6.863059499e+10
51528 simplex iterations
1 branching node
absmipgap=0.0397339, relmipgap=5.78953e-13
```

```
catastrophe_10_runs_mean_neg01 =
pd.read_csv('./catastrophe_10_runs_mean_neg01.csv')
avg_df =
catastrophe_10_runs_mean_neg01.groupby(catastrophe_10_runs_mean_neg01[
'Unnamed: 0']).mean()
catastrophe_df_reset = avg_df.reset_index()
ax = catastrophe_df_reset[['GAS', 'HYDRO','NUCLEAR', 'SOLAR', 'WIND',
'STORAGE']].plot(kind='bar', stacked=True, figsize=(6, 6))
catastrophe_df_reset['TOTAL_COST'].plot(kind='line', marker='x',
color='k', secondary_y=True,ax=ax)

ax.set_xlabel('Standard deviation of Gaussian noise added to weather
availability (mean=-0.1)')
ax.set_ylabel('MW')
ax.right_ax.set_ylabel('Total Cost (billion dollars)')

plt.title('Variability in weather availability vs. resource mix
averaged over 10 runs, 70% by 2030',y=1.05)
variance_range = [str(i/20) for i in range(1,6)]
plt.xticks(range(5), variance_range)
plt.show()
```



Iterate over 10 times, mean = 0

```
# Initialize a list to store the results of each run
summary_dfs = []

# Number of runs
n_runs = 10

for run in range(n_runs):
    summary_df = pd.DataFrame(columns=['GAS', 'HYDRO','NUCLEAR',
'SOLAR', 'WIND', 'STORAGE', 'TOTAL_COST'])

    for variance in np.linspace(0.05, 0.25, 5):
        # Initialize AMPL instance
        ampl = AMPL()
        solver = 'gurobi'
        ampl.set_option("solver", solver)
        ampl.read('final_proj_decarb.mod')

        # Define sets and parameters
        ampl.set_data(gen_df, "G")
        ampl.set_data(cost_N_df, "N")
```

```
        ampl.set_data(storage_df, "S")
        ampl.param['nPeriods'] = len(demand_2030)
        ampl.param['power_viol_penalty'] = 10000
        ampl.param['demand'] = demand_2030

        # Generate catastrophe scenario
        big_noise = np.random.normal(loc=0, scale=variance,
size=len(avail_df))
        avail_2030_catastrophe = avail_2030.copy()
        avail_2030_catastrophe['SOLAR']+=big_noise
        avail_2030_catastrophe['WIND']+=big_noise
        avail_2030_catastrophe['HYDRO']+=big_noise
        avail_2030_catastrophe['SOLAR'] =
np.clip(avail_2030_catastrophe['SOLAR'], 0, 1)
        avail_2030_catastrophe['WIND'] =
np.clip(avail_2030_catastrophe['WIND'], 0, 1)
        avail_2030_catastrophe['HYDRO'] =
np.clip(avail_2030_catastrophe['HYDRO'], 0, 1)

        ampl.param['availability'] = avail_2030_catastrophe
        ampl.param['decarb_percent'] = 70 / 100
        capacity_g = ampl.get_variable("capacity_g")
        capacity_g['NUCLEAR'].fix(3400) #3.4 GW of nuclear
        capacity_g['HYDRO'].fix(6085) #6.085 GW of hydro

        # help it run faster
        ampl.set_option('gurobi_options', 'mipgap=0.1')

        ampl.solve()

        resource_mix_list =
np.array(ampl.get_variable("capacity_g").get_values().to_pandas()).fla
tten()
        storage_mix_list =
np.array(ampl.get_variable("capacity_s").get_values().to_pandas()).fla
tten()
        total_cost_list =
np.array(ampl.get_objective("total_cost").get_values().to_pandas()).fl
atten()

        # Create DataFrame for current iteration
        iteration_df = pd.DataFrame({
            'GAS': resource_mix_list[0],
            'HYDRO': resource_mix_list[1],
            'NUCLEAR': resource_mix_list[2],
            'SOLAR': resource_mix_list[3],
            'WIND': resource_mix_list[4],
            'STORAGE': storage_mix_list[0],
            'TOTAL_COST': total_cost_list[0]
        }, index=[0])
```

```
        # Concatenate iteration DataFrame to summary DataFrame
        summary_df = pd.concat([summary_df, iteration_df],
ignore_index=True)

    # Append the summary DataFrame of this run to the list
    summary_dfs.append(summary_df)

# Concatenate all the summary DataFrames
all_runs_df = pd.concat(summary_dfs)

# Calculate the average for each column
average_df = all_runs_df.groupby(all_runs_df.index).mean()

Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 6.390718901e+10
60492 simplex iterations
1 branching node
absmipgap=0.00934601, relmipgap=1.46243e-13
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 6.355368073e+10
54726 simplex iterations
1 branching node
absmipgap=0.0323715, relmipgap=5.09357e-13
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 6.301630577e+10
56070 simplex iterations
1 branching node
absmipgap=0.0190887, relmipgap=3.02918e-13
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 6.163597435e+10
52908 simplex iterations
1 branching node
absmipgap=0.0413208, relmipgap=6.70401e-13
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 6.244162495e+10
51553 simplex iterations
1 branching node
absmipgap=0.0770493, relmipgap=1.23394e-12
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 6.391916516e+10
57818 simplex iterations
1 branching node
absmipgap=0.0299301, relmipgap=4.68249e-13
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 6.406696333e+10
56201 simplex iterations
1 branching node
absmipgap=0.0439529, relmipgap=6.86047e-13
Gurobi 11.0.1:   mip:gap = 0.1
```

```
Gurobi 11.0.1: optimal solution; objective 6.357991199e+10
54971 simplex iterations
1 branching node
absmipgap=0.0125504, relmipgap=1.97395e-13
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 6.357933809e+10
54299 simplex iterations
1 branching node
absmipgap=0.0981827, relmipgap=1.54425e-12
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 6.24730665e+10
56405 simplex iterations
1 branching node
absmipgap=0.0542068, relmipgap=8.67683e-13
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 6.378396409e+10
54179 simplex iterations
1 branching node
absmipgap=0.0208969, relmipgap=3.2762e-13
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 6.272425178e+10
52027 simplex iterations
1 branching node
absmipgap=0.0444565, relmipgap=7.08761e-13
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 6.357661729e+10
65220 simplex iterations
1 branching node
absmipgap=0.0475693, relmipgap=7.4822e-13
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 6.329563339e+10
55153 simplex iterations
1 branching node
absmipgap=0.0255585, relmipgap=4.03795e-13
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 6.251720583e+10
56100 simplex iterations
1 branching node
absmipgap=0.0285797, relmipgap=4.5715e-13
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 6.401760388e+10
55799 simplex iterations
1 branching node
absmipgap=0.0233917, relmipgap=3.65395e-13
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 6.392640243e+10
68994 simplex iterations
1 branching node
absmipgap=0.02565, relmipgap=4.01243e-13
```

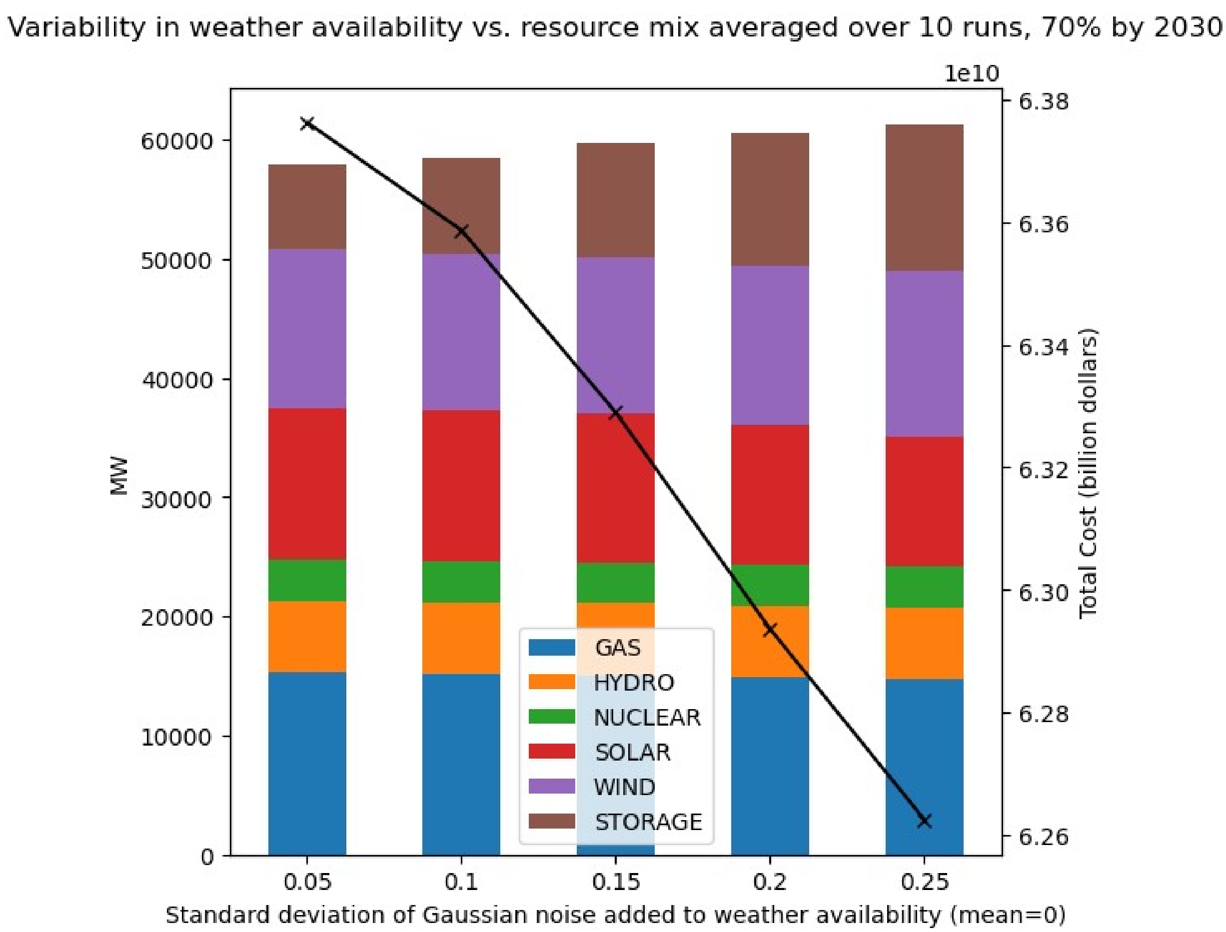
```
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 6.365935584e+10
52844 simplex iterations
1 branching node
absmipgap=0.0460968, relmipgap=7.24117e-13
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 6.375956902e+10
64825 simplex iterations
1 branching node
absmipgap=0.0552521, relmipgap=8.66569e-13
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 6.218602696e+10
53103 simplex iterations
1 branching node
absmipgap=0.0839157, relmipgap=1.34943e-12
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 6.408728821e+10
51817 simplex iterations
1 branching node
absmipgap=0.0161362, relmipgap=2.51784e-13
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 6.327772456e+10
53228 simplex iterations
1 branching node
absmipgap=0.0272522, relmipgap=4.30676e-13
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 6.341393185e+10
53314 simplex iterations
1 branching node
absmipgap=0.0369186, relmipgap=5.82185e-13
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 6.230412508e+10
56149 simplex iterations
1 branching node
absmipgap=0.0740891, relmipgap=1.18915e-12
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 6.321363481e+10
51126 simplex iterations
1 branching node
absmipgap=0.0731583, relmipgap=1.15732e-12
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 6.360797887e+10
51191 simplex iterations
1 branching node
absmipgap=0.0135727, relmipgap=2.1338e-13
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 6.388675474e+10
54193 simplex iterations
1 branching node
```

```
absmipgap=0.0400391, relmipgap=6.26719e-13
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 6.331383072e+10
56673 simplex iterations
1 branching node
absmipgap=0.0243912, relmipgap=3.85242e-13
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 6.28773807e+10
53807 simplex iterations
1 branching node
absmipgap=0.0767822, relmipgap=1.22114e-12
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 6.140459978e+10
55654 simplex iterations
1 branching node
absmipgap=0.0876389, relmipgap=1.42724e-12
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 6.337603261e+10
53851 simplex iterations
1 branching node
absmipgap=0.0443268, relmipgap=6.99425e-13
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 6.369500146e+10
55651 simplex iterations
1 branching node
absmipgap=0.0392151, relmipgap=6.1567e-13
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 6.352296851e+10
57156 simplex iterations
1 branching node
absmipgap=0.0205154, relmipgap=3.22961e-13
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 6.303522933e+10
50887 simplex iterations
1 branching node
absmipgap=0.0591354, relmipgap=9.38133e-13
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 6.286462334e+10
62792 simplex iterations
1 branching node
absmipgap=0.088089, relmipgap=1.40125e-12
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 6.360661551e+10
52665 simplex iterations
1 branching node
absmipgap=0.023468, relmipgap=3.68956e-13
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 6.291551261e+10
60733 simplex iterations
```

```
1 branching node
absmipgap=0.0389252, relmipgap=6.1869e-13
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 6.304383701e+10
56345 simplex iterations
1 branching node
absmipgap=0.0668793, relmipgap=1.06084e-12
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 6.317598064e+10
55373 simplex iterations
1 branching node
absmipgap=0.0896454, relmipgap=1.41898e-12
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 6.296596827e+10
60054 simplex iterations
1 branching node
absmipgap=0.0905685, relmipgap=1.43837e-12
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 6.399338558e+10
58957 simplex iterations
1 branching node
absmipgap=0.022316, relmipgap=3.48723e-13
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 6.344701025e+10
55691 simplex iterations
1 branching node
absmipgap=0.0606766, relmipgap=9.56335e-13
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 6.282357303e+10
66199 simplex iterations
1 branching node
absmipgap=0.0476532, relmipgap=7.58524e-13
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 6.302945968e+10
66223 simplex iterations
1 branching node
absmipgap=0.0445938, relmipgap=7.07507e-13
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 6.381296517e+10
53070 simplex iterations
1 branching node
absmipgap=0.0228424, relmipgap=3.57959e-13
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 6.333059911e+10
57375 simplex iterations
1 branching node
absmipgap=0.00511169, relmipgap=8.07144e-14
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 6.437890832e+10
```

```
53041 simplex iterations
1 branching node
absmipgap=0.0410614, relmipgap=6.37808e-13
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 6.294840564e+10
59792 simplex iterations
1 branching node
absmipgap=0.0503769, relmipgap=8.00289e-13
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 6.267002e+10
53300 simplex iterations
1 branching node
absmipgap=0.0307083, relmipgap=4.9e-13
Gurobi 11.0.1:   mip:gap = 0.1
Gurobi 11.0.1: optimal solution; objective 6.236964736e+10
52816 simplex iterations
1 branching node
absmipgap=0.0645905, relmipgap=1.03561e-12
```

```
catastrophe_10_runs_mean0 = pd.read_csv('./catastrophe_10_runs_mean0')
avg_df =
catastrophe_10_runs_mean0.groupby(catastrophe_10_runs_mean0['Unnamed:
0']).mean()
catastrophe_df_reset = avg_df.reset_index()
ax = catastrophe_df_reset[['GAS', 'HYDRO','NUCLEAR', 'SOLAR', 'WIND',
'STORAGE']].plot(kind='bar', stacked=True, figsize=(6, 6))
catastrophe_df_reset['TOTAL_COST'].plot(kind='line', marker='x',
color='k', secondary_y=True,ax=ax)

ax.set_xlabel('Standard deviation of Gaussian noise added to weather
availability (mean=0)')
ax.set_ylabel('MW')
ax.right_ax.set_ylabel('Total Cost (billion dollars)')

plt.title('Variability in weather availability vs. resource mix
averaged over 10 runs, 70% by 2030',y=1.05)
variance_range = [str(i/20) for i in range(1,6)]
plt.xticks(range(5), variance_range)
plt.show()
```



Unused code

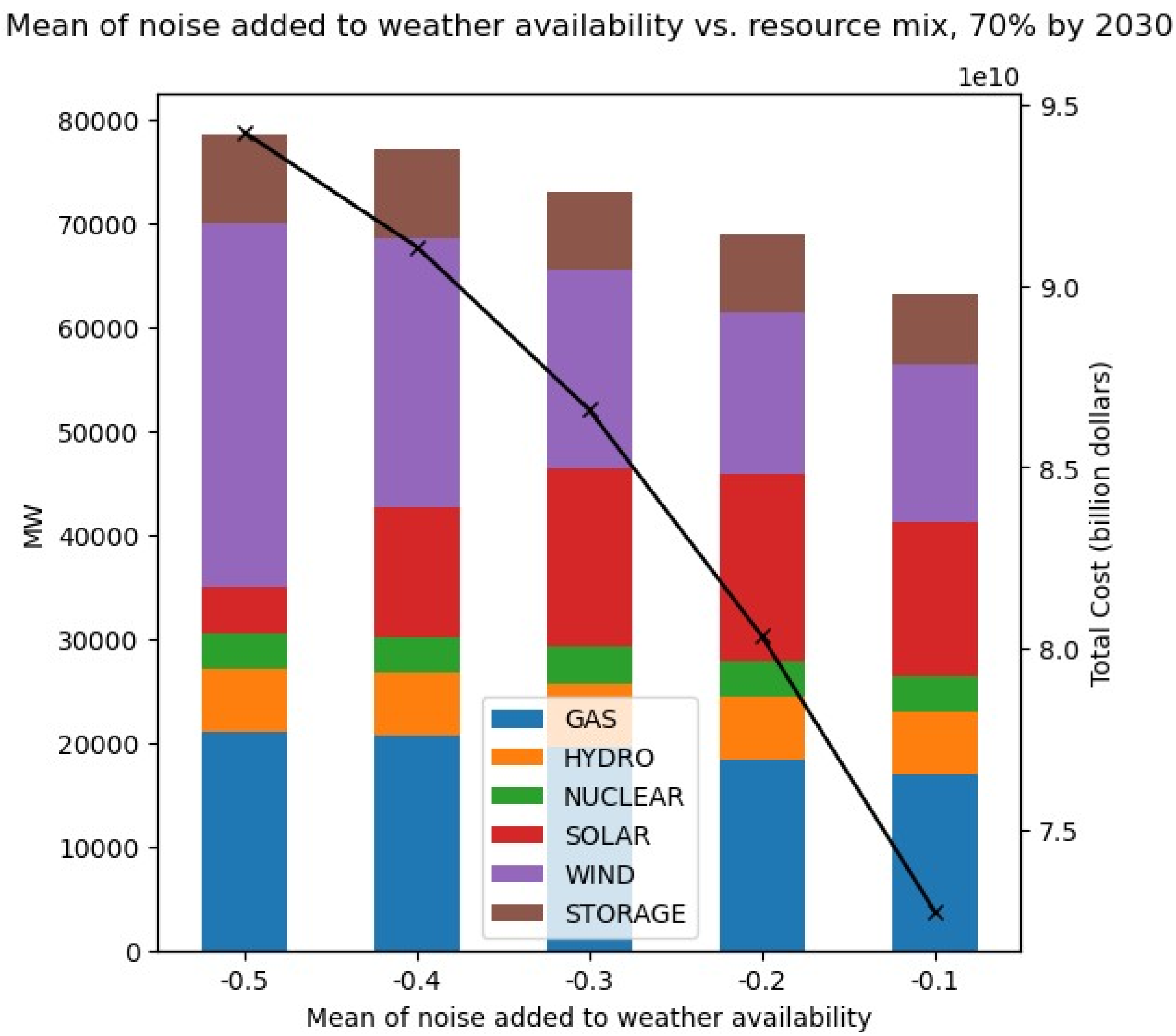
```
summary_df = pd.DataFrame(columns=['GAS', 'HYDRO','NUCLEAR', 'SOLAR',
'WIND', 'STORAGE', 'TOTAL_COST'])

for mean in np.arange(-0.5,0,0.1):
        # Initialize AMPL instance
        ampl = AMPL()
        solver = 'gurobi'
        ampl.set_option("solver", solver)
        ampl.read('final_proj_decarb.mod')

        # Define sets and parameters
        ampl.set_data(gen_df, "G")
        ampl.set_data(cost_N_df, "N")
        ampl.set_data(storage_df, "S")
        ampl.param['nPeriods'] = len(demand_2030)
        ampl.param['power_viol_penalty'] = 10000
        ampl.param['demand'] = demand_2030
```

```
        # Generate catastrophe scenario
        big_noise = np.random.normal(loc=mean, scale=0.05,
size=len(avail_df))
        avail_2030_catastrophe = avail_2030.copy()
        avail_2030_catastrophe['SOLAR']+=big_noise
        avail_2030_catastrophe['WIND']+=big_noise
        avail_2030_catastrophe['HYDRO']+=big_noise
        avail_2030_catastrophe['SOLAR'] =
np.clip(avail_2030_catastrophe['SOLAR'], 0, 1)
        avail_2030_catastrophe['WIND'] =
np.clip(avail_2030_catastrophe['WIND'], 0, 1)
        avail_2030_catastrophe['HYDRO'] =
np.clip(avail_2030_catastrophe['HYDRO'], 0, 1)

        ampl.param['availability'] = avail_2030_catastrophe
        ampl.param['decarb_percent'] = 70 / 100
        capacity_g = ampl.get_variable("capacity_g")
        capacity_g['NUCLEAR'].fix(3400) #3.4 GW of nuclear
        capacity_g['HYDRO'].fix(6085) #6.085 GW of hydro
        ampl.solve()

        resource_mix_list =
np.array(ampl.get_variable("capacity_g").get_values().to_pandas()).fla
tten()
        storage_mix_list =
np.array(ampl.get_variable("capacity_s").get_values().to_pandas()).fla
tten()
        total_cost_list =
np.array(ampl.get_objective("total_cost").get_values().to_pandas()).fl
atten()

        # Create DataFrame for current iteration
        iteration_df = pd.DataFrame({
            'GAS': resource_mix_list[0],
            'HYDRO': resource_mix_list[1],
            'NUCLEAR': resource_mix_list[2],
            'SOLAR': resource_mix_list[3],
            'WIND': resource_mix_list[4],
            'STORAGE': storage_mix_list[0],
            'TOTAL_COST': total_cost_list[0]
        }, index=[0])

        # Concatenate iteration DataFrame to summary DataFrame
        summary_df = pd.concat([summary_df, iteration_df],
ignore_index=True)
```

```
Gurobi 11.0.1:Gurobi 11.0.1: optimal solution; objective
9.424054097e+10
44638 simplex iterations
1 branching node
```

```
absmipgap=0.00683594, relmipgap=7.25371e-14
Gurobi 11.0.1:Gurobi 11.0.1: optimal solution; objective
9.107903031e+10
35748 simplex iterations
1 branching node
absmipgap=0.00630188, relmipgap=6.91913e-14
Gurobi 11.0.1:Gurobi 11.0.1: optimal solution; objective
8.659316515e+10
69946 simplex iterations
1 branching node
absmipgap=0.00248718, relmipgap=2.87226e-14
Gurobi 11.0.1:Gurobi 11.0.1: optimal solution; objective
8.035065113e+10
51625 simplex iterations
1 branching node
absmipgap=0.00228882, relmipgap=2.84854e-14
Gurobi 11.0.1:Gurobi 11.0.1: optimal solution; objective
7.276816547e+10
53849 simplex iterations
1 branching node
absmipgap=0.00454712, relmipgap=6.24878e-14
```

```
catastrophe_df_mean=summary_df.copy()

catastrophe_df_mean_reset = catastrophe_df_mean.reset_index()
ax = catastrophe_df_mean_reset[['GAS', 'HYDRO','NUCLEAR', 'SOLAR',
'WIND', 'STORAGE']].plot(kind='bar', stacked=True, figsize=(6, 6))
catastrophe_df_mean_reset['TOTAL_COST'].plot(kind='line', marker='x',
color='k', secondary_y=True,ax=ax)

ax.set_xlabel('Mean of noise added to weather availability')
ax.set_ylabel('MW')
ax.right_ax.set_ylabel('Total Cost (billion dollars)')

plt.title('Mean of noise added to weather availability vs. resource
mix, 70% by 2030',y=1.05)
variance_range = [str(-i/10) for i in range(5,0,-1)]
plt.xticks(range(5), variance_range)
plt.show()
```




```
n_years = 20

demand_repeated = np.tile(demand_df.values, (n_years, 1))
demand_n_year = pd.DataFrame(demand_repeated, columns=['demand'])
growth_rates = np.repeat([1.0005] * 10 + [1.0129] * 10,8760)
#([1.0005] * 10 + [1.0129] * 10 + [1.089] * 10,8760)
demand_n_year['growth_rate'] = growth_rates

demand_n_year['updated_demand'] = demand_n_year['demand']
for i in range(1, n_years):
    demand_n_year.loc[8760 * i:, 'updated_demand'] =
(demand_n_year.loc[8760 * (i - 1):, 'updated_demand']
                                                       *
demand_n_year.loc[8760 * i:, 'growth_rate'])
demand_n_year.index = demand_n_year.index +1
demand_n_year.drop(['demand', 'growth_rate'], axis=1, inplace=True)
demand_n_year.rename(columns={'updated_demand': 'demand'},
```

```
inplace=True)

demand_n_year.tail()
```

	demand
175196	2471.544619
175197	2478.050933
175198	2537.283907
175199	2613.190905
175200	2568.629032